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Are Superluminal Connections Necessary? (*)(**).

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Summary. — The following theorem is proved: If the statistical predictions of quantum theory are true in general and if the macroscopic world is not radically different from what is observed, then what happens macroscopically in one space-time region must in some cases depend on variables that are controlled by experimenters in far-away, spacelike-separated regions. By what happens macroscopically in one space-time region is meant specifically the occurrence or nonoccurrence of a macroscopic event, such as the detection and recording of a particle by some macroscopic device. By a variable controlled by an experimenter in a certain space-time region is meant specifically the experimental setting in that region of some macroscopic device, in which this setting is controlled by an experimenter acting within that region. The theorem pertains specifically to experimental situations in which there are two far-apart, spacelike-separated regions in each of which there is a device that can be set at either of two alternative settings by an experimenter acting within that region. There is also a long sequence of experimental results (*i.e.* events) in each of the two regions. The theorem asserts that, for some such cases, it is mathematically impossible, within the manifold of all conceivable results compatible with the statistical predictions of quantum theory (to within a generous limit of, for example, 1000 standard deviations), that what happens in each region be independent of the experimental setting of the device in the far-away region. In short, there are situations in which it is mathematically impossible to meet both the statistical requirements of quantum theory and also the locality requirement that what happens in each region be independent of the setting made in the far-away, spacelike separated region. This result is a sharpening of a result due to Bell. Bell's result was formulated

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in terms of unspecified local hidden variables, and claimed merely to rule out the notion of local hidden variables, which was believed by hardly anyone anyway. The present theorem is formulated directly in terms of specified macroscopic quantities, and within the philosophic framework of contemporary quantum theory. The aim of this work is to discuss the significance of this theorem and its possible uses.

1. – Proof of the theorem.

The theorem stated in the abstract is a sharpening of a result due to BELL (1). It has been proved in ref. (2,3). However, it will be useful to give here an alternative proof that is perhaps simpler and more informative.

Consider a spin correlation experiment in which two spin-$\frac{1}{2}$ fermions are allowed to scatter off each other and then move apart into two spacelike-separated space-time regions R_1 and R_2, where each is allowed to pass through a Stern-Gerlach device. This device produces a deflection of the particle either up or down relative to some experimental axis, which can be controlled by a human experimenter (or by a random number generator). The particle is then detected and recorded by suitable devices, and it is thereby determined whether the particle went up or down.

The above account describes what the physicist imagines to be happening. What is actually observed are the settings of the axes of the two devices and the macroscopic events that are interpreted as the detection and recording of the particles. The question is whether the events in each region can be independent of the variable controlled by the experimenter in the far-away, spacelike-separated region. The theorem states that, if the statistical predictions of quantum theory are valid in general, and if the world is not radically different from what it is observed to be, then what happens at the macroscopic level in each region cannot be independent of how the apparatus was set in the far-away, spacelike-separated region.

The requirement of the theorem that the macroscopic world be not radically different from what it is observed to be means that, if a conceivable event is reliably observed not to occur, then it does not occur. This requirement rules out the so-called many-world interpretation of quantum theory, in which what is observed is regarded as fundamentally an illusion. We assume, specifically, in this situation in which we can observe either the events corresponding to the

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(1) J. S. BELL: *Physics, Physique, Fisika*, **1**, 195 (1965).

(2) H. P. STAPP: *Correlation Experiments and the Nonvalidity of Ordinary Ideas About the Physical World* (Berkeley 1968) and LBL-5333.

(3) H. P. STAPP: *Phys. Rev. D*, **3**, 1303 (1971).

particle going up or the events corresponding to the particle going down, but never both sets of events together, that some *choice* is made between these two alternative possibilities. No restriction is placed on the method by which this choice is made: it could be by the action of chance, or by some deterministic process, or by the will of God, or by anything else. But there must be a real choice, for it is precisely the dependence of this choice on the far-away variable that is the subject of the theorem.

Now we proceed with the proof.

Each of the two particles can go either up or down relative to the chosen axis of the Stern-Gerlach device. Thus the result of the experiment can be assigned to one of the four small boxes in the diagram shown below (fig. 1):

↑↑	↑↓
↓↑	↓↓

Fig. 1. – Diagram indicating the four possible results of the experiment.

If the original scattering of the two fermions is at low energy, so that the scattered spin state is the state of zero spin, then quantum theory gives the following predictions (fig. 2) for the probabilities of finding each of the four possible results:

$\frac{1}{4}-\frac{\cos\theta}{4}$	$\frac{1}{4}+\frac{\cos\theta}{4}$
$\frac{1}{4}+\frac{\cos\theta}{4}$	$\frac{1}{4}-\frac{\cos\theta}{4}$

Fig. 2. – The quantum theoretic probabilities for the results indicated in fig. 1.

Here θ is the angle between the axes of the two Stern-Gerlach devices, measured in an appropriate way.

Each axis has two allowed directions. These are chosen so that the four alternative angles θ are as follows (here the arrows show the directions of the axes):

$$\theta_{11} = 0^\circ \quad (\uparrow\uparrow), \qquad \theta_{12} = 90^\circ(\uparrow\rightarrow),$$

$$\theta_{21} = 135^\circ(\searrow\uparrow), \qquad \theta_{22} = 45^\circ(\searrow\rightarrow).$$

Then the four corresponding sets of probabilities are shown in fig. 3.

The experiment discussed above corresponds to a single pair of fermions. Consider now a long sequence consisting of N such pairs. The choice between the four alternative experiments is to be made just before the batch of N pairs of particles enters regions R_1 and R_2. The conceivable results in each of the four alternate experiments are represented by distributing the N integers in all possible ways among the four little boxes in the big box corresponding to that experiment. The number in each small box of fig. 3 gives, to a high degree of accuracy, which can be increased by increasing N, the fraction of the set of N integers that is predicted by quantum theory to be in that small box.

(↑↑)

0	$\frac{1}{2}$ (*a*)
$\frac{1}{2}$	0

(↑→)

$\frac{1}{4}$ (*b*)	$\frac{1}{4}$
$\frac{1}{4}$	$\frac{1}{4}$

(↘↑)

$\frac{1}{4}+\frac{\sqrt{2}}{8}$	$\frac{1}{4}-\frac{\sqrt{2}}{8}$
$\frac{1}{4}-\frac{\sqrt{2}}{8}$	$\frac{1}{4}+\frac{\sqrt{2}}{8}$ (*c*)

(↘→)

$\frac{1}{4}-\frac{\sqrt{2}}{8}$	$\frac{1}{4}+\frac{\sqrt{2}}{8}$
$\frac{1}{4}+\frac{\sqrt{2}}{8}$ (*d*)	$\frac{1}{4}-\frac{\sqrt{2}}{8}$

Fig. 3. – The probabilities for the various cases. The small boxes labelled by the letters (*a*), (*b*), (*c*) and (*d*) are discussed below.

In terms of this geometric picture, the locality requirement is the requirement that, as one moves laterally from one big box to another (*i.e.* changes the setting of the second device), the integers that represent the events can move only laterally, from one small box to another. This locality requirement expresses the condition that what happens in the first region R_1 be unaltered by a change of setting in R_2. Similarly, in a vertical shift from one big box to another the integers can shift only vertically between the little boxes.

There is no way to satisfy both this locality requirement and the quantum theoretical requirement that within each of the big boxes the fraction of the N integers lying in each small box be approximately that shown in fig. 3. To show this, one may ask, for any arrangement that conforms to the above quantum-theoretical requirement, what fraction f of the set of N integers lies both in box a and in box d of fig. 3. Considering the intermediate step through the

little box b, one sees that this fraction f cannot be larger than $\frac{1}{4}$, since only those integers that lie in b can be both in a and d. Considering the step through the little box c, one sees that the fraction f must be at least

$$\left(\frac{1}{4}+\frac{\sqrt{2}}{8}\right)-\left(\frac{1}{4}-\frac{\sqrt{2}}{8}\right)=\frac{\sqrt{2}}{4},$$

since at least this quantity must move from c to d in the second (lateral) step. * Thus we have a contradiction, and can conclude that there is no way that one can arrange the conceivable results of the four experiments in such a way as to meet both locality and quantum-theoretical requirements.

The proof of this result in ref. ([2,3]) involved more arithmetic, which tended to obscure the origin of the contradiction, but was more straightforward. Both proofs are merely variations of Bell's original argument.

To avoid possible confusion, it will be mentioned that our locality requirement is not the same as the locality requirement of quantum field theory, which refers to the operators of field theory. The present locality requirement makes no reference to the formalism of quantum theory; it is formulated directly in terms of the macroscopic observables.

2. – Fact and necessity.

The idea that what happens depends on a variable can be formulated in two ways. In the first formulation, one considers a theoretical manifold of possibilities and asks whether what happens must *necessarily* depend on the variable. In the second formulation, one considers a sequence of actually occurring instances and asks whether in this sequence there is a correlation between what actually happens in a given instance and the choice actually made by the experimenter in that instance. In this latter situation, the question of dependence is purely experimental. Long ago, HUME ([4]) emphasized that one can never deduce from such empirical evidence the existence of a necessary connection. Rather one can observe what has happened in the past and make a theoretical assumption that the same pattern will be found in the future.

Both ideas of dependence are used in our analysis. First, the statistical regularities of quantum theory are accepted on the basis of past experience. Then, on the basis of this theoretical assumption, it is shown by mathematical analysis that what happens in one region must, in some instances, necessarily depend on the variable controlled by the experimenter in the far-away, space-like-separated region.

([4]) D. HUME: *An Inquiry Concerning Human Understanding* (1748).

* The point is that all of the $N(\frac{1}{4}+\frac{\sqrt{2}}{8})$ pair identifiers in (c) come from (a), and the minimum going to (d) is obtained by putting as many of them as possible into the box on the lower far right, namely $\frac{1}{4}-\frac{\sqrt{2}}{8}$. Aug 2010

3. – Bohr's complementarity principle.

Our theorem is formulated in a theoretical framework in which experimenters are considered free to choose which experiment they will perform and theorists are free to consider in a single analysis the conceivable results of several alternative experiments. However, Bohr's principle of complementarity imposes a limitation on the simultaneous use of evidences from alternative incompatible experiments. The question thus arises whether our theoretical framework is compatible with the canons of quantum theory, as expounded by BOHR.

BOHR claims that, in order to widen our conceptual framework sufficiently to account for the observed regularities in atomic phenomena, we must renounce the demand for classical pictorial description in favor of a description based on the idea of complementarity. Bohr's argument goes as follows: « The critical point is here the recognition that any attempt to analyse, in the customary way of classical physics, the "individuality" of atomic processes as conditioned by the quantum of action, will be frustrated by the unavoidable interaction between the atomic objects concerned and the measuring instruments indispensable for that purpose.

« An immediate consequence of this situation is that observations regarding the behaviour of atomic objects obtained with different experimental arrangements cannot in general be combined in the usual way of classical physics. In particular, any imaginable procedure aiming at the co-ordination in space and time of the electrons in an atom will unavoidably involve an essentially uncontrollable exchange of momentum and energy between the atom and the measuring agencies, entirely annihilating the remarkable regularities of atomic stability for which the quantum of action is responsible. Conversely, any investigation of such regularities, the very account of which implies the conservation laws of energy and momentum, will in principle impose a renunciation as regards the space-time co-ordination of the individual electrons in the atom. Far from being inconsistent, the aspects of quantum phenomena revealed by experience obtained under such mutually exclusive conditions must thus be considered complementary in quite a novel way. The viewpoint of "complementarity" does, indeed, in no way mean an arbitrary renunciation as regards the analysis of atomic phenomena, but is on the contrary the expression of a rational synthesis of the wealth of experience in this field, which exceeds the limits to which the application of the concept of causality is naturally confined. » (5)

« While, within the scope of classical physics, the interaction between object and apparatus can be neglected or, if necessary, compensated for, in

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(5) N. BORH: *Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 19.

quantum physics this interaction ... forms an inseparable part of the phenomena. ... Within the scope of classical physics all characteristic properties of a given object can in principle be ascertained by a single experimental arrangement ... and can be combined into a consistent picture of the object under investigation. In quantum physics, however, evidence about atomic objects obtained by different experimental arrangements exhibits a novel kind of complementary relationship. Indeed, it must be recognized that such evidence, which appears contradictory when combination into a single picture is attempted, exhausts all conceivable knowledge about the object. Far from restricting our efforts to put questions to Nature in the form ofe xperiments the notion of *complementarity* simply characterizes the answers we can receive by such inquiry whenever the interaction between the measuring instruments and the objects forms an integral part of the phenomena. » (6)

« The element of wholeness, symbolized by the quantum of action and completely foreign to classical physical principles, has, however, the consequence that in the study of quantum processes any experimental inquiry implies an interaction between the atomic object and the measuring tools which, although essential for the characterization of the phenomena, evades a separate account if the experiment is to serve its purpose of yielding unambiguous answers to our questions. It is indeed the recognition of this situation which makes the recourse to a statistical mode of description imperative as regards the expectations of the occurrence of individual quantum effects in one and the same experimental arrangement, and which removes any apparent contradiction between phenomena observed under mutually exclusive experimental conditions. However contrasting such phenomena may at first appear, it must be realized that they are complementary in the sense that taken together they exhaust all information about the atomic object which can be expressed in common language without ambiguity.

« The notion of complementarity does not imply any renunciation of detailed analysis limiting the scope of our inquiry, but simply stresses the character of objective description, independent of subjective judgment, in any field of experience where unambiguous communication essentially involves regard to the circumstances in which evidence is obtained. » (7)

« A most conspicuous characteristic of atomic physics is the novel relationship between phenomena observed under experimental conditions demanding different elementary concepts for their description. Indeed, however contrasting such experiences might appear when attempting to picture a course of atomic processes on classical lines, they have to be considered as com-

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(6) N. Bohr: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1963), p. 4.

(7) N. Bohr: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1963), p. 60.

plementary in the sense that they represent equally essential knowledge about atomic systems and together exhaust this knowledge. The notion of complementarity does in no way involve a departure from our position as detached observers of Nature, but must be regarded as the logical expression of our situation as regards objective description in this field of experience. The recognition that the interaction between the measuring tools and the physical systems under investigation constitutes an integral part of quantum phenomena has not only revealed an unsuspected limitation of the mechanical conception of Nature, as characterized by attribution of separate properties to physical system, but has forced us, in the ordering of experience, to pay proper attention to the conditions of observation. » (8)

« However great the contrasts exhibited by atomic phenomena under different experimental conditions, such phenomena must be termed complementary in the sense that each is well defined and that together they exhaust all definable knowledge about the objects concerned. » (9)

« The freedom of experimentation presupposed in classical physics is of course retained and corresponds to the free choice of experimental arrangement for which the mathematical structure of quantum theory offers the appropriate latitude. » (10)

« The renunciation of pictorial representation involves only the state of atomic objects, while the foundation of the description of the experimental conditions, as well as our freedom to choose them, is fully retained. » (11)

We see from the above quotations that what is rejected by the notion of complementarity is not the general theoretical contemplation of alternative experiments, but rather the attempt to combine the evidence obtained from alternative incompatible experiments into a single classical-type picture of the atomic object. There is no rejection of the idea that the experimenters are free to choose the experiment they wish to perform. In fact, this freedom of experimentation is explicitly recognized and retained. Moreover, there is no rejection of the idea that theorists should try to combine the evidence obtained from the alternative possible measurements into a single theoretical scheme. On the contrary, the main point of complementarity is precisely that one can combine the evidence from alternative measurements into one theoretical structure, which, however, does not provide a classical-type picture of the atomic object.

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(8) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 74.

(9) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 90.

(10) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 73.

(11) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 90.

Bohr's argument for the need for complementarity in the analysis of atomic phenomena rests on the claim that the interaction between the object and the measuring instruments is an integral and inseparable part of the phenomena. It follows from this inseparability that during the process of measurement there is, strictly speaking, no separate atomic object; the atomic process is inseparably linked to the apparatus. Thus there is no reason why one should be able to ascribe aspects of this evidence to an atomic object conceived as a separately existing entity. The experimental data should be associated rather with the whole experimental arrangement.

This argument provides a rational physical basis for the claim that evidences from different experiments cannot be combined into a classical-type picture of an independently existing atomic object. But it in no way rules out the simultaneous consideration of alternative possibilities if, as in our procedures, one treats the conceivable data from alternative experiments as nothing but the conceivable data from alternative experiments.

One might introduce a new principle of « strong complementarity » that would simply preclude any use in a single theoretical analysis of the results of alternative incompatible experiments. This principle would, of course, provide a basis for rejecting our theorem, if such a basis were desired. However, this principle would directly conflict with Bohr's complementarity because it would exclude the idea that the data obtained from alternative measurements are complementary, in the sense that they can be combined together to form an exhaustive characterization of the individual atomic object.

This new principle of strong complementarity might be justified on the basis of the positivistic principle that nothing that is in principle unknowable should be allowed in the conceptual framework of science. Bohr was careful to avoid any such blanket restriction on allowed concepts. His aim was not the positivistic one of narrowing our conceptual framework to bring it into accord with some epistemological statute, but rather the pragmatic one of widening the conceptional framework of science for the purpose of ordering and augmenting those aspects of human experience that are objective in the sense that they refer to no particular individual and can be unambiguously formulated and communicated.

« ... the notion of complementarity is called for to provide a framework wide enough to embrace the account of fundamental regularities of Nature which cannot be comprehended in a single picture. » (12) « The history of physical science thus demonstrates how the exploration of ever wider fields of experience, in revealing unsuspected limitations on accustomed ideas, indicates new ways of restoring logical order. » (13) « Indeed, the development of atomic

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(12) N. Bohr: *Essays 1958/1962 on Atomic Physics and Human Knowledge* (New York, N. Y., 1963), p. 12.

(13) N. Bohr: *Essays 1958/1962 on Atomic Physics and Human Knowledge* (New York N. Y., 1958), p. 74.

physics has taught us how, without leaving common language, it is possible to create a framework sufficiently wide for an exhaustive description of new experience. » (14)

Thus BOHR did not advocate an arbitrary renunciation of traditional ideas on the basis of some philosophical principle, but rather aimed to show on the basis of *physical* considerations that in quantum mechanics « we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is *in principle* excluded. » (15) The physical basis of his argument was « the recognition that no sharp separation can be made between an independent behaviour of the objects and their interaction with the measuring instruments.... » (16)

The positivistic principle of « strong complementarity » could, in spite of Bohr, nevertheless be introduced. However, now philosophers appear to agree that the positivistic criterion of meaning is untenable, because it excludes useful theoretical constructions. A valid argument for the exclusion of a theoretical construction must demonstrate that it cannot be useful. However, the notion of alternative possibilities plays a basic role in the conduct of daily life. It is useful in classical physics and lies at the heart of Bohr's philosophy of quantum theory.

These arguments in defense of the idea that theorists should be free to contemplate alternative possibilities do not imply that the idea does not fail in the present case. However, Bohr's line of thought would not favor an arbitrary renunciation of a traditional idea, but would demand an explanation of the reason for its failure. The proper function of a criterion of meaning is not to mask embarrassing ignorance, but to exclude what is necessarily useless.

4. – Conclusions.

The theorem forces one to accept at least one of the following five possibilities:

1) Experiments of the required type cannot actually be performed.

Comment: Experiments have been performed that are similar to the one described in sect. **1**, but involve photons instead of fermions and polarizers instead of Stern-Gerlach devices (17). Contradictions between locality and

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(14) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 88.

(15) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 62.

(16) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 52.

(17) S. J. FREEDMAN and J. F. CLAUSER: *Phys. Rev. Lett.*, **28**, 938 (1972); J. F. CLAUSER: *Phys. Rev. Lett.*, **36**, 1223 (1976).

quantum theory can be obtained also from these photon experiments. In these actual experiments, the distances between the two devices are not great enough to satisfy the conditions of the theorem. However, it appears that the replacement of polarizers controlled by human experimenters by Kerr cells controlled by fast random number generators would be a practical and feasible method of making the two experimental regions spacelike separated (18). Each experimental region would then be defined as the product of the spatial region occupied by the Kerr cell, the photon detectors and recorders, and the controlling random number generator times the temporal interval between the initiation of the random number routine and the recording of the result of the photon detection.

The efficiencies of detection in the experiment performed so far are not sufficient to derive the contradiction: information is lost due to the failure to detect many of the particles. However, this problem appears to be only financial (19).

2) Experiments of the required type can be performed, but the predictions of quantum theory fail.

Comment: In the experiments of ref. (17), the predictions of quantum theory are borne out, and there seems to be no physical reason to expect the necessary changes to make any difference.

3) Nature makes no choice: although we observe either the up-event or the down-event, not both, Nature makes no choice between these two alternative possibilities.

Comment: This possibility corresponds to the many-world interpretation of quantum theory (20-22).

4) Variables controlled by experimenters are not effectively free.

Comment: The theorem is formulated in a theoretical framework in which the variables controlled by the experimenters are considered free variables. The setting of each of these variables could be controlled, for example, by the arrival times of photons coming down a telescope directed at the far reaches of space, and away from the other region. In this case, the notion that the variables controlled by the experimenter are effectively free corresponds to the notion that some photon could have arrived several microseconds earlier or later than it actually did, and that the setting would consequently have been changed, but that the statistical predictions of quantum theory would

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(18) J. F. Clauser: private communication.

(19) J. F. Clauser: private communication.

(20) H. Everett III: *Rev. Mod. Phys.*, **29**, 454 (1957).

(21) J. A. Wheeler: *Rev. Mod. Phys.*, **29**, 463 (1957).

(22) B. DeWitt: *The Many Worlds Interpretation od Quantum Mechanics* (Princeton, N. J., 1973).

still retain their validity. This idea that the experimental settings are free variables is the basis of Bohr's idea that the quantum-theoretical state gives an exhaustive description of the atomic system.

5) A spacelike connection exists: a change in the setting in one region must in some cases be accompanied by a change in the course of events in a far-away, spacelike-separated region, if the approximate validity of the statistical predictions of quantum theory are to be maintained.

There are two subcases.

a) No information is transferred superluminally.

Comment: The spacelike connection could conceivably be a nonsuperluminal connection (issuing from the points common to the backward light-cones from the two regions) that controls both the setting in one region and the course of events in the other region. In our example, the setting is controlled by the fluctuations of certain far-away stars. The selection of these stars is controlled by the setting of the telescope, which could be fixed in accordance with the calorie count of the experimenter breakfast. Thus an effective control over the choice of setting involves an effective control over a diverse set of factors that can be picked in an unlimited variety of ways, and at the whim of the experimenter. It seems unlikely that the necessary inflexible connection would be maintained in such a roundabout way.

b) Information is transferred superluminally.

Comment: The central mystery of quantum theory is « how does information get around so quick? ». How does the particle know that there are two slits? How does the information about what is happening everywhere else get collected to determine what is likely to happen here? How does the particle know that it was looked for in some far-away place and not found? Quantum phenomena provide *prima facie* evidence that information gets around in ways that do not conform to classical ideas. Thus the idea that information is transferred superluminally is, *a priori*, not unreasonable.

Everything we know about Nature is in accord with the idea that the fundamental process of Nature lies outside space-time (surveys the space-time continuum globally), but generates events that can be located in spacetime (23,24). The theorem of this paper supports this view of Nature by showing that superluminal transfer of information is necessary, barring certain alternatives that have been described above and that seem less reasonable. Indeed, the reasonable philosophical position of Bohr seems to lead to the rejection of the other possibilities, and hence, by inference, to the conclusion that superluminal transfer of information is necessary.

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(23) H. P. Stapp: *Nuovo Cimento*, **29**, 270 (1975).

(24) H. P. Stapp: *Theory of reality*, LBL-3837, to appear in *Foundations of Physics*.

One must ask, however, what use acceptance of the necessity of superluminal transfer of information could have, in view of Bohr's argument that quantum theory is complete.

5. – The completeness of quantum theory.

The question of the completeness of quantum theory was debated by BOHR and EINSTEIN. BOHR claimed that quantum theory provides answers in principle to all properly formulated questions about atomic phenomena that can be answered by experiment, and is, therefore, complete. He admitted, on the other hand, that quantum theory is merely a set of rules for deriving expectations about observations obtained under special circumstances: « Strictly speaking, the mathematical formalism of quantum mechanics and electrodynamics merely offers rules of calculation for the deduction of expectations about observations obtained under well-defined experimental conditions specified by classical concepts. » (25) « The quantum mechanical formalism, the sole aim of which is the comprehension of observations obtained under experimental conditions described by simple physical concepts, gives just such an exhaustive account of a very large domain of experience. ... The whole formalism which can be applied only to closed phenomena must in all such respects be considered a rational generalization of classical physics. » (26) « Every atomic phenomenon is closed in the sense that its observation is based on registrations obtained by means of suitable amplification devices with irreversible functioning such as, for example, permanent marks on a photographic plate caused by the penetration of electrons into the emulsion. In this connection it is important to realize that the quantum mechanical formalism permits well-defined application referring only to such closed phenomena. » (27)

This closure requirement is related to the « fundamental distinction between the measuring apparatus and the objects under investigation ». This « distinction between the *objects* under investigation and the *measuring instruments* » is a main point of Bohr's interpretation of quantum theory, because the object is represented in Hilbert space, while the apparatus is represented in ordinary space. The need to make this distinction entails that quantum theory can apply only to an object that is sufficiently isolated from its environments to justify its idealization as a separate entity. This isolation

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(25) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1963), p. 60.

(26) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 90.

(27) N. BOHR: *Essays* 1958/1962 *on Atomic Physics and Human Knowledge* (New York, N. Y., 1958), p. 73.

must occur after the preparation of the object and before its final observation, since during the measurement object and apparatus are inseparably linked. These restrictions entail, for example, that quantum theory cannot apply to objects being continuously observed. In fact, quantum theory applies only under very special conditions of isolation and closure.

The scope of quantum theory is, therefore, limited and it becomes the proper task of science to seek a conceptual framework that will encompass broader domains of experience. Bohr's argumentation against a return to the « customary way of classical physics » does not exclude every attempt to enlarge, on any basis, the conceptual framework of science. Thus the construction of a more comprehensive framework based on superluminal information transfer at the individual-event level could conform to Bohr's arguments and yet fulfill the demand of Einstein for a theory that is more complete.

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● RIASSUNTO (*)

Si dà una prova del seguente teorema: se le predizioni statistiche della teoria quantistica sono vere in generale e se il mondo macroscopico non è radicalmente differente da quello che si osserva, allora ciò che accade macroscopicamente in una regione dello spazio-tempo deve in alcuni casi dipendere da variabili che sono controllate da sperimentatori in regioni a separazione di tipo spaziale lontane tra loro. Per ciò che accade macroscopicamente in una regione dello spazio-tempo si intende specificamente il verificarsi o il non verificarsi di eventi macroscopici come la rivelazione o la registrazione di una particella per mezzo di qualche meccanismo macroscopico. Per variabile controllata da uno sperimentatore in una certa regione dello spazio-tempo si intende specificamente la messa in opera sperimentale in quella regione di qualche meccanismo macroscopico, il cui funzionamento è controllato da uno sperimentatore che opera in quella regione. Il teorema si riferisce specificamente a situazioni sperimentali in cui ci sono due a separazione di tipo spaziale lontane fra loro in ciascuna delle quali c'è un meccanismo che può essere posto a ciascuna delle due messe in opera alternative da uno sperimentatore che agisce in quella regione. C'è anche una lunga sequenza di risultati sperimentali (cioè eventi) in ciascuna delle due regioni. Il teorema afferma che, per alcuni di questi casi, è matematicamente impossibile, nella moltitudine di tutti i concepibili risultati compatibili con le predizioni della teoria quantistica (fino a un generoso limite di, per esempio, 1000 deviazioni standard), che quello che accade in ciascuna regione sia indipendente dalla messa in opera sperimentale del meccanismo nella regione lontana. In breve, ci sono situazioni in cui è matematicamente impossibile incontrare entrambe le condizioni statistiche della teoria quantistica ed anche le condizioni di località secondo la quale ciò che accade in ogni regione è indipendente dalla messa in opera

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(*) *Traduzione a cura della Redazione.*