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Jamming nonlocal quantum correlations

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We present a possible scheme to tamper with nonlocal quantum correlations in a way that is consistent with relativistic causality, but goes beyond quantum mechanics. A nonlocal ''jamming'' mechanism, operating within a certain space-time window, would not violate relativistic causality and would not lead to self-contradictory causal loops. The results presented in this paper do not depend on any model of how quantum correlations arise and apply to any jamming mechanism. [S1050-2947(96)02206-8]

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I. INTRODUCTION

The question of nonlocal quantum correlations versus local realism, first raised in the famous Einstein-Podolsky-Rosen (EPR) paper [1], has held the interest of the physics community since. Bell [2] showed that the predictions of quantum mechanics are incompatible with any model based on local realism. The experimental work of Freedman and Clauser [3], Clauser [4], Fry and Thompson [5], Aspect and co-workers [6], and others [7] supports the predictions of quantum mechanics and contradicts local realism: Bell inequalities applicable to the various experimental arrangements were shown to be violated. It should be mentioned that some aspects of the experimental setups have been criticized and questioned [8]. Problems of experimental bias or enhancement of particular polarization states by detection systems were experimentally checked by Haji-Hassan *et al.* [9] and found absent. And more recently Kwiat *et al.* [10] have proposed and described an experimental arrangement that overcomes shortcomings of previous experiments. While experiments are still open to criticism, it is generally accepted that local realism is untenable. In this paper we assume that in nature there exist nonlocal correlations, as predicted by quantum mechanics, and we address the following question: Can an experimenter *nonlocally tamper* with nonlocal correlations, without violating relativistic causality?

Quantum mechanics predicts nonlocal correlations; however, it does not provide an ''explanation'' about what creates them. Several theoretical models go beyond quantum mechanics and propose to explain the phenomenon of nonlocal correlations via a superluminal ''communication link'' [11]. If one accepts the possibility of a communication link, then a natural next step would be to probe whether it is possible to tamper with this link and *jam* the superluminal communication [12]. Up to now, the possibility of jamming nonlocal correlations has not received due consideration, perhaps because of a tacit assumption that such tampering necessarily violates relativistic causality. (The expression *relativistic causality* is used here to denote the principle that information cannot be transferred at speeds exceeding the speed of light). In this paper we show that jamming of nonlocal correlations can be consistent with relativistic causality. Our results are independent of the model used to describe how the nonlocal quantum correlations arise, that is, the nature of the superluminal communication link, and they apply to any jamming mechanism.

II. THE JAMMING SCHEME

Jamming might take many forms. The following discussion does not define a mechanism for jamming; rather, it defines the constraints that any jamming mechanism must obey in order to be consistent with relativistic causality. In order to derive and illustrate the constraints, it is convenient to consider a particular experimental arrangement which can be subjected to jamming [13]. We will consider an EPR-Bohm experimental arrangement to study pairs of spin-1/2 particles entangled in a singlet state [14]. Spacelike separated spin measurements on these pairs allow a test of the Bell inequalities. Suppose that two experimenters, Alice and Bob, perform the spin measurements. One particle of each entangled pair arrives at Alice's analyzing station and the other particle arrives at Bob's. When Alice and Bob get together and combine the results of their measurements, they will find violations of the Bell inequalities, as predicted by quantum mechanics [2].

We now introduce a third experimenter, Jim, the jammer, who has access to a jamming device which he can activate, at will, and tamper with the communication link between each entangled pair of particles. His action is spacelike separated from the measurements of Alice or Bob or from both of them. Jamming acts at a distance to modify the correlations between the particles; it disturbs the conditions which make possible the phenomenon of nonlocal quantum correlations. Therefore the correlations measured jointly by Alice and Bob will not agree with the predictions of quantum mechanics.

Jamming is truly nonlocal and cannot be carried out within the framework of quantum mechanics. For example, consider three systems, S_1, S_2, and S_3, in a quantum state Ψ_{123}. Let experimenters near S_1 and S_2 measure $A^{(1)}$ and $A^{(2)}$, with eigenstates denoted by $|a_i^{(1)}\rangle$ and $|a_j^{(2)}\rangle$, respectively. The only freedom available to an experimenter near S_3 is the choice of what local operator $A^{(3)}$ to measure. But the probabilities $P(a_i^{(1)},a_j^{(2)})$ for outcomes $A^{(1)}=a_i^{(1)}$ and $A^{(2)}=a_j^{(2)}$,

$$P(a_i^{(1)},a_j^{(2)})=\sum_k |\langle\Psi_{123}|a_i^{(1)},a_j^{(2)},a_k^{(3)}\rangle|^2, \qquad (1)$$

are *independent* of the choice of operator $A^{(3)}$. Thus no measurement on S_3 can affect the results of the measurements performed on S_1 and S_2, even if the three systems have interacted in the past [15].

In general, jamming would allow Jim to send superluminal signals. The constraints that must be satisfied in order to ensure that Jim cannot send superluminal signals are embodied in two conditions. The first condition, the *unary condition,* a necessary but not sufficient condition, requires that Jim not be able to send signals to Alice or Bob *separately.* In effect this condition demands that Alice and Bob, separately, measure zero average spin along any axis. Explicitly, let $N_a(+)$ and $N_a(-)$ tally the number of spin-up and spin-down results, respectively, found by Alice for a given axis. For the same axis, let $n(k,l)$ tally, in the absence of jamming, the joint results of Alice and Bob. The parameters k and l denote, respectively, the results ($+$ or $-$) of the polarization measurements carried out by Alice and Bob. Let $n'(k,l)$ tally, in the presence of jamming, the corresponding polarization measurements carried out by Alice and Bob. The unary condition imposes the following relations between $n(k,l)$ and $n'(k,l)$:

$$\begin{aligned} N_a(+)&=n(+,+)+n(+,-)=n'(+,+)+n'(+,-),\\ N_a(-)&=n(-,+)+n(-,-)=n'(-,+)+n'(-,-). \end{aligned} \tag{2}$$

A similar set of relations holds for the results $N_b(+)$ and $N_b(-)$ found by Bob. Hence regardless of whether Jim has activated the jamming device, Alice and Bob will find that the average spin projection along any axis tends to zero, and Jim cannot send superluminal signals, separately, to either Alice or Bob.

The unary condition allows a range of possibilities for the jammed correlations: from correlations which are only slightly different from those predicted by quantum mechanics, down to completely random correlations. In particular, the unary condition allows conservation of angular momentum, i.e., perfect anticorrelation of spin components along any parallel axes.

III. THE SPACE-TIME WINDOW

As stated in the preceding section, the unary condition is a necessary but not sufficient condition. For jamming to respect relativistic causality, we must also restrict the relationships in space and time among the three events $a,b,$ and j generated, respectively, by Alice, Bob, and Jim. Figure 1 shows the geometry of three different configurations of an EPR-Bohm experimental setup along with the corresponding Minkowski diagrams of the events $a,b,$ and j. In the configuration shown in Fig. 1(a), jamming is *not* permitted. Here Alice and Bob are in close proximity while Jim is far away. If jamming were permitted, Alice and Bob could—immediately after Jim activates the jamming device—measure the spin projections of their respective particles and combine their results to determine the spin correlations. They would find spin correlations differing from the predictions of quantum mechanics and infer that Jim activated the jamming device. The corresponding Minkowski diagram, Fig. 1(b), shows that the future light cones of a and b overlap, in part, outside the future light cone of j. A light signal originating at j cannot reach this overlap region of a and b, where Alice and Bob can combine their results. Were jamming possible here, it would violate relativistic causality.

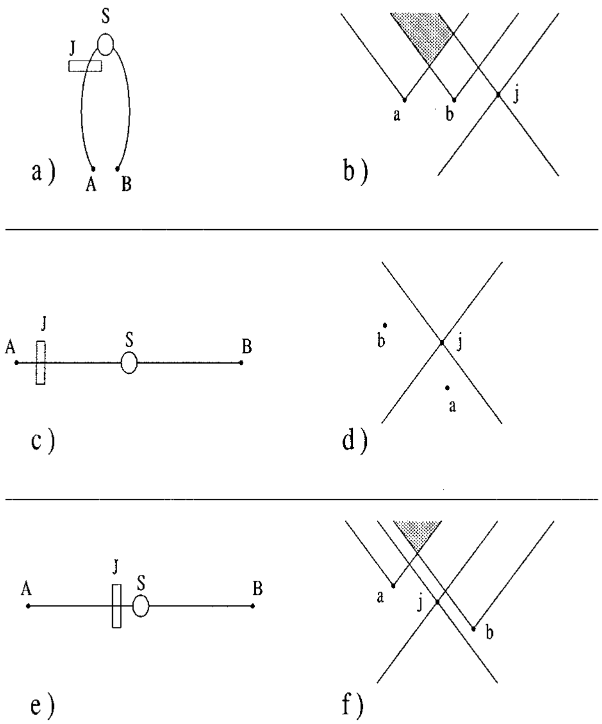

FIG. 1. The geometrical configurations showing the source S of pairs of quantum systems, the jammer J, and the experimenters Alice, A, and Bob, B. (a) A and B are close to each other while J is far from both of them. (c) A and J are close to each other while B is far from both of them. (e) A, B, and J are all far from each other; J is stationed near the source and A and B are at opposite ends of an EPR-Bohm setup. Corresponding Minkowski diagrams showing the events a, b, and j. (b) The future light cones of a and b have some overlap outside the future light cone of j. (d) A possible configuration for selective jamming. (f) A configuration satisfying the binary condition. The future light cones of a and b overlap only within the future light cone of j.

Figure 1(c) shows a configuration that would also permit superluminal signaling: Jim obtains the results of Alice's measurements prior to deciding whether to activate the jamming device. Bob is far from both Alice and Jim. The corresponding Minkowski diagram, Fig. 1(d), shows that a precedes j by a timelike interval and both a and j are spacelike separated from b. Since Jim has access to Alice's results, he can send a superluminal signal to Bob by *selectively* jamming: For instance, suppose Jim activates the jamming device only when Alice obtains the value $+1/2$ for the projection of the spin of a particle. Bob will, then, find that the average spin component along a given axis does *not* tend to zero. The preceding can be demonstrated by comparing the results of the spin measurements, $N_b(+)$ and $N_b(-)$, carried out by Bob in the absence of jamming, Eqs. (3) and in the presence of selective jamming, Eqs. (4). The notation previously defined is used in Eqs. (3) and (4).

$$\begin{aligned} N_b(+)&=n(+,+)+n(-,+),\\ N_b(-)&=n(+,-)+n(-,-). \end{aligned} \tag{3}$$

$$N_b(+)=n'(+,+)+n(-,+),$$
$$N_b(-)=n'(+,-)+n(-,-). \tag{4}$$

Hence the results obtained by Bob in the presence of selective jamming will be different from those obtained in the absence of jamming unless $n'(+,+)=n(+,+)$ and $n'(+,-)=n(+,-)$. However, the latter requirements imply that jamming, in this configuration, cannot have any discernible effect, i.e., jamming in this configuration is impossible.

To eliminate configurations which allow violations of relativistic causality, as shown in Figs. 1(a)–1(d), we further restrict jamming by imposing a second condition, the *binary condition*. The binary condition, which is manifestly covariant, demands that the overlap of the future light cones of a and b lie entirely within the future light cone of j and therefore a light signal emanating from j can reach the overlap region. The configuration shown in Figs. 1(a) and 1(b), which allows an overlap of the future light cones of a and b outside of the future light cone of j, is therefore forbidden. The configuration shown in Figs. 1(c) and 1(d), a configuration for selective jamming, violates the unary condition and it is also disallowed by the binary condition. A configuration which satisfies the binary condition is shown in Figs. 1(e) and 1(f).

The constraints to which a jamming configuration must conform, in order not to violate relativistic causality, are embodied in the unary and binary conditions. These conditions are manifestly Lorentz invariant. However, the time sequence of the events a, b, and j is not. A time sequence a, j, and b in one Lorentz frame may transform into b, j, and a in another Lorentz frame. Hence while one observer will claim that Alice completed her measurements before Jim activated his jamming mechanism and thus Jim affected only the results of Bob's measurements, another observer will claim that Bob carried out his measurements first and Jim affected only Alice's results. Similar situations are encountered in quantum mechanics where different observers in different Lorentz frames will give conflicting interpretations of the same set of events. For example, with respect to an entangled pair of particles in an EPR-Bohm experiment, the question of which observer caused the collapse of the entangled state has no Lorentz-invariant answer [16].

If jamming is possible then one must accept the possibility of reversal of the *cause-effect* sequence [17]; however, the allowed configuration which satisfies the *unary* and *binary* conditions does not lead to contradictory causal loops, i.e., no *effect* can send a signal to its *cause*. Indeed, consider one jammer, J, who acts on the correlations between two spacelike separated events, a and b. We first recall that the unary condition precludes signaling to a and b, separately, by j; therefore only the combined results of the measurements of a and b can reveal whether J activated a jamming mechanism. In order to complete a contradictory causal loop one must gather the results of the measurements of a and b into the past light cone of j and then send a signal to j, the *cause*. But the binary condition requires that the overlap of the future light cones of a and b be completely contained in the future light cone of j, so the only place where information from a and b can be put together by means of ordinary signals is the future of j. One might suppose that other jammers, using their nonlocal action, could somehow transmit the information from a and b into the past light cone of j. Such a scheme would require at least two more jammers. Since these jammers must have access to the results of a and b, we place j_1 and j_2 (generated by J_1 and J_2) at timelike separations, respectively, from a and b. Events a and b are spacelike separated from each other and from j, so j_1 and j_2 will either be spacelike separated from j or in its future light cone.

The cases of J_1 and J_2 are similar, so we discuss only J_1; however, the conclusions reached apply equally to J_1 and J_2. The jammer, J_1, can communicate the results of a by jamming or not jamming the nonlocal correlations between pairs of entangled particles measured at events a_1 and b_1. Notice that in order to communicate the result of a single measurement done at a, J_1 must jam (or not jam) an ensemble of EPR pairs. The result of a single measurement carried out at a is recovered from the correlations determined from the combined measurements made at a_1 and b_1.

For the jammer J_1 to gather the information at a into the past light cone of j requires that both a_1 and b_1 lie in the past light cone of j, i.e., j lies in the overlap of the future light cones of a_1 and b_1. This requirement, however, is incompatible with the binary condition when applied to the triplet of events, a_1, b_1, and j_1, which requires that the overlap of a_1 and b_1 be contained within the future light cone of j_1. This, in turn, implies that j will lie in the future light cone of j_1, contradicting the assumption that j_1 is either spacelike separated from j or in j's future light cone. Consequently, a_1 and b_1 cannot both be in the past light cone of j. Therefore the introduction of J_1 does not help to gather the results of a into the past light cone of j. Then, by induction, we find that no scheme to close a contradictory causal loop, by introducing any number of jammers, can succeed.

IV. CONCLUSIONS

In quantum mechanics nonlocal correlations are well established; however, these correlations cannot be used to send superluminal signals. In this paper we have raised the question of whether a form of nonlocality beyond quantum mechanics—nonlocal tampering with quantum correlations—could also respect relativistic causality. We find that jamming configurations which obey two conditions—the *unary* condition, which forbids superluminal signaling to either of two experimenters, and the *binary* condition, which restricts the space-time configuration of the two experimenters and the jammer—respect relativistic causality. For these configurations, the cause-effect sequence might not be preserved in all Lorentz frames; however, they do not lead to contradictory causal loops. Hence we find that a stronger form of nonlocality than that arising in quantum mechanics—action at a distance rather than nonlocal correlations—is consistent with relativistic causality [12,18,19].

The results presented in this paper are independent of the model used to describe the nature of the nonlocal correlations and apply to any jamming mechanism. Experimental studies to date have not tested the possibility of jamming. We suggest that current and projected EPR-Bohm experiments test the possibility of jamming in configurations consistent with the constraints derived in this paper. The constraints on jamming configurations do not themselves suggest a jamming mechanism; nevertheless, specific possibilities for a jamming procedure, such as one suggested by Shimony [12], may be of interest and suitable for current and planned experiments.

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