Begging the Signalling Question:
Quantum Signalling and the Dynamics of Multiparticle Systems.

Kent A. Peacock

Department of Philosophy,
University of Lethbridge,
4401 University Drive,
Lethbridge, Alberta, Canada. T1K 3M4
kent.peacock@uleth.ca

Brian Hepburn

Departments of Philosophy and Physics,
University of Lethbridge,
4401 University Drive,
Lethbridge, Alberta, Canada. T1K 3M4
hepbbs@uleth.ca

ABSTRACT
The abundant experimental confirmation of Bell’s Theorem has made a compelling case for the nonlocality of quantum mechanics (QM), in the precise sense that quantum phenomena exhibit correlations between spacelike separate measurements that are inconsistent with any common cause explanation. Nevertheless, many authors state that this odd nonlocality could not involve any controllable superluminal transmission of momentum-energy, signals, or information, since there are several proofs in the literature apparently showing that the expectation value of any observable at one location in a phase-entangled multi-particle system cannot be affected by any choice of measurement strategy employed on some other spacelike-separate part of the system. However, we claim that most or all no-signalling proofs published to date are question-begging, in that they depend upon assumptions about the locality of the dynamics of the measurement process that are the very points that need to be established in the first place. In this paper, we undertake a critical examination of no-signalling proofs by Bohm and Hiley [1] and Shimony [2], which illustrate the problem in an especially striking way.

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Pronouncements of experts to the effect that something cannot be done have always irritated me.

—Leo Szilard [3, p. 28]

It seems to me that it is among the most sure-footed of quantum physicists, those who have it in their bones, that one finds the greatest impatience with the idea that the ‘foundations of quantum mechanics’ might need some attention. Knowing what is right by instinct, they can become a little impatient with nitpicking distinctions between theorems and assumptions.

—J. S. Bell [4, p. 33]

1 INTRODUCTION

Let us imagine a typical EPR (Einstein-Podolsky-Rosen) experimental scenario, in which a centrally-located source is sending out pair after pair of correlated particles, which we shall label $A$ and $B$, in opposite directions. At equal distances from the source we shall suppose that there are two detectors, $D_A$ and $D_B$, at rest with respect to the source. (We make these stipulations to evade the considerable complications entailed by relative motions of source and detectors.) At $D_A$ and $D_B$ sit Agents Mulder and Scully respectively, patiently writing down the results of each run of the apparatus. Mulder is holding his detector at a constant angle, while Scully varies her detector angle from time to time, hoping to send a message to her partner.

We know that the results recorded by Mulder and Scully will be correlated. To be a bit more specific, if the particles are fermions of spin 1/2, and if we are recording spin up or down in a particular direction, then the correlation will be given by $-\cos\theta_{AB}$, where $\theta_{AB}$ is the relative angle between the two detectors. We know that this correlation violates a Bell Inequality [1, p. 140–147], and we know that this means that the particular results our two agents get could not have been encoded in the particles when they left the source. But we also know that Scully’s attempts to communicate with Mulder directly will be thwarted, for no matter what manipulations she performs on her detector, all that either she or Mulder will record will be an apparently random sequence of ups and downs. Only when the two sequences of results are compared at a later time, will it be seen that correlations stand between them, satisfying the above formula.

The best that Scully can do is impose a signal upon the correlations by varying her detector angle; and indeed, this would make possible, in principle at least, the most theoretically perfect encryption scheme that one could imagine. Either agent’s string of random results would serve as the unique key for the other, and eavesdropping could be detected by a tendency of the results to obey a Bell Inequality (since eavesdropping destroys the correlations). But there does not seem to be any way that Scully can send a message that shows up in Mulder’s local statistics. If all she does is adjust her detector angle, Mulder just continues to see what looks like random noise. If, on the other hand, Scully interposes some magnets or other devices to force the particles to go through her detector in a particular direction, she will discover later on, after the results are compared, that not only does Mulder continue to receive random noise, but that she has also washed out the correlations.
The relativistic prohibition against superluminal signalling thus seems to be protected. However, Mulder is still puzzled, because he is swayed by Tim Maudlin’s very persuasive arguments that the violation of the Bell Inequalities in experiments such as this can only be accounted for by the assumption that there is some sort of superluminal causation, in apparent violation of the theory of relativity. Mulder is well aware that if there were something Scully could do that would preserve the correlation between their results, but at the same time allow her to control which way her particles go, then this would not only threaten causal paradoxes, but would allow him and Scully to synchronize their watches instantaneously and thereby violate Einstein’s relativity of simultaneity. But he quite fails to see why this might not, in principle at least, be possible. Finally, in utter frustration, Mulder concludes that there is a hidden conspiracy between quantum mechanics and relativity, such that relativity will always appear to be obeyed even when it is being covertly violated.

The ever-sensible Scully will assure Mulder that things are just as they should be, since numerous authors have published proofs demonstrating, or supposedly demonstrating, that no-controllable-signalling is a completely general property of quantum mechanics. However, Mulder, never content merely to accept the authority of experts, reads some of this literature, and begins to develop suspicions about the logical pedigree of the widely-cited proofs it contains. In this paper, we will put two especially pertinent examples of no-signalling proofs under the microscope, and show that Mulder’s worries are justified.

2 Can We Explain the Correlations?

To place the discussion of signalling in context, we will consider two strongly contrasting approaches to the following question: How can we explain correlations between spacelike-separated events, when recourse to a common cause is ruled out?

1. “Don’t ask”. One notes that we already have an empirically adequate set of algorithms for predicting observable correlations, and combines this fact with the warning of Bohr that to ask for a spatio-temporal account of the interactions between correlated particles is to ask an experimentally ill-posed question. As David Mermin puts it,

   My own view on EPR which keeps changing—I offer this month’s version—is that barring some unexpected and entirely revolutionary new developments, it is indeed a foolish question to demand an explanation for the correlations beyond that offered by the quantum theory. This explanation states that they are the way they are because that’s what the calculation gives. [p.202]

This very Humean view has it that there is no basis for belief in “hidden powers” or “necessary connexions” between events. The price we have to pay for the huge predictive effectiveness of quantum mechanics, is, in effect, to give up the hope of understanding the actual basis of physical phenomena.
2. One accepts that if there is any sensible explanation of the correlations at all, then it must involve some sort of direct (and therefore superluminal) causal interaction between the distant particles. Tim Maudlin puts it bluntly:

Bell concluded that violations of the inequality demonstrate that the world is not locally causal, i.e., that these phenomena cannot be reproduced by any theory which postulates only locally defined physical states which cannot influence states at space-like separation... Philosopers of physics have been wont to question this conclusion... Bell was, however, quite correct in his analysis. Statistics such as those displayed by the photons [in an EPR scenario] cannot be reliably reproduced by any system in which the response of each particle is unaffected by the nature of the measurement carried out on its distant twin. The photons remain "in communication" no matter how great the spatial separation between them. Instead of trying to deny these non-local (i.e., superluminal) influences, we should begin to study the role such influences must play in generating the phenomena. [20, p. 405]

We take the notion of studying "the role such influences must play in generating the phenomena", to mean that we should find out what features of a theory of superluminal influences would be necessary in order to reproduce the observed behavior. As we shall see below, there is one class of candidate theories—the causal interpretations of quantum mechanics proposed by Louis de Broglie and David Bohm—that are apparently sufficient to account for the observed phenomena. However, we still do not know how much choice we have in adopting such theories.

These are only two of the many attempted interpretations of QM, some of which are of great subtlety and ingenuity. However, it is not too much of an exaggeration to say that most interpretations of QM are aimed at finding some way of accepting the nonlocality implied by Bell's Theorem—which, as noted above, is essentially a negative result, amounting to the elimination of common-cause explanations of quantum correlations—without going as far as alternative 2 contemplates; that is, without swallowing the idea that one particle literally exerts an instantaneous influence on its distant partner. Hence, it is useful to focus on these two views, since they represent two extremes of thought on the problem.

Note carefully that a supporter of position 1 (above) could say that there is a non sequitur in Maudlin's argument: from the fact that no local explanation is available, it does not follow that some other sort of explanation is possible. It might well be that there is no explanation at all; in other words, that the Bell-Inequality-violating correlations of QM are simply basic, raw data that are the starting points for any full development of physics, not something that could be explained by any deeper physical theory. (This has been proposed, for instance, by Fine [21] and Pitowsky [7].) A defender of position 2, therefore, will ideally have to show that there are other motivations for considering non-local causation, apart from the fact that it would furnish a prima facie explanation for the correlations. And, indeed, supporters of the Bohm/de Broglie alternatives do have some grounds to claim that their theories are broadly motivated by the mathematical structure of wave mechanics.

The "don't ask" option is widely endorsed, especially by many working physicists. It does have the advantage that it tends to keep one out of trouble, and this has some
survival value in today’s scientific ethos, according to which it is impermissible to be perceived to have made a mistake.\footnote{At the risk of over-stating the obvious, we believe that this aspect of the contemporary scientific ethos is counter-productive.} Furthermore, option 2 has been long regarded by many as outside serious discussion both because it leads to possible conflicts with relativity, and because of a deeply-felt instinct that physics should be local. Einstein himself dismissed the notion of nonlocal causation as “spooky action at a distance”.

An important difference between answers 1 and 2, is that according to the latter, there is new physics to be uncovered; while according to 1 there is no reason to suppose that the present formulation is not as good a theory as we are going to get. According to 1, nonlocality would not be something one understands, but something to which one adjusts. Interpreting QM would be a typical case of what Wittgenstein famously called “letting the fly out of the fly-bottle”—seeing that if only we think about a problem the right way, there is no problem at all. It must be said that this position, while logically open given our present state of knowledge, is most uninteresting, since it virtually guarantees that our understanding will not move much beyond its present state.

### 3 Causal Interpretations of QM

Despite long-standing prejudices against taking the idea of superluminal or nonlocal causation seriously, there is increasing recognition that the causal interpretations inspired by the theories of David Bohm \cite{Bohm} and Louis de Broglie \cite{deBroglie} are among the best contenders to provide a deeper explanation, if not a generalization, of QM. The central feature of such theories is that they countenance some sort of direct dynamic interaction between correlated particles. Bohm’s theory (which is much more widely studied) can be considered to be a non-relativistic approximation to the relativistic theory of de Broglie. In Bohm’s theory, interactions between particles are mediated by a mysterious potential having the form

\[
Q = \frac{\hbar^2 \nabla^2 R}{2m} \frac{1}{R} 
\]  

where \(m\) is the particle mass, and \(R\) is the amplitude of the wave function

\[
\Psi = R \exp(iS/\hbar). 
\]

(The quantity \(S\) is the action of the system.) In the case of phase-entangled multiparticle systems, the quantum potential for the system cannot, in general, be written merely as the sum of the quantum potentials for the individual particles. Rather, it is a global property of the system as a whole. (See \cite{Diosi}, p. 62–63.) The quantum potential contributes to the total mass-energy of a multi-particle system, and, when differentiated with respect to distance, defines a force—literally, a sort of action at a distance—that Bohm frequently argued would be a natural way to account for the correlations between distant particles.\footnote{There is a recent variant of Bohm’s theory known as “Bohmian Mechanics,” in which particle motions are supposed to be correlated by a sort of pre-established harmony. We will not consider that here, save to note that it is subject to the same objections to any theory with a local Hamiltonian, that we raise in the next section. For a superbly perspicuous overview of the various flavours of the causal interpretation, see \cite{Diosi}.}
There are many questions to be asked about the best way to interpret and develop the insights of Bohr and de Broglie. The crucial point to grasp, though, is that the quantum potential $Q$ is by no means an arbitrary construct, but something that can be derived straightforwardly from certain basic assumptions of wave mechanics. (See [17, 18, 22], or many other sources.) Option 2 is, therefore, to be taken very seriously, both because (as Maudlin insists) it seems, \textit{prima facie} at least, to be demanded by the observed failure of the Bell Inequalities, and also because something like the theories of de Broglie or Bohm have been implicit in the mathematical structure of quantum theory from the outset. But this makes the question of signalling especially acute, as we shall see.

4 Bohm and Hiley on Signalling

In their \textit{Undivided Universe} [1, Chapter 7], David Bohm and Basil Hiley attempt to address the problem of superluminal signalling in quantum mechanics. Our claim will be that their argument is question-begging, since, as we shall see, they rule out of consideration from the beginning the very possibility they most need to examine — \textit{especially} given their stated commitment to causal interpretations of QM.

The charge of circularity has already been leveled against a large class of no-signalling proofs within non-relativistic quantum mechanics and local quantum field theory by J. B. Kennedy [24], and also by one of us [25, 26]. The value in studying this particular argument by Bohm and Hiley is that they express in a remarkably clear form the fallacy that is typical of virtually all the no-signalling arguments with which we are familiar. We say this in all due respect for these authors, who have made great contributions to physical science. (It is, in particular, a disgrace that Bohm, like J. S. Bell, was not awarded the Nobel Prize in Physics.) Our claim is not that they have been especially careless, but that, given the long-standing commitment of science to locality, theirs is a remarkably easy mistake to make.

In discussing various possible interpretations of the EPR experiment, they remark,

\ldots it seems very reasonable to suggest that $A$ and $B$ [the spacelike separate particles] are directly connected, though in a way that is perhaps not yet known. [1] p. 139

This is essentially a variant of alternative 2, above, and it is, indeed, the central claim of causal accounts of QM such as the theories of Bohm and de Broglie. The ultimate problem, of course, is to elucidate the nature of the “connection” between the particles.

However, they then set out to immediately scotch any fears that such hypothetical direct connections, whatever they might look like in detail, could be used to signal superluminally. Their argument is given in wave-mechanical terms; what follows here is their derivation re-expressed in the more perspicuous Dirac notation.

We shall suppose that “an external system [measurement device] with coordinate $y$ is allowed to interact with the spin of particle $A$.” The initial state vector for a system of two spin-coupled particles $A$ and $B$, and a measuring apparatus with coordinate $y$, will be

$$|\psi_0\rangle = |\phi_0^y\rangle \frac{1}{\sqrt{2}} [|_A^+\rangle |_B^-\rangle - |_A^-\rangle |_B^+\rangle]$$

(3)
where the superscripts $A, B, y$ indicate the Hilbert spaces for particle $A$, particle $B$, and the measuring apparatus, respectively. The subscripts $\alpha$ and $\beta$ indicate the spin direction for which the $|+\rangle, |-\rangle$ is a basis set, and the ket $|\phi^y_0\rangle$ represents the initial wave function for the measuring device. (The ket products are to be understood as direct products, although we have dropped the usual $\otimes$ notation).

An interaction between the measuring device and the spin of particle $A$ is then “carried out”. The immediate question is how we should represent this. Here is the key passage:

The most general possible result of this interaction will be represented by a unitary transformation on the subsystem consisting of $y$ and $A$, because, by hypothesis, we are assuming our interaction does not directly disturb $B$. If it did then this would not constitute sending a signal from $A$ to $B$, but would just be a direct disturbance of $B$ by its interaction with $y$. [1, p. 139]

Bohm and Hiley then go on to show that given this assumption there is no change in the expectation value of the spin operator for particle $B$ as a consequence of the measurement made on $A$. We will comment, below, on the cogency of the reasoning expressed in this passage. First, though, we summarize the calculation.

We represent such a unitary transformation by the operator $U_{A,y}^{A,y}$ where the superscripts indicate that this operator only works on the Hilbert spaces of the apparatus and particle $A$ and the subscripts show that it performs the operation of rotating the initial basis states of $A$ from the direction $\alpha$ to $\alpha'$. The state of the system then becomes

$$U_{A,y}^{A,y}\psi_0 = \frac{1}{\sqrt{2}} [U_{A,y}^{A,y}\phi^y_0 |^+_\alpha |^-_\beta ] - [^-_\alpha |^+_\beta ].$$

(4)

By assumption, the basis kets of $B$ are unaffected by this transformation. Bohm and Hiley then go on to show, unsurprisingly, that given this assumption there is no change in $\langle \sigma^B_\beta \rangle'$, the new expectation value of the spin operator (in direction $\beta$) for particle $B$ as a consequence of the measurement made on $A$. We write

$$\langle \sigma^B_\beta \rangle' = \langle U_{A,y}^{A,y}\psi_0 | \sigma^B_\beta | U_{A,y}^{A,y}\psi_0 \rangle$$

$$= \frac{1}{2} \langle U_{A,y}^{A,y}\phi^y_0 | U_{A,y}^{A,y}\phi^y_0 \rangle$$

$$[\langle +_\alpha' |^-_\beta | -_-\alpha' |^+_\beta |^+_\alpha |^+_\beta |^-_\beta | -^-\alpha' |^+_\beta |^+_\alpha |^+_\beta \rangle].$$

(5)

Since the orthonormality of the states is retained under a unitary transformation, and since $\sigma^B_\beta$ operates on particle $B$ alone (as if it “passes through” the $A$-kets), this gives

$$\frac{1}{2} [\langle -^-\beta | -^-\beta | -^+_\beta -^-\alpha |^+_\beta |^+_\alpha |^+_\beta \rangle = \langle \sigma^B_\beta \rangle'.$$

(6)

To sum up: since ex hypothesi the unitary transformation only operates on the Hilbert spaces of the measuring device and particle $A$, the expectation value for the spin of particle $B$ is the same before and after the interaction.

Several comments come to mind. First, this whole line of reasoning is very odd, since the authors only a few lines above on the same page readily concede that $A$ and $B$ may be
“directly connected”, and it is hard to see how, if this were so, something done to $A$ might not produce a “direct disturbance” of $B$. (Presumably, “direct” means “nonlocal”, at least in the sense of being instantaneous, or not involving only retarded reactions.) Bohm and Hiley therefore seem to contradict themselves; they insist on the plausibility of a direct connection between the particles, but then describe the situation in a way that excludes that very possibility.

Does their proof amount to anything more than an illustration of the fact that an operator that doesn’t operate on a wave-function doesn’t change the wave-function? (Kennedy argues that virtually all no-signalling arguments within nonrelativistic quantum mechanics boil down to this unexceptionable claim, at least mathematically. [24]) That would not seem to be especially illuminating.

Here is a more charitable reading: even though proofs of this sort cannot show that there is no direct causal interaction between left and right particles, they do show that there is no inconsistency in the formalism of quantum mechanics, such that we would get evidence of a superluminal causal interaction if we assume there is none. In other words, one cannot beat the house merely by some sort of statistical trickery.

It was, no doubt, a salutary exercise to have shown this, but the use of such a calculation in support of a general no-signalling claim is completely question-begging. This is because it is very hard to see how any sort of signal from $A$ to $B$ would not require the disturbance of $B$ by $A$, albeit in some fashion “that is perhaps not yet known”.

This point requires special emphasis. It is a basic result of information theory that any form of information transmission requires the expenditure of free energy. The reason is that to encode information in a physical structure (for instance, to do something that causes a measurement device to display some definite outcome) is to lower the entropy of that structure. There are many ways in which this can be accomplished, but all require the doing of some work on that structure. Transmission of information from $A$ to $B$ without direct disturbance—whether controllable or not—would be a violation of the Second Law of Thermodynamics, since one would have achieved an energetically free reduction in entropy. Therefore, to suppose that one could signal without “direct interaction” is to misunderstand the nature of signalling in general.

In other words, the most that the no-signalling argument by Bohm and Hiley really shows—and this is true of all the no-signalling arguments we cite above, and most in the literature—is that the quantum mechanical measurement process cannot be used to violate the Second Law of Thermodynamics. One cannot signal by sheer sympathetic magic; that is, without actually, physically interacting with the receiver. However, these arguments utterly fail to show whether or not there exists a direct interaction between the distant particles, even though this is precisely the point that is at issue. It is not relativity that is protected by the no-signalling arguments, but thermodynamics.

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4 A. Valentini has a highly original treatment of the signalling problem in his own version of Bohmian Mechanics. [25] Valentini, following Bohm and Vigier [28], treats the equation $P(x) = |\Psi(x)|^2$, which he dubs the “quantum equilibrium” condition, not as a mathematical identity, as it is in the standard abstract formulation of quantum mechanics, but as a thermodynamic average which could have been violated in the early universe. Valentini shows that, in his theory, no-signalling holds so long as quantum equilibrium holds. Whether or not Valentini’s approach is sound, it is less obviously question-begging than the usual no-signalling arguments. However, all presently extant versions of Bohmian Mechanics assume a local Hamiltonian for the multi-particle system, and are thus open to objections we raise in the next section.
5 Nonlocality of Multiparticle Dynamics

It will be instructive to take a closer look at the widely-cited no-signalling argument by Abner Shimony [2], which (by using the Hamiltonian formalism) explicitly considers the dynamics of “entangled” states.

Shimony invites us to consider an EPR scenario with correlated particles $A$ and $B$. We want to write the Hamiltonian for this system, in the case that a measurement device $D_B$ acts on $B$. Shimony assumes that this total Hamiltonian can be written in the form

$$H_{\text{tot}} = H_A \otimes 1_B + H_{DB} \otimes 1_A,$$

where $H_A$ is the Hamiltonian of particle $A$, $1_A$ is the identity operator on $\mathcal{H}_A$, the Hilbert space for $A$ (and similarly for $1_B$), and $H_{DB}$ is the Hamiltonian of the combined system of $D_B$ and particle $B$. Adopting a Hamiltonian of this form amounts to assuming dynamic locality at two levels:

S1 It assumes that $D_B$ interacts only with $B$;

S2 It assumes that the combined system of $D_B$ and $B$ does not interact with $A$.

These assumptions do seem to be perfectly reasonable given normal classical intuitions about how particles interact, since we would assume that once the particles are sufficiently far apart, any immediate reactions between them would drop rapidly to zero. (There could be retarded interactions, of course, but here we are only concerned with what happens at some definite time in the lab frame of reference.) However, in the context of this investigation, we are not entitled to rely upon such classical intuitions, because the entire point is to see whether or not they are sound.

In any case, given Eq. 7, one can show (by series expansion) that the time evolution operator for the total system factorizes:

$$U(t) = e^{iH_{\text{tot}}t} = e^{iH_At} \otimes e^{iH_{DB}t}. \quad (9)$$

Shimony then sets out to calculate the expectation value of some operator $G$ acting on particle $A$ alone, given this action of $D_B$ on $B$. If any such measurement carried out on $B$ can influence the expectation value of any observable measurable on $A$, then Scully can, indeed, signal to Mulder, by varying the parameters of the apparatus $D_B$.

We first need an expression for the total system state. Let $|a_i\rangle$ be basis states for $\mathcal{H}_A$, and $|b_i\rangle$ be basis states for the Hilbert space $\mathcal{H}_B$ of particle $B$. The assumption that $D_B$ acts dynamically on $B$ alone implies that we can represent the effect of $D_B$ on the total system in terms of operators acting strictly on a Hilbert space $\mathcal{H}'_B = \mathcal{H}_{DB} \otimes \mathcal{H}_B$, where $\mathcal{H}_{DB}$ is the Hilbert space of the measurement apparatus. Writing the basis states of $\mathcal{H}'_B$ as $|b'_i\rangle$, the state of the total system (apparatus plus entangled particles $A$ and $B$), at time $t_0$, can be written as

$$|\psi(t_0)\rangle = \sum c_i |b'_i a_i\rangle. \quad (10)$$

Clearly this is not, in general, factorizable—even though we are assuming that its time evolution is!
After a time $t$ the system has evolved to a state

$$|\psi(t)\rangle = U(t-t_0)|\psi(t_0)\rangle.$$ \hspace{1cm} (11)

As with Bohm and Hiley’s calculation, we are assuming that the measurement interaction with $D_B$ does not collapse (i.e., project) the state, but evolves it in a unitary way.

To calculate $\langle G \rangle$, we observe that $G$’s action on the global system can be represented by $G_{\text{tot}} = G \otimes 1_B$. Then we get

$$\langle G_{\text{tot}} \rangle = \langle \Psi(t) | G \otimes 1_B | \Psi(t) \rangle = \langle \Psi(t) | U(t-t_0)(G \otimes 1_B)U(t-t_0) | \Psi(t) \rangle = \langle \Psi(t) | (e^{-iH_A(t-t_0)} \otimes e^{-iH_{DB}(t-t_0)})(G \otimes 1_B) \rangle = \langle \Psi(t) | (e^{-iH_A(t-t_0)}G e^{iH_A(t-t_0)})(e^{-iH_{DB}(t-t_0)}1_B e^{iH_{DB}(t-t_0)}) | \Psi(t) \rangle = \langle \Psi(t) | G | \Psi(t) \rangle = \langle G \rangle.$$ \hspace{1cm} (12-17)

In the end, $\langle G \rangle$ shows no dependency on whatever may have been done on particle $B$. In other words, since $A$ and $B$ are presumed causally independent, a measurement on $B$ cannot influence the statistics of measurements on $A$. This is, of course, just a more general version of the argument of Bohm and Hiley.

Abner Shimony himself is well aware of the relevance of the dynamics for the signalling problem. Elsewhere, he states,

... quantum mechanical predictions concerning ensembles of pairs of particles do not violate Parameter Independence [no-signalling], provided that nonlocality is not explicitly built into the interaction Hamiltonian of the particle pair. [12, p. 191]

Evidently, Shimony did not believe that there was any physical justification for considering explicitly nonlocal Hamiltonians. However, we need only look a few pages ahead in Bohm and Hiley’s book to see that there is.

### 6 Symmetrization and Nonlocality

In a section of *The Undivided Universe* entitled “Symmetry and antisymmetry as an EPR correlation,” [1, pp. 153–157] Bohm and Hiley point out that wave functions of multi-particle systems may be symmetric or antisymmetric. Particles belonging to systems with symmetric wave functions exist in identical states, and accordingly obey Bose-Einstein statistics, while particles with antisymmetric wave functions obey Fermi-Dirac statistics, and must obey the exclusion principle.

Suppose our particles $A$ and $B$ are bosons. We wish to measure some operator $O_A$ on particle $A$. There will have to be a corresponding operator $O_B$ acting on $B$, since $A$ and $B$ must obey identical statistics. Therefore, as Bohm and Hiley explain ([1, p. 153–154]), in
order to maintain the symmetry of the Hamiltonian between the two particles, we must write the Hamiltonian of the measurement interaction as

\[ H^S_I = \lambda (O_A + O_B) \frac{\partial}{\partial y} \]

(18)

This obviously violates assumption S1 above, because of the dependence upon \( O_B \), and thus renders Eq. 7 entirely inapplicable. It also, again obviously, contradicts the behavior of the unitary transformation used by Bohm and Hiley only a few pages earlier in their own book. We note, also (a point not explicitly mentioned by Bohm and Hiley), that, as far as we know, all particles are either bosons or fermions, and must therefore obey symmetrization conditions. The best we can say, therefore, is that the whole treatment of signalling typified by the Bohm-Hiley and Shimony proofs could only be applicable in cases in which these symmetrization conditions can be ignored.

Nothing we have said here shows that systems with nonlocal Hamiltonians such as Eq. 18 could, indeed, be used for controllable signalling. However, proofs of the type offered by Shimony, or Bohm and Hiley, are clearly powerless to show that they cannot.

Finally, observe that one has to use the nonlocal Hamiltonian of Eq. 18 whether or not one accepts a causal interpretation of QM. As Bohm and Hiley carefully note, we have to use a symmetrized Hamiltonian like this if we want to get the right predictions for Bose particles, and that fact is quite independent of whatever interpretation of QM one chooses. Hence, the question of signalling is, in the last analysis, just as unavoidable for Option 1 as for Option 2.

The notion of nonlocal energy is, admittedly, difficult to grasp. One might be inclined to think that according to a causal interpretation, there must be some sort of superluminal transmission of a localized pulse of mass-energy between the remote particles. However, if we ask whether energy is being shuttled superluminally between \( A \) and \( B \), by tachyons perhaps, we miss the point. Some such description might be useful in some contexts. However, the real point is that mass-energy is nonlocal, a global property of a multi-particle system. The multiparticle system as a whole will have a spectrum of possible energy states, and the energy is not any place in particular at all; it is just a general property of the system, that may make itself manifest in a variety of ways. It is probably safe to say that this is analogous to the way in which the energy of an electron orbital in an atom is a global property of the orbital as a whole. Localization of mass-energy is a process that happens in certain specific circumstances that we do not fully understand as yet.

Our remarks here can only serve to indicate some enticing possibilities. The important point to note is that there are numerous indications within quantum physics that the dynamics of multiparticle systems are, in general, nonlocal. It seems to be largely philosophical prejudice against nonlocality that has prevented us, so far, from following up on these leads—a philosophical prejudice against which Bohm and Hiley argue persuasively ([1]), but to which they appear to have fallen victim themselves.

Any satisfactory treatment of the signalling problem must employ a formalism that explicitly takes into account the possibility of nonlocal causal interactions. Exactly how we should do this remains to be seen, although the causal versions of quantum mechanics of de Broglie and Bohm offer promising leads. Bohm’s interpretation, however, suffers from the possible defect that it takes as a starting point the Hamiltonian

\[ H = -\frac{\hbar^2}{2m} \nabla^2 + V. \]

(19)
Begging the Signalling Question

(See [1, p. 28].) The first term represents the kinetic energy of the particle, and the second represents local potentials such as electromagnetic potentials. It is likely that this Hamiltonian represents some sort of semi-classical limiting approximation, not the accurate potential for a system of correlated particles. However, this point requires much further investigation.

In the end, we can safely say to Agent Mulder that there is no hidden conspiracy, but merely a confusion. Except for systems in which the Hamiltonian approximates to a local form, as in Eq. 7, we still simply do not know whether one can violate relativity by means of some sort of controllable nonlocal effect in entangled multiparticle states. The truth is still out there.

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