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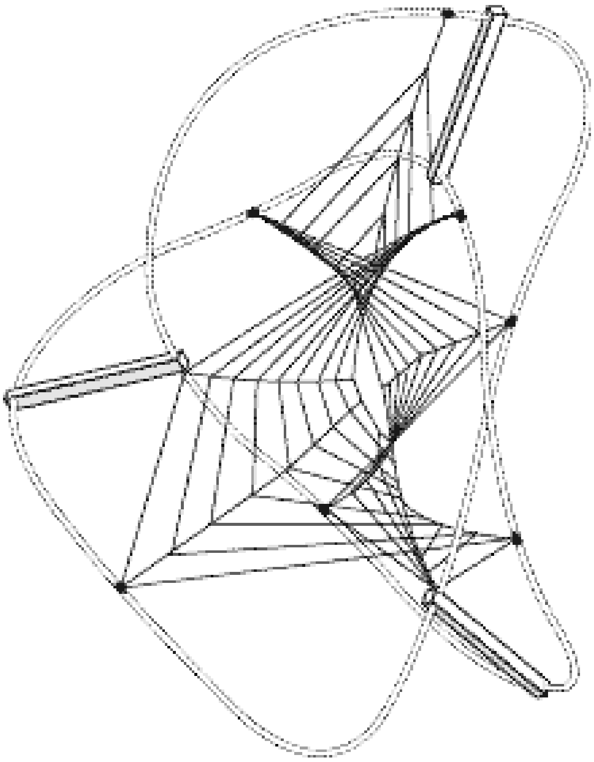

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A Causal Model for EPR[1]

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Abstract

We present a causal model for the EPR correlations. In this model, or better framework for a model, causality is preserved by the direct propagation of causal influences between the wings of the experiment. We show that our model generates the same statistical results for EPR as orthodox quantum mechanics. We conclude that causality in quantum mechanics can not be ruled out on the basis of the EPR-Bell-Aspect correlations alone.

1. Conditional Statements and the EPR Correlations

The Einstein-Podolski-Rosen *gedankenexperiment* (Einstein, Podolski and Rosen, 1983) describes two individual systems, S_1 and S_2, originally in pure states, ϕ_1 and ϕ_2, that come into interaction with each other. The composite system, S_{1+2}, remains in a pure state. However, the two subsystems, S_1 and S_2, individually taken, have gone into mixtures. The mixtures represent virtual ensembles of pure states with corresponding statistical weights. When a measurement is performed, according to the projection postulate, one of the pure states is selected.

[1] This paper has been long in the making. The first draft dates from May 1992, and we presented it at the International Quantum Structures Association meeting in Castiglioncello in September 1992. Improved versions were presented by NC in Cambridge in 1993; and by MS in Milan and in Cambridge in 1994, and in St Andrews in 1996. We delivered the definitive version during the conference in honour of Arthur Fine at Ohio State University in May 1999. We thank these audiences and all the individuals who have given us comments and feedback on previous drafts. We would like to thank the Modelling in Physics and Economics Project, at the Centre for the Philosophy of the Natural and Social Science at the LSE, for its support throughout. MS would also like to thank the Arts Faculty Research Fund of the University of Bristol for its financial support.

After interaction, the global system can be represented by the entangled state: $\Phi_{1+2} = \Sigma_i c_i |u_i\rangle |v_i\rangle$. The subsystems, S_1 and S_2, are represented by the statistical operators:

$$W_1 = \Sigma_i |c_i|^2 |u_i\rangle \langle u_i|,$$

$$W_2 = \Sigma_i |c_i|^2 |v_i\rangle \langle v_i|,$$

where the $|c_i|^2$ indicate the weights ascribed to each element of the mixture.

The description offered by Φ_{1+2} contains maximal knowledge of both systems. However, W_1 and W_2 represent mixtures: somehow we seem to have lost knowledge. Schrödinger quickly realised that such "*portion of the combined knowledge*" was "*squandered on conditional statements that operate between the sub-systems*" (Schrödinger, 1983, page 161). Schrödinger's conditional statements are as follows: If we were to measure some observable on S_1 and to find that the outcome is the eigenvalue corresponding to, say, u_k, then a measurement of the same observable on S_2 would give the eigenvalue corresponding to v_k. Hence once a measurement is performed on, say, S_1, some consequences seem to follow for measurements on S_2. These conditional statements are at the heart of the EPR correlations.

It is worthwhile to emphasize that the nature of the Schrödinger's conditional statements is *nomological*, as opposed to *physical*. The quantum mechanical treatment of EPR does not provide physical processes for the transmission of information from one system to another. There is only the nomological necessity that results from the peculiar way in which statistics for the combined systems are calculated in the quantum mechanical formalism. Therefore a causal explanation of the EPR correlations would need to introduce some physical mechanism in order to ground Schrödinger's conditional statements. In a causal model of the EPR experiment, the "extra" portion of knowledge would not be "*squandered on conditional statements*". For instance, in a model where causes operate directly between the wings of the experiment, the "extra" portion of knowledge is explicitly carried from one subsystem to another by "mark-transmitters", or *carriers*.

2. Fine's argument

Arthur Fine (Fine, 1989) has argued that no essentialist explanation of the EPR correlations is forthcoming. And more specifically he has argued that the experimental refutation of the Bell inequalities provides no grounds for explanations involving faster-than-light influences between the wings of an EPR experiment. We find the logic of Fine's argument impeccable. But we believe that it is possible to take the empirical violation of the Bell inequalities to provide evidence in favour of, rather than against, causal models of the EPR correlations. So we have some explaining to do. How can Fine's argument be reconciled with our claim that it is possible to take the violation of the inequalities as evidence for causal models?

Fine begins by stating a principle that he calls the Strong Locality Condition (SLOC): " a principle denying *any* influence between happenings in different wings [of the EPR experiment]" (Fine, 1989, page 183). He then argues that this principle is built into the quantum theoretical description of the EPR experiment, "according to which there is no physical influence between the two wings of the experiment, that is, no physical interaction of any sort that is represented by terms in the Hamiltonian of the composite system at the time one or the other component is measured".

Fine shows that (SLOC) is consistent with the denial of the Bell inequalities. This is consistency relative to the quantum theory itself, at least in its present form. For quantum mechanics *both* predicts the failure of the Bell inequalities *and* adheres to (SLOC). As a result, any weaker principle –any principle strictly entailed by (SLOC), must also be consistent with the denial of the Bell inequalities. In particular the principle that denies the existence of faster-than-light influences (LOC) is entailed by the stronger principle (SLOC) and hence is consistent with the denial of the Bell inequalities. But the experimental refutation of the Bell inequalities cannot be used to provide evidence against any principle that is consistent with their denial. Therefore, Fine concludes, for all we know the denial of faster-than-light influences is perfectly consistent with experiment, and we are not entitled to invoke the EPR experimental results as evidence for faster-than-light influences.

The reasoning is correct. But here as anywhere else, one person's modus tollens is another person's modus ponens. It is possible to turn the logical machinery of Fine's argument around, in order to provide ammunition against (SLOC) and in favour of faster-than-light, or superluminal, influences.

The crucial premise in Fine's argument is the thought that, because the standard quantum model for the EPR experiment has no term in the Hamiltonian representing a physical interaction between the two distant particles, (SLOC) is "built into the quantum theory". What can this possibly mean? It may mean first that a quantum theoretical description of the EPR experiment representing superluminal influences is impossible. Or it may mean that no such description has been developed to date. On what grounds could the stronger, impossibility, claim be asserted? It would be, for instance, mistaken to conclude that no description of this type is possible *because* no such description has been developed to date. The history of science is full of examples of surprising and novel applications of established scientific theories to well known phenomena.[2]

This indicates that we could only know that (SLOC) is built into the quantum theory on *a priori* grounds, as it would be impossible to infer this from the present state of knowledge. Among contemporary philosophers of quantum mechanics, Arthur Fine is possibly the least likely to want to argue on *a priori* grounds. A driving motive behind Fine's 1982 theorems was to show that no 'a priori' reasoning could ever establish the impossibility of local realistic models for the EPR correlations. With some ingenuity such models could always be constructed, and Fine himself advanced two types of models that, he claimed, satisfied conditions of physical locality: the *prism* and the *synchronisation* models (Fine, 1982).

[2] To give but one example that we are familiar with: all electromagnetic accounts of superconductivity prior to the discovery of the Meissner effect in 1933 assumed that a superconductor is a ferromagnet. There were moreover, some "theorems" at the time that purported to show that an electromagnetic treatment of superconductivity as a diamagnetic phenomenon would be impossible. But a few months after Meissner's discovery, and against all odds, Fritz and Heinz London provided an electromagnetic description of the Meissner effect. For the details, see Suárez (1999).

Fine's meaning must then be that a quantum theoretical description of the EPR experiment involving superluminal influences has not yet been developed. And it would be a fallacy of classical logic to conclude from the fact that *x* has not been proved to date that *x* is not true. Whether such a description is actually available then becomes an empirical matter, to be decided by doing some physics. Fine's own logic points the way. For his argument shows that any attempt to ground superluminal influences on the experimental violation of the Bell inequalities must involve a denial that (SLOC) is built into every quantum mechanical description. Otherwise the experimental results can have no bearing whatsoever on the existence of superluminal influences. Thus any such attempt must begin by building a framework for the EPR experiment that is capable of representing the physical interaction between the two particles. This is precisely what we aim to do in this paper.

3. Causality

We follow the sufficient conditions proposed by Salmon (Salmon, 1985, chapter 5) for the propagation of causal influences. Salmon's two principles (the principle of structure transmission and the principle of propagation of causal influences) can be reformulated as follows, in a single, more condensed, statement:

> *If a process is capable of transmitting changes in structure due to marking interactions, then that process can be said to be capable of propagating a causal influence from one space-time locale to another.*

Our aim is to produce a formal framework for EPR in which some sort of "*mark*-transmittors", or *carriers*, are responsible for the transmission of causal influences between the separated subsystems. Our model makes three assumptions:

i) Separability: quantum systems can be assigned individual states of their own after having interacted, even if formally treated as subsytems of a "composite" system. These individual states will generally not be represented by idempotent operators; i.e. they will be mixed rather than pure states.
ii) Stochasticity: measurements on a subsystem result in a stochastic outcome with the usual Born probabilities.
iii) Causal Locality: causality is preserved by physical transmission of information.

Every one of these assumptions has sometimes been contested. But we think that they are reasonable assumptions to impose on a physical theory. Quantum mechanics satisfies assumption ii) fully. And it satisfies assumption i) in a qualified form, by providing a procedure (that of tracing over the degrees of freedom) that enables one to derive uniquely the state of each individual particle from the state of the composite. It has however, been claimed that the third assumption is ruled out by the EPR correlations alone. As these correlations are predicted by quantum mechanics, it follows that quantum mechanics does not satisfy assumption iii). For instance Van Fraassen claims that "*no causal model can fit the phenomena that violate Bell's inequalities*" (Van Fraassen, 1993, chapter 5).

Chang and Cartwright (Chang and Cartwright, 1993) and Cartwright (Cartwright, 1989, chapter 6) have argued against this claim. They have provided a description of the features that a possible causal account of the EPR correlations would need to possess. The two simplest causal accounts of the EPR correlations are a common-cause model and a direct-cause model. The common-cause model only seems impossible when one does not take genuinely probabilistic causality seriously enough.[3] In this paper we develop a framework for models of the latter kind: causality is preserved via the *direct* propagation of causal influences between the wings.

Although we refer to our framework as a "model" we emphasise that this is a rather abstract kind of model –one that sets the general formal conditions that could be met by more concrete, physical direct-cause models of the EPR correlations. It is a widely accepted result of the Aspect et al. experiments that any possible direct causal connection in the EPR set-up must be transmitted at a speed larger than light. We stress that we do not provide here a physical model for these superluminal connections. Rather we provide a formal framework in which such physical models may be embedded. And we show that physical models that fit our formal framework will *ipso facto* replicate precisely the quantum mechanical statistics for all possible measurements of correlated quantities in the EPR experiment.

4. A Causal Model for EPR

4.1. Carriers.

The conventional representation of the EPR set-up in quantum mechanics already presupposes that there is no causal (or physical) transmission between the systems. In a case like EPR, neither an interaction Hamiltonian is used to model the relation between cause and effect, nor is a third system –a field or a photon for instance-- introduced to mediate the interaction. In order to work out the results, the combined state is always used and the individual mixtures are ignored. In the simplified EPR case that we are concerned with, the state of the composite is the singlet:

$$\Phi_{1+2} = \sqrt{(1/2)}\ |+x\rangle^1 |-x\rangle^2 - \sqrt{(1/2)}\ |-x\rangle^1 |+x\rangle^2 \qquad (4.1)$$

According to (4.1.), the results of possible measurements of spin are correlated. If we measure the spin on system S_1 along the x direction and find spin "up", then we can infer that the result of a measurement of spin of system S_2 will be "down". Conversely, when the spin of system S_1 is "down" the spin of system S_2 will be found to be "up".

Hence the conventional formalism already presupposes Schrödinger's counterfactuals. Something must be added to the formalism in order to make physical transmission possible. In our direct-cause model, the "mark" transmitters or carriers, are

[3] Previous discussions of causality in EPR have tried to rule out particular causal connections on the basis of the probabilities alone. But this strategy will not work, because any single causal connection is consistent with any arrangement of probabilities. Which particular probabilistic relation can serve as a criterion for a given causal relation depends very sensitively not only on the entire causal structure in which that causal relation is embedded, but also on the details of how the causes in that structure are supposed to operate (see (Nancy Cartwright, 1989), for a discussion.)

responsible for causal transmission. Carriers both record and transmit information. A carrier attached to a system records two kinds of information about the system:

- Information about measurements made on the system. A carrier might say, for example, whether a measurement of spin along a particular direction *x* has taken place and what is the result of this measurement.

- Information about the history of the system since its separation from its partner system. Since, in the simple case of spin states we are considering, any outside influence on the system can be represented as a rotation, the carrier records whether the associated system has been subject to some specified rotation *R*.

Carriers also contain information about their own "internal states". A carrier can exist in three different "states": it can be <u>bound</u> to its system, <u>unbound</u>, or in the <u>ground</u> state (the state such that information contained in the carrier is not relevant anymore.) Carriers become unbound when a measurement is made on their associated systems. They are then free to interact with other systems. Once a carrier goes into its ground state, it is no longer capable of transmitting causal information.

We ascribe quantum states to the carriers, which we write as follows:

$$|j; k; R; w; \tau\rangle^{i,n},$$

where *j* is the internal state of the carrier: it can take the value *b* for bound, *u* for unbound, and *g* for ground. *k* records the initial state of the system to which this carrier is attached. *R* is the total rotation the system has undergone. *w* is a record of the result just after a measurement has occurred on the associated system. τ is a placeholder for the further quantum characteristics the carrier will have to be assigned in any genuinely physical model. The τ's matter because they are where the real physics will be represented, but for ease of presentation we shall omit them in the rest of the paper. The first superscript, $i = 1,2$, indicates which Hilbert space, H_1 or H_2, the state of the carrier's associated system is represented in. The second superscript, *n*, identifies those carriers that are attached to systems that have interacted in the past. (EPR predicts correlations between particles that have interacted in the past only). *n* takes the same value for those and only those particles that have interacted in the past.

For convenience of notation, we will record only the final result of all the rotations. A typical carrier state will then look like this: $|b; +x; R_1; +y\rangle^{1,n}$. This carrier would be bound to a system S_1 originally in an "up" state of spin along the *x* direction that has been rotated by R_1, then projected by a measurement into state $|+y\rangle$.

Carrier states obey two sets of orthogonality relations. First, independently of whether bound or unboud, and independently of what system they are attached to, two carriers are orthogonal if they record at any point information about orthogonal states of some system: $|m; k, R; y\rangle \perp |m'; k', R'; y'\rangle$ if $k \perp k'$ or $Rk \perp Rk'$ or $y \perp y'$. Second, carriers in any one of the possible carrier-states (bound, unbound, ground) are orthogonal to carriers in any other carrier-state, i.e. $|b; y\rangle \perp |u; y'\rangle \perp |g; y''\rangle$.

4.2. EPR in a Causal Framework.

Let us now consider the EPR case within this framework. We assume that the state of the composite ($S_1 + S_2$) at any one time is given by (4.1), appropriately modified in order to account for each system's carrier states. It is then possible to work out the individual states of the physically separated systems S_1 and S_2. The state of S_1, for instance, can be derived from (4.1) by tracing over the degrees of freedom of S_2. And vice-versa: the state of S_2 can be found by tracing over the degrees of freedom of S_1. The resulting states of S_1 and S_2 are the following mixtures, represented by statistical operators W_1 and W_2 respectively:

$$W_1\text{: } 1/2\ |{+x}\rangle^{1n}\langle{+x}|^{1n} \otimes |b; {+x}\rangle^{1n}\langle b; {+x}|^{1n} +$$

$$|{-x}\rangle^{1}\langle{-x}|^{1n} \otimes |b; {-x}\rangle^{1n}\langle b; {-x}|^{1n} \qquad (4.2)$$

$$W_2\text{: } 1/2\ |{+x}\rangle^{2n}\langle{+x}|^{2n} \otimes |b; {+x}\rangle^{2n}\langle b; {+x}|^{2n} +$$

$$|{-x}\rangle^{2n}\langle{-x}|^{2n} \otimes |b; {-x}\rangle^{2n}\langle b; {-x}|^{2n}. \qquad (4.3)$$

In principle, however, the states of S_1 and S_2 do not necessarily have to be as simple as those given here: the systems may have been subjected to physical rotations, the overall effect of which may be represented by operators R_1 and R_2. These take a system in +x into +w, a system in –x into –w, etc; and they record the total effect of whatever physical rotations the systems have been subject to.

But note that, as is well known, the mixtures W_1 and W_2, are improper –they are not the result of a preparation procedure, but merely of a formal derivation from the state of the composite—, and thus they cannot be given the ignorance interpretation. Indeed in our account, reduction occurs only on measurement, and the reduction only affects the measured system and not its partner system.

In our causal model, a measurement of S_1's spin has two effects. First, the measurement has a stochastic outcome; and we may assume that the state of S_1 reduces to an eigenstate of spin, up or down, just as in conventional quantum mechanics. So we are not postulating any sort of *hidden variables*: there need be no "possessed values" for the main dynamical quantities of S_1.

Secondly, a measurement performed on S_1 releases the associated carrier, which travels to the other wing of the experiment and interacts with the companion system, S_2 and its own associated carrier. However, unlike conventional quantum mechanics, and due to our assumptions of separability and causal locality, the state of system S_2 (plus its associated carrier, plus the attached carrier initially associated to system S_1) evolves quantum mechanically, in accordance with the Schrödinger equation. This state evolution occurs whether or not a measurement is ever performed on S_2. [4] (If a

[4] The labels S_1 and S_2 are conventional, and do not necessarily refer to "the system on the left" and "the system on the right". S_1 is rather the system that is measured first, in the rest frame of the experimental set up.

measurement of S_2 *is* subsequently performed, it will then reduce this state of S_2 to an eigenstate corresponding to the measured outcome.)

In our model then only the state of the system measured, say S_1, represented by the corresponding density matrix, is reduced when it is measured. In the next section, we provide a specific "reduction rule" to represent this process. On the other hand, the dynamics of the triplet (S_2 – carrier bound to S_2 – carrier unbound from S_1) is in our model given by a quantum Hamiltonian. We do not provide a specific Hamiltonian here, but we offer a General Rule of Evolution that constrains the action of possible Hamiltonians in any genuinely causal model of EPR within our framework.

4.3. The Rules of a Causal Model

We have already explained that, according to our model the first measurement on system S_1 has a double effect: the states of S_1 and of its associated carrier are reduced; and the associated carrier is ejected. We may represent this dual process by means of the following "Reduction Rule":

> RR: On measurement of spin along the y direction on system S_1, the states of S_1 and its associated carrier undergo the following transition:
>
> $|\gamma\rangle^{1n}\ |b; k; R\rangle^{1n} \rightarrow |\phi\rangle^{1n} |u; k; R; \phi\rangle^{1n}$, with probability: $|\langle\phi|\gamma\rangle|^2$. (Or, more generally, if the initial state of S_1 is not the pure state $|\gamma\rangle^{1n}$, but rather the mixture W_1 the transition occurs with probability Tr ($P_\phi\ W_1$).)

On the other hand, the evolution of the trio (S_2 + carrier bound to S_2 + carrier unbound from S_1) is quantum mechanical and will be given by a specific quantum Hamiltonian. The main constraint on this Hamiltonian is that it must yield the same statistics for the measurement outcomes as conventional quantum mechanics in all possible experimental set-ups. We propose the following "General Rule of Evolution for EPR":

> GREPR: The Hamiltonian for the system-carrier-carrier interaction on S_2 must satisfy the following constraint:
>
> $|R_2\ \alpha\rangle^{2m}\ |b; \alpha; R_2\rangle^{2m}\ |u; \delta; R_1; \phi\rangle^{1n} \rightarrow$
>
> $\rightarrow \quad |\psi\rangle^{2m}\ |g; \alpha; R_2; \psi\rangle^{2m}\ |g; \delta; R_1; \phi\rangle^{1n}$,
>
> if m=n; otherwise the Hamiltonian has no effect.
>
> In this expression, $|\psi\rangle^2$ (the resulting, evolved, state of system S_2) is defined as follows:
>
> $|\psi\rangle^2 =_{df} \langle\phi\ |R_1\ R_2\ |\Phi_{1+2}\rangle / \sqrt{\{\langle R_1\ R_2\ \Phi_{1+2}|\phi\rangle^1\ \mathbf{I}_2\ {}^1\langle\phi|R_1\ R_2\ \Phi_{1+2}\rangle\}}$.
>
> Here R_1, R_2 are rotation operators that include information about the whole history of the systems previous to any measurements, ϕ is the outcome of the measurement upon S_1, $\mathbf{I}_2$ is the identity operator on H_2.

It is important to remark that this rule describes a unitary transformation. That this is so is guaranteed by the orthogonality relations that we have defined between carrier states. Consider for example when the left-hand side of the expression for GREPR involves orthogonal states of the system S_2, because $|R_2\,\alpha\rangle \perp |R_2\,\alpha_\perp\rangle$, and therefore it represents orthogonal states of the system$_2$-carrier$_2$-carrier$_1$ composite. Then the right-hand side expression involves orthogonal states of the carrier$_2$, because carriers recording orthogonal states are in orthogonal states, and it therefore also represents orthogonal states of the composite system$_2$-carrier$_2$-carrier$_1$.

5. Comparison of the Statistics

The function of RR and GREPR in our model is analogous to that of the statistical algorithm in conventional quantum mechanics: together these rules enable us to calculate the statistics for measurement outcomes. In this section we show that the statistics predicted by our model are in agreement with the quantum mechanical predictions for measurement outcomes in EPR situations.

Suppose that the state of the composite is then given by the singlet Φ_{1+2} (see equation (4.1)). We are interested in conditional probabilities for outcomes of measurements of spin on such entangled systems, such as:

$$P(-x^2 / +x^1) = P(-x^2 \,\&\, +x^1) / P(+x^1). \qquad (5.1)$$

This is the conditional probability of obtaining a "-" in a measurement of spin along the x direction on system S_2, given that a previous measurement along the x direction on system S_1 has yielded outcome "+".

In quantum mechanics the joint probability is given by:

$$P(-x^2 \,\&\, +x^1) = \langle \Phi_{1+2} \,|\, \mathbf{J}_{1+2} \,|\, \Phi_{1+2} \rangle, \qquad (5.2)$$

where $\mathbf{J}_{1+2}$ is the following operator in the tensor product Hilbert space ($H_1 \otimes H_2$):

$$\mathbf{J}_{1+2} = |+x\rangle^1 \langle +x|^1 \otimes |-x\rangle^2 \langle -x|^2.$$

Furthermore quantum mechanics requires $P(+x^1)$ (the probability of outcome "+" in a measurement of system S_1 only) to be worked out in the tensor product Hilbert space as well:

$$P(+x^1) = \langle \Phi_{1+2} \,|\, \mathbf{O}_{1+2} \,|\, \Phi_{1+2} \rangle, \qquad (5.3)$$

where $\mathbf{O}_{1+2}$ is the following operator on the tensor product Hilbert space:

$$\mathbf{O}_{1+2} = (|+x\rangle \langle +x|) \otimes \mathbf{I}_2,$$

and $\mathbf{I}_2$ is the identity operator on the Hilbert space H_2 of S_2.

A range of possible statistical cases can be derived for EPR by considering combinations of the two possible operations that may be performed upon the separated systems. These two operations are: a) rotations, and b) measurements of spin along specified but arbitrary directions. In this section we only consider two cases, the simplest and the most general. The first case illustrates the workings of RR and GREPR; the second proves that the model always generates the same statistics as quantum mechanics.

5.1. The Simplest Case

Suppose that systems S_1 and S_2 are a matched pair that have in no way been rotated, and suppose that we make straightforward measurements of spin on them along the direction *x*.

Quantum Mechanical Prediction. We can then easily calculate, by means of (5.3), that the quantum mechanical probability for a "+" outcome on an unconditional measurement on S_1 is $P(+x^1) = ½$. And, by means of (5.2), we can calculate the joint probability for a "+" outcome of the measurement on S_1 and a "-" outcome of the measurement on S_2. This is: $P(-x^2 \,\&\, +x^1) = ½$. And we obtain for the conditional probability: $P(-x^2 / +x^1) = 1$.

Causal Model Prediction. We take the individual states of S_1 and S_2, with their associated carriers, to be represented by (4.2) and (4.3). Suppose that we make a measurement of S_1 and obtain the outcome "+". According to RR the state of S_1 is then reduced into $|+x\rangle^1$, and the associated carrier is then ejected in the state $|u; +x; +x\rangle$. The action of this carrier on system S_2 is given by GREPR. Suppose that $n=m$, and suppose that there are no rotations; then GREPR takes the simple form[5]:

$$|\pm x\rangle^2 \;|b; \pm x\rangle^2 \;|u; +x; +x\rangle^1 \rightarrow |\phi\rangle^2 \;|g; \pm x\rangle^2 \;|g; +x; +x\rangle^1,$$

$$\text{where } \;|\phi\rangle^2 =_{df}\; {}^1\langle +x\,|\,\Phi_{1+2}\rangle \,/\, \sqrt{\{\langle\Phi_{1+2}\,|+x\rangle^1 \,\mathbf{I}_2\; {}^1\langle +x\,|\,\Phi_{1+2}\rangle\}} =$$

$$= \sqrt{(1/2)}\,|-x\rangle^2 / \sqrt{(1/2)} = |-x\rangle^2.$$

Hence the result of any Hamiltonian that obeys GREPR is the following dynamically evolved state of the S_2 system:

$$W_2(t)\text{: } ½\; |-x\rangle^2 \langle -x|^2 \otimes |g; +x\rangle^2 \langle g; +x; +x|^2 \otimes \;|g; +x; +x\rangle^1 \langle g; +x; +x|^1$$

$$+\; ½\; |-x\rangle^2 \langle -x|^2 \otimes |g; -x\rangle^2 \langle g; -x|^2 \otimes |g; +x; +x\rangle^1 \langle g; +x; +x|^1.$$

A measurement of spin along the *x* direction on a system in a state $W_2(t)$ will yield outcome "-" with probability one. Thus our model predicts that $P(-x^2 / +x^1) = 1$, and therefore yields the same perfect statistical anticorrelation in this case as quantum mechanics.

5.2.The Most General Case

[5] We suppress the superscript indicating that the systems are a matched pair for notational simplicity.

Suppose that first we rotate both S_1 and S_2 by R_1 and R_2 where R_1 and R_2 need not be equal. We then set to measure spin in S_1 along some direction *y*, and in S_2 along some direction *z*, where *y* and *z* need not be equal.

First, we may consider the case where $n \neq m$, i.e. the two systems are unmatched, in the sense that they have not interacted in the past. Although quantum mechanics does not provide a formal notation for situations in which measurements are made on systems from non-matched pairs, it is clear that the predictions will agree with our causal model. For in the causal model: $P(-z^2 \,\&\, +y^1) = P(-z^2) \times P(+y^1) = ½ \times ½ = ¼$, which is just what we would naturally expect in quantum mechanics.

We now show that the predictions of our causal model agree with quantum mechanics also in the case $n = m$. (We again drop the superscripts *n*, *m*.)

<u>Quantum Mechanical Prediction.</u> The rotation on S_1 is given by:

$$W_1: ½ (|+x\rangle^1 \langle +x|^1 \otimes |b; +x\rangle^1 \langle b; +x|^1) + ½ (|-x\rangle^1 \langle -x|^1 \otimes |b; -x\rangle^1 \langle b; -x|^1) \rightarrow$$

$$\rightarrow ½ (|+w\rangle^1 \langle +w|^1 \otimes |b; +x; R_1\rangle^1 \langle b; +x; R_1|^1) +$$

$$+ ½ (|-w\rangle^1 \langle -w|^1 \otimes |b; -x; R_1\rangle^1 \langle b; -x; R_1|^1),$$

where:

$$|+w\rangle^1 = \Gamma_1 |+x\rangle^1 + \sqrt{\{1- \Gamma_1^2\}}\, e^{i\theta 1} |-x\rangle^1$$

$$|-w\rangle^1 = \sqrt{\{1- \Gamma_1^2\}}\, e^{-i\theta 1} |+x\rangle^1 + \Gamma_1 |-x\rangle^1. \qquad (5.4)$$

But we shall make measurements on S_1 along the *y* direction, given by the transformations:

$$|+x\rangle^1 = \alpha_1 |+y\rangle^1 + \sqrt{\{1- \alpha_1^2\}}\, e^{i\delta 1} |-y\rangle^1$$

$$|-x\rangle^1 = \sqrt{\{1 - \alpha_1^2\}}\, e^{-i\delta 1} |+y\rangle^1 + \alpha_1 |-y\rangle^1. \qquad (5.5)$$

Analogously, the rotation on S_2 is given by:

$$W_2: ½ (|+x\rangle^2 \langle +x|^2 \otimes |b; +x\rangle^2 \langle b; +x|^2) + ½ (|-x\rangle^2 \langle -x|^2 \otimes |b; -x\rangle^2 \langle b; -x|^2) \rightarrow$$

$$\rightarrow ½ (|+v\rangle^2 \langle +v|^2 \otimes |b; +x; R_2\rangle^2 \langle b; +x; R_2|^2) +$$

$$+ ½ (|-v\rangle^2 \langle -v|^2 \otimes |b; -x; R_2\rangle^2 \langle b; -x; R_2|^2),$$

where:

$$|+v\rangle^2 = \Gamma_2 |+x\rangle^2 + \sqrt{\{1- \Gamma_2^2\}}\, e^{i\theta 2} |-x\rangle^2$$

$$|-v\rangle^2 = \sqrt{\{1- \Gamma_2^2\}}\, e^{-i\theta 2} |+x\rangle^2 + \Gamma_2 |-x\rangle^2. \qquad (5.6)$$

But then again, the measurements on S_2 will be along a different direction *z* given by:

$$|+x\rangle^2 = \alpha_2 \; |+z\rangle^2 + \sqrt{\{1- \alpha_2^2\}} \; e^{i\delta 2} \, |-z\rangle^2$$

$$|-x\rangle^2 = \sqrt{\{1 - \alpha_2^2\}} \; e^{-i\delta 2} \, |+z\rangle^2 + \alpha_2 \, |-z\rangle^2. \qquad (5.7)$$

Now we substitute in the entangled state (4.1), both $|+x\rangle^1$ by $|+w\rangle^1$ and $|-x\rangle^1$ by $|+w\rangle^1$; also we substitute $|+x\rangle^2$ by $|+v\rangle^2$ and $|-x\rangle^2$ by $|-v\rangle^2$ (i.e. we perform rotations on both S_1 and S_2). Then we do the appropriate substitutions of basis vectors, by means of (5.5) and (5.7). And we calculate on the resulting state the conditional probability $P(-z^2 / +y^1)$.

First, it can be shown that the probability of obtaining outcome "+" in the singlet state always remains ½ whatever the rotation: $P(+y^1) = ½$. By applying (5.2) we find that

$$P(-z^2 \,\&\, +y^1) =$$

$$= ½ \; |\{\Gamma_1 \alpha_1 + \sqrt{\{1 - \Gamma_1^2\}} \sqrt{\{1- \alpha_1^2\}} \, e^{i(\theta 1 - \delta 1)}\} \times$$

$$\times \{ \sqrt{\{1- \Gamma_2^2\}} \, \{\sqrt{\{1 - \alpha_2^2\}} \, e^{i(\delta 2 - \theta 2)} + \Gamma_2 \alpha_2\} +$$

$$+ \{\alpha_1 \sqrt{\{1 - \Gamma_1^2\}} \, e^{-i\theta 1} + \Gamma_1 \sqrt{\{1 - \alpha_1^2\}} \, e^{-i\delta 1}\} \times$$

$$\times \{\Gamma_2 \sqrt{\{1 - \alpha_2^2\}} \, e^{i\delta 2} + \alpha_2 \sqrt{\{1 - \Gamma_2^2 \, e^{i\theta 2}\}} \, |^2.$$

Hence, according to (5.2),

$$P(-z^2 / +y^1) =$$

$$= |\{\Gamma_1 \alpha_1 + \sqrt{\{1 - \Gamma_1^2\}} \sqrt{\{1- \alpha_1^2\}} \, e^{i(\theta 1 - \delta 1)}\} \times$$

$$\times \{ \sqrt{\{1- \Gamma_2^2\}} \, \{\sqrt{\{1 - \alpha_2^2\}} \, e^{i(\delta 2 - \theta 2)} + \Gamma_2 \alpha_2\} +$$

$$+ \{\alpha_1 \sqrt{\{1 - \Gamma_1^2\}} \, e^{-i\theta 1} + \Gamma_1 \sqrt{\{1 - \alpha_1^2\}} \, e^{-i\delta 1}\} \times$$

$$\times \{\Gamma_2 \sqrt{\{1 - \alpha_2^2\}} \, e^{i\delta 2} + \alpha_2 \sqrt{\{1 - \Gamma_2^2\}} \, e^{i\theta 2}\} \, |^2. \qquad (5.8)$$

<u>Causal Model Prediction</u>

We write the mixtures representing the rotated states of S_1 and S_2 together with their associated carriers. These are:

W_1: $\quad ½ \, (|R_1 +x\rangle^1 \langle R_1 +x|^1 \otimes |b; +x; R_1\rangle^1 \langle b; +x; R_1|^1) +$

$\qquad + ½ \, (|R_1 -x\rangle^1 \langle R_1 -x|^1 \otimes |b; -x; R_1\rangle^1 \langle b; -x; R_1|^1),$

W_2: $\quad ½ \, (|R_2 +x\rangle^2 \langle R_2 +x|^2 \otimes |b; +x; R_2\rangle^2 \langle b; +x; R_2|^2) +$

$$+ \tfrac{1}{2} (| R_2\ {-x}\rangle^2 \langle R_2\ {-x} |^2 \otimes | b; -x; R_2\rangle^2 \langle b; -x; R_2 |^2).$$

Suppose next that a measurement is made of spin on S_1. According to RR the probability for an outcome "+" is given by Tr ($W_1 P_{+y}$) = ½. Once the measurement is performed and the outcome "+" is found, RR further entails that the state of S_1 is reduced into $|{+y}\rangle^1$, and a carrier is then ejected in the mixed state:

C_1: $\tfrac{1}{2}\ |u; +x; R_1; +y\rangle^1\ {}^1\langle u; +x; R_1; +y| + \tfrac{1}{2}\ |u; -x; R_1; +y\rangle^1\ {}^1\langle u; -x; R_1; +y|$.

We can then write the state of the composite (system S_2 + carrier$_2$ + carrier$_1$) as follows:

W_2:

$$\tfrac{1}{4} (| R_2 +x\rangle^2 \langle R_2 +x |^2 \otimes | b; +x; R_2\rangle^2 \langle b; +x; R_2 |^2 \otimes | u; +x; R_1; +y\rangle^1 \langle u; +x; R_1; +y |^1)$$

$$+ \tfrac{1}{4} (| R_2 +x\rangle^2 \langle R_2 +x |^2 \otimes | b; +x; R_2\rangle^2 \langle b; +x; R_2 |^2 \otimes | u; -x; R_1; +y\rangle^1 \langle u; -x; R_1; +y |^1)$$

$$+ \tfrac{1}{4} (| R_2\ {-x}\rangle^2 \langle R_2\ {-x} |^2 \otimes | b; +x; R_2\rangle^2 \langle b; +x; R_2 |^2 \otimes | u; +x; R_1; +y\rangle^1 \langle u; +x; R_1; +y |^1)$$

$$+ \tfrac{1}{4} (|R_2\ {-x}\rangle^2 \langle R_2\ {-x} |^2 \otimes | b; +x; R_2\rangle^2 \langle b; +x; R_2 |^2 \otimes | u; -x; R_1; +y\rangle^1 \langle u; -x; R_1; +y |^1).$$

The interaction between these three systems is then given by GREPR, and the state of S_2 becomes W_2' (for ease of notation, we do not fill in the "bra" parts in the following expression):

W_2':

$$\tfrac{1}{4} (| \psi\rangle \langle \psi | \otimes | g; +x; R_2, \psi\rangle^2 \langle \ldots | \otimes | u; +x; R_1; +y\rangle^1 \langle \ldots |) +$$

$$+ \tfrac{1}{4} (|\psi\rangle \langle \psi | \otimes | g; +x; R_2, \psi\rangle^2 \langle \ldots | \otimes | u; -x; R_1; +y\rangle^1 \langle \ldots |) +$$

$$+ \tfrac{1}{4} (|\psi\rangle \langle \psi | \otimes | g; +x; R_2, \psi\rangle^2 \langle \ldots | \otimes | u; +x; R_1; +y\rangle^1 \langle \ldots |) +$$

$$+ \tfrac{1}{4} (|\psi\rangle \langle \psi | \otimes | g; +x; R_2, \psi\rangle^2 \langle \ldots | \otimes | u; -x; R_1; +y\rangle^1 \langle \ldots |),$$

where $| \psi\rangle = {}^1\langle +y |R_1R_2\ \Phi_{1+2}\rangle / \sqrt{(\langle R_1\ R_2\ \Phi_{1+2}\ | +y\rangle^1\ \mathbf{I}_2\ {}^1\langle +y | R_1\ R_2\ \Phi_{1+2}\rangle)}$

Thus according to our model: $P(-z^2\ \&\ +y^1) = P(| -z^2\rangle / | \psi\rangle) = | \langle -z^2 | \psi\rangle |^2$.

And $P(-z^2 / +y^1) = P(-z^2\ \&\ +y^1) / P(+y^1)$. A brief calculation shows that this probability is identical to its quantum mechanical counterpart (5.8).

6. Why Robustness is no Objection

A number of authors have argued that a causal account for the EPR correlations is impossible, invoking one version or another of an *invariance condition* for causal links. Very roughly, these invariance conditions suppose that a given pattern of association between two quantities expresses a causal link from one of the quantities to the other just in case the right kind of manipulations of the cause leave the pattern of association intact. So, as the cause changes under manipulation, the effect follows in train according to the given pattern. In this section we will explain why these objections misfire. They do not rule out plausibly formulated hypotheses about how measurement results in one wing of the experiment might cause results in the other wing, so *ipso facto* they do not rule out models that fit the structure that we describe.

The invariance conditions begins from the assumption that if one quantity Q causes another R, then, for each arrangement of values of the other causes of R, there is some fixed related pattern of association between Q and R – what we might think of as the "natural expression" of Q's effect on R. Consider, for example, Einstein and Infeld's claim that "forces cause motions". In this case the pattern of association is given by the equation $a = f / m$. Exponential decay can provide an example where the pattern is probabilistic. In this case when we consider "The excited state at $t=0$ causes the de-excited state at t" the pattern of association is given by the familiar exponential rule for conditional probability: P *(de-excited state at t / excited state at 0)* $= e^{-\lambda t}$. Alternatively, looking at "The transition from the excited state (of energy E_{ex}) to the de-excited state (energy: E_d) causes a photon of energy E_{ex} - E_d", the related pattern of association is given by the conditional probability: *P (photon of energy* $E = E_{ex} – E_d$ */ transition from excited to de-excited state) = 1.*

A number of authors have discussed invariance criteria[6] -- Michael Redhead's "robustness condition" is probably the central example in the EPR literature. Although there is some debate about what exactly a correct condition should require, for the purposes of our discussion we shall assume the following, which we take to be both plausible and defensible. (Here [] → is an arrow of counterfactual implication: A[]→ means "if A were to be the case, then B would be the case"):

> Causal Invariance Condition: A pattern of association between Q and R expresses a causal effect of Q on R iff (an *intervention* affects Q) [] → (R is still in accord with that pattern).

Clearly a good deal of the plausibility of this condition depends on how the term "intervention" is understood. Interventions are generally meant to fix either the level or the probability of the putative cause arbitrarily, without changing anything else relevant. That is, an intervention fixes the level / probability of the cause without affecting the level / probability of the effect *in any other way*. But a lot depends on how we explicate "in any other way", and how to do so for any specific case will depend on the specific kind of causal structure involved. In all cases, though, two conditions have to be worked out explicitly for the causal structure at hand. An *intervention* i) does not simultaneously affect "other" causes of the effect, and ii) does not change any causal laws involved, except those fixing the cause and anything that follows from that.[7]

In particular, where the pattern of association is given by a conditional probability, changing the probability of the cause Q should change the probability of the effect,

[6] We are familiar with the discussion in the economics and physics literature. There, see for example, (Simon, 1977), (Redhead, 1987), (Cartwright and Jones, 1993), (Cartwright, 1995), (Hoover, 2000), (Hausman and Woodward, 2000). See also (Spirtes, Glymour and Scheines, 1993).
[7] Point ii) is the basis of the criticism of Michael Redhead's argument against a causal connection between the wings of an EPR experiment in (Cartwright and Jones, 1993).

but the conditional probability of the effect on the cause (holding fixed the appropriate other causal factors) does not change. Clearly this is the central assumption underlying the methodology of the randomised treatment / control experiment, which is the gold standard for establishing causal hypotheses in medicine and widely throughout the social sciences. In discussions of the treatment / control experiments, though, the focus is on the fact that the (marginal) probability of the effect is different when the probability of the cause is different, whereas most of the deployment of this kind of condition in the EPR literature focuses on the constancy of the conditional probability between the two.

For instance, let us look at Michael Redhead's specific use of invariance conditions to argue against the claim that outcomes in one wing cause those in the other. Redhead takes the invariance condition to require that, for a disturbance *d* of the right kind (i.e. what we have called an "intervention"), $P_\psi (\pm x^2 / \pm y^1 \ \& \ d) = P_\psi (\pm x^2 / \pm y^1)$. That means that the causal hypothesis entertained for a causal link between the first wing and the second in the EPR described must be:

C: An outcome "±x" in a measurement of the first member S_1 of a pair prepared in the singlet state Φ_{1+2} causes an outcome "±y" in a measurement of the second member S_2 of the pair, where the associated pattern of association is given by $P_\Phi = (\pm x^2 / \pm y^1)$.

How then would we test **C** using the invariance condition? Note first that we cannot arbitrarily set the level of the cause because of the quantum indeterminism of measurement outcomes. So we try to change the probability by a physical interaction. Physical interactions on the spin states look in this set-up like rotations. That means that, under the interaction Hamiltonian H:

$$|+x\rangle^1 \rightarrow |+w\rangle^1 = \Gamma_1 |+x\rangle^1 + \sqrt{\{1-\Gamma_1^2\}}\, e^{i\theta 1} |-x\rangle^1$$

$$|-x\rangle^1 \rightarrow |-w\rangle^1 = \sqrt{\{1-\Gamma_1^2\}}\, e^{-i\theta 1} |+x\rangle^1 + \Gamma_1 |-x\rangle^1.$$

So under *H*, $\Phi_{1+2} \rightarrow \Phi'_{1+2}$, where:

$$\Phi'_{1+2} = \sqrt{(1/2)}\ |+w\rangle^1 |-x\rangle^2 - \sqrt{(1/2)} |-w\rangle^1 |+x\rangle^2.$$

Consider then, for example, $P_\Phi (-x^2 / +x^1)$. This equals 1. But $P_{\Phi'} (-x^2 / +x^1)$ equals Γ_1^2. So invariance would seem to be violated.

The intuition behind Redhead's argument is surely the reasonable idea that if "+x" on S_1 is causing "-x" on S_2, then when S_1 is rotated, it should drag S_2 along with it, which is not what happens. How do we know that S_2 is not *dragged* along? We are not able to tell this from the marginal probabilities, because $P_\Phi (+x^1) = P_{\Phi'} (+x^1) = 1/2 = P_\Phi (+x^2) = P_{\Phi'} (+x^2)$, but we can tell it from the conditional probabilities. If rotations of S_1 were always accompanied by identical physical rotations of S_2, the conditional probability $P_{\Phi'} (-x^2 / +x^1)$ should remain unchanged, and that is not what happens.

Why then does invariance not show that models that fit our framework are impossible? First we should notice that it is frequently pointed out – and by Redhead himself—that Redhead's proposed intervention would destroy the singlet state. How then can we be assured that the rotation on the first system is a proper intervention? The answer, we think, involves a very plausible physical intuition.

Consider the two requirements that we singled out that all interventions must satisfy: i) the rotation on the first member of the pair is a purely local interaction, both physically and in its mathematical representation. So it is reasonable to suppose that indeed it cannot affect the outcome on the second member except via the hypothesized causal link between outcomes on the first and outcomes on the second system. ii) As for the second requirement, the interaction is, after all, just a rotation. So it is reasonable to suppose that it cannot affect the capacity of outcomes on one wing to cause outcomes on the other (if such capacity exists). And there seems no other way that any of the relevant laws could be affected either.

These are good physical intuitions, and ones not to be ignored. But they must be carefully distinguished from those intuitions underpinning the Causal Invariance Condition. This Condition states that *if* we were able to manipulate the cause so as to change its probability, while making sure that in so doing we are not in any way affecting the connection between the cause and its effect, then the probability of the effect should change in accordance with the pattern of association. And notice that in the EPR case the antecedent of this condition is not satisfied: the only possible local disturbance on system S_1 is a rotation that does not change the probabilities of a "+" or "-" outcome of a measurement of S_1's spin.

If matters were left here, it seems it would be hard to say how heavily invariance counts against the possibility of a causal influence from one wing to the other. But let us look more closely at the kind of causal framework we have described. In particular, notice that when a rotation is executed on the first system, the state of the carriers attached to that system changes, since the state of the carriers records the full history of interactions undergone by their associated system. Since the carriers are affected, and since they are responsible for the transmission of causal influence from outcomes on one wing to outcomes in the other, condition ii) on interventions is in danger. So there may good reason to think that the rotation cannot after all count as an intervention, and the invariance condition cannot be applied as Redhead has proposed.

In fact, this is not really what goes wrong with the argument from the invariance principle to the impossibility of a causal influence between the wings. The state of the carriers is indeed affected, which does raise worries about whether the intervention affects the capacity of the results in one wing to cause those in the other wing. But more importantly, it points out a fundamental problem that besets this kind of argument in general, whether it is directed against the models that fit our framework or against any others that claim a causal connection between the wings. The problem is that *the wrong causal hypothesis is put to the test*.

Granting the physical intuitions that guarantee that rotations can count as interventions, the invariance argument correctly rules out the causal hypothesis we have so far entertained, hypothesis **C**. But that is not the natural starting hypothesis. For notice: if you think correlations need causal explanation, you have a problem with any systems that have ever interacted. Consider the joint state of any two such systems:

$$\Phi_{1+2} = \Sigma_{i,j} \,|\, u_i\rangle^1 \,|v_j\rangle^2.$$

In general for this kind of state,

$$P\,(\,|\,v_j\rangle^2 \,/\, |\,u_j\rangle^1) \neq P\,(\,|\,v_j\rangle^2).$$

So for cases where two systems have interacted, the appropriate causal hypothesis for a causal link between the two must be one that includes this conditional probability as its associated pattern of association.

In the EPR case we are considering then, the natural starting hypothesis is more elaborate than **C**, with a number of co-operating conditions that must be met both in the cause and in the effect:

C':

c_1: preparing a system as the "first" member of a pair (*n*) jointly in state Φ_{1+2},
c_2: and then subjecting it to rotation R_1,
c_3: and then obtaining a measurement result with outcome "$\pm x^1$",
c_4: and preparing a system as the "second" member of a pair (*n*) jointly in state Φ_{1+2},
c_5: and then subjecting it to rotation R_2,
c_6: and then measuring it for spin along the *z* axis

causes

e: outcomes "$\pm z^2$".

with the following rule of association: $P\,(e \,/\, c_1 \,\&\, c_2 \,\&\, c_3 \,\&\, c_4 \,\&\, c_5 \,\&\, c_6) =$
$= |\langle \pm z\,|\,\langle \pm x\,|\; R_1\, R_2\, \Phi_{1+2}\rangle\,|^2 \,/\, |\langle \pm x\,|\,R_1\, R_2\, \Phi_{1+2}\rangle\,|^2.$

We may ask now whether *this* causal hypothesis for EPR can be tested using standard experimental methodology: if we intervene to change the probability of the cause, will the effect change according to the prescribed rule of association? And will the conditional probability given in this rule remain unchanged? That depends on exactly what question we are asking. The answer for a number of obvious questions is, trivially, "yes". We can create Φ_{1+2} or not at will, set R_1 and R_2 as we wish, or look at will either at particle pairs created together at the source or at ones artificially matched up by us. For all these experiments we already know, given that we believe quantum predictions, what the outcome will be. For instance, we know trivially that if we have no other source of "$\pm z^2$" outcomes on the second wing, and we want them, then creating pairs in the singlet state and measuring in the second wing is one way to get them, though perhaps not the most efficient.

There is, though, one factor in the conjunctive cause whose efficacy we cannot test in this kind of controlled experiment: we can set neither the outcome of the first measurement nor its probability arbitrarily. What worry might this raise though?

Usually the concern is spurious correlation. So perhaps, after ψ, R^1 and R^2, *n* and *m* are all in place, there is still a common cause operating to bring about the correlated results on measurement. But if we want to resolve that issue, we will have to look to some different methodology.

Of course these are not the questions that the invariance condition was invoked to answer in the first place. But the point is that the invariance condition is not equipped to deal with the real question at issue. For once the correct kind of causal hypothesis is formulated – one that goes along with rules of association that actually obtain – then the question at stake turns out to be essentially this: are the EPR correlations, *which pass all standard statistical tests for expressing causal relations between the wings*, really the result of a causal connection or are they instead just fixed to occur? This is a question that the methodology of the controlled experiment is not geared to answer.

7. Conclusion

Let us review the main features of the model. Each partner system of an EPR pair has an associate *carrier*. These carriers are released when a measurement is made upon their associated system, say S_1. The outcome of this measurement is stochastic. The mixed state of system S_1 is reduced and the probabilities for the different possible outcomes are given by the standard Born interpretation. The released carrier interacts quantum mechanically with the system S_2 (with its corresponding carrier) on the other wing of the experiment according to the general rule GREPR. The evolution of S_2 is guaranteed to be quantum mechanical via the orthogonality relations for the carrier states, and is not stochastic in any way. The correlations are generated by the first measurement only, together with a causal influence transmitted from one wing to the other.

Our causal model for EPR is intended to provide an abstract framework within which questions about causality can be seriously considered and discussed. We believe that this framework can shed light on what a possible *physical* model will look like. The framework also shows that proofs ruling out causal influence as the source of the EPR correlations are wanting. We believe that the situation as regards causal explanations of the EPR correlations bears similarities with the history of the so-called impossibility proofs for hidden variable theories. For some time impossibility proofs exerted powerful pressure against attempts to construct empirically adequate hidden-variable theories for quantum phenomena. But eventually these proofs regularly met the same fate: once the issues involved in the discussion were more widely discussed and clarified, the proofs were seen not to support the strong conclusions originally claimed for them. This dialectic seems to have been fruitful in the development of hidden variable theories. We see no reason why a similar heuristics should not prove similarly fruitful for developing causal models for quantum phenomena.

In this spirit, we approach Fine's argument. If Fine's Strong Locality Condition (SLOC), prohibiting any influence between spatially separated wings of an EPR experiment, is not built into the quantum theory, is there any other –weaker – condition that is so built in? In investigating this question, we will be *ipso facto* clarifying the notion of causality in modern physics.

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