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Quantum Nonlocality

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The novel physical property of quantum nonlocality is described, and contrasted with the equivalent classical property of simple location. Several experiments which illustrate the property are described, and it is shown to be a very general characteristic of microphysical objects. An interpretation in terms of a concept of immediate perception is presented, microphysical objects being conceived as centres having an immediate perception of events in distant regions. The possible relevance of nonlocality for an understanding of the physical basis of psychical phenomena, such as telepathy and psychokinesis, is briefly indicated.

It is over fifty years since nonrelativistic quantum theory was essentially completed. By now, it is widely known that this theory introduced into physics an element of indeterminism completely foreign to classical physics. However, whereas indeterminism was acknowledged very early in the development of quantum theory, physicists in general have only recently begun to acknowledge another novel feature of the theory which may prove even more revolutionary for our conception of the physical world than indeterminism has been. This feature is nonlocality. First drawn to attention by A. Einstein, B. Podolsky and N. Rosen (1935) as a paradoxical consequence of the quantum formalism, which they thought proved the incompleteness of quantum theory, it is today widely regarded as one of the characteristics of microphysical objects which distinguish them most radically from the objects of classical physics.

The material particle of classical physics was conceived as a completely localised entity. In the terminology proposed by A.N. Whitehead (1925), these particles are described as having "simple location" in space and time. Each particle was conceived as a quantity of passive substance, or matter, occupying a minute spatial region. Furthermore, the behaviour of a particle could only change as a result of changes in its immediate neighbourhood. This is the property of locality, or simple location. In fact, in Newtonian physics, gravitational, electric and magnetic forces had the character of action at a distance, but they became interpreted in terms of the propagation of radiation particles or waves from one material body to another. Thus, two particles could only influence one another either by direct contact, as in a collision, or as a result of a material influence propagated at finite speed along a continuous trajectory between the two. At an instant of time, each particle is simply located, independent of all other particles spatially separated from it. Following Whitehead, we can describe a classical particle as being simply "there", in some spatial region, without referring to any other regions.

Maxwell's electromagnetic field theory and modern, non-quantal, field theories, such as Einstein's theories of relativity, retain the notion of locality. Thus, the field parameters at any point can only change as a result of changes in the immediate neighbourhood. These changes, in turn, can only change as a result of changes in *their* immediate neighbourhood, and so on. Thus, two spatially separated regions of the field can only influence one another as a result of changes propagated with finite speed along a continuous path between them. At any instant, they are completely isolated from one another.

It is now widely recognised that quantum theory is a nonlocal theory. According to quantum theory, microphysical objects observed in widely separated spatial regions may be in immediate connection with each other. To illustrate this, we will consider some quantum phenomena in detail.

S.J. Freedman and J.F. Clauser (1972) performed an experiment which confirmed a quantum phenomenon implied by the so-called "Einstein-Podolsky-Rosen Paradox". The apparently paradoxical character of this phenomenon is now understood to be due to the nonlocal behaviour of microphysical objects.

In this experiment, some excited calcium atoms, cascading to their ground state, simultaneously emit two photons in opposite directions (Figure 1). Two linear polarizers, with associated photon detectors, are placed opposite each other, equidistant from the calcium source, in order to receive the photons. The polarizers can be rotated independently of one another in the plane perpendicular to the incident photons. Some associated electronic apparatus records the rate of coincident detection of photon 1 from polarizer 1 and photon 2 from polarizer 2. Quantum theory predicts that the rate of simultaneous detection when the polarizers are in place, compared with the rate of simultaneous detection when they are removed, should depend on the angle between the directions in which the polarizers are set. Thus, if the direction of one polarizer is fixed, the rate of coincident detection varies as we vary the direction of the other. If the interactions of the two photons with their respective polarizers were independent of one another, we would expect a constant coincidence rate, independent of the relative orientation of the polarizers. Thus, the dependence of the coincidence rate on the relative orientation implies that the interactions are correlated in some way.

We might suggest a classical explanation of this correlation as follows: Suppose that, when together at the source, some, as yet unknown, properties of the objects become correlated. Such properties are usually described as "local hidden variables". R.P. Feynman (1965) has likened them to an "internal clockwork" of the objects. In terms of this analogy, we can imagine that, when they

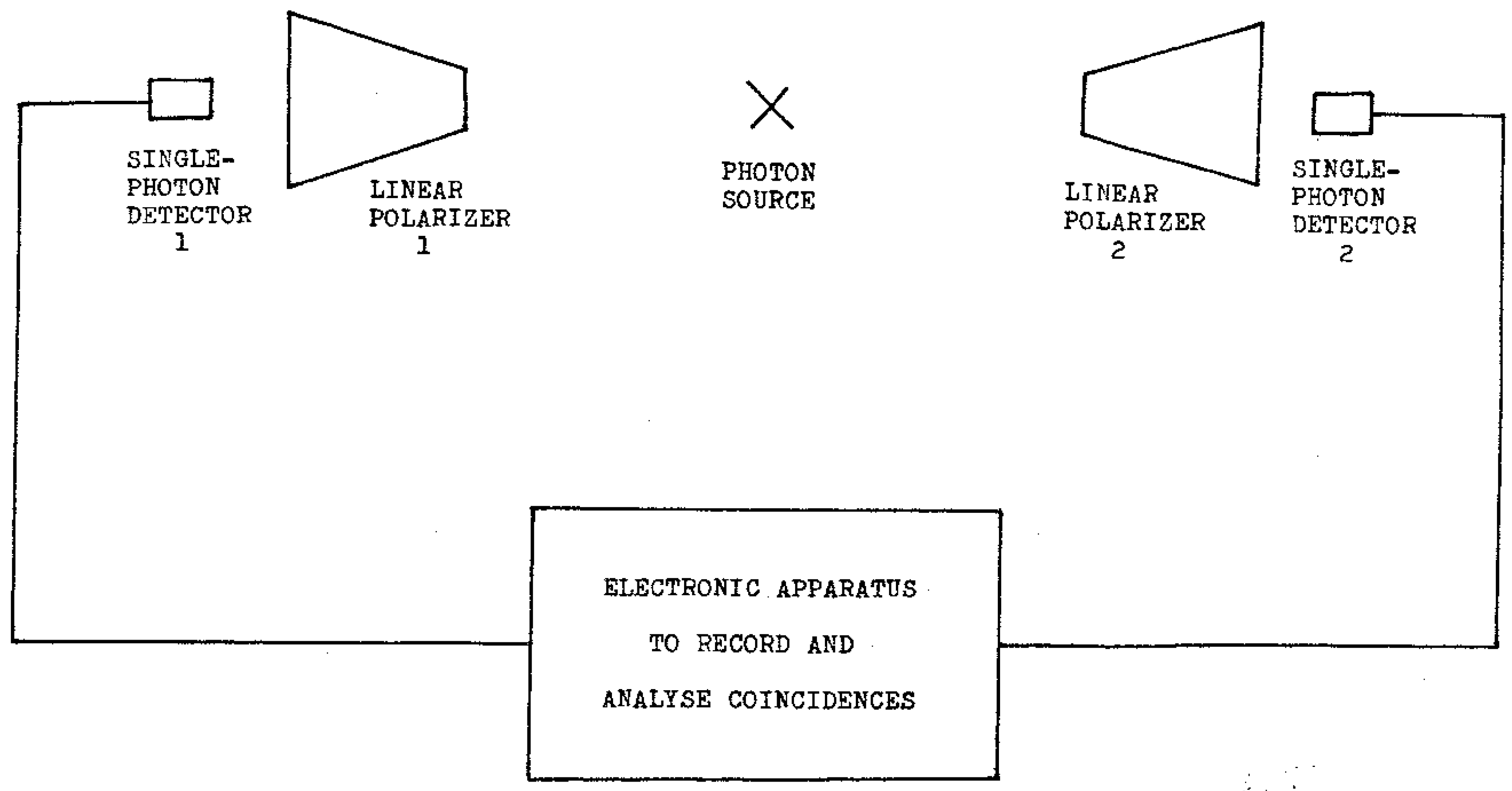

FIGURE 1 Simplified schematic diagram of the correlated photons experiment of S.J. Freedman and J.F. Clauser (1972). The photon source consists of calcium atoms raised to a particular excitation state by absorbing photons from a deuterium arc lamp. Some of these atoms decay to their ground state by cascading through an intermediate state and thereby simultaneously emit two photons in opposite directions. Filters placed between the source and the polarizers select those particular pairs of photons, which then interact with their respective polarizers. As a result of this interaction, each photon is either transmitted or not. Single-photon detectors, consisting of sensitive photomultipliers, are positioned behind each polarizer to receive the transmitted photons. Finally, an electronic system collects impulses from both detectors and records the rate of simultaneous detection.

are together, as a result of some kind of interaction, the settings of the internal clockworks of the objects become correlated. We suppose that this correlation is preserved as the objects separate and speed toward the polarizers. If their interactions with the polarizers are dependent on this internal clockwork, we see that the separate interactions of the objects would be correlated. It is a consequence of the correlation of their hidden properties at the source. Thus it seems that the correlation of the separate interactions does not necessitate modifying the classical notion of simply located particles.

However, it has been proved by J.S. Bell (1964) that, though local hidden variables could explain some types of correlation of spatially separated interactions, they cannot explain the correlations predicted by quantum theory. In view of Bell's theorem, Freedman and Clauser's experiment becomes crucial. The results of the experiment strongly confirm the quantum prediction. The simultaneity of the interactions prevents us interpreting the correlation in terms of any transmission of influence at finite speed between the photons. Thus, the correlation of the photon interactions in this experiment cannot be accounted for in terms of the classical notion of a completely localised particle,

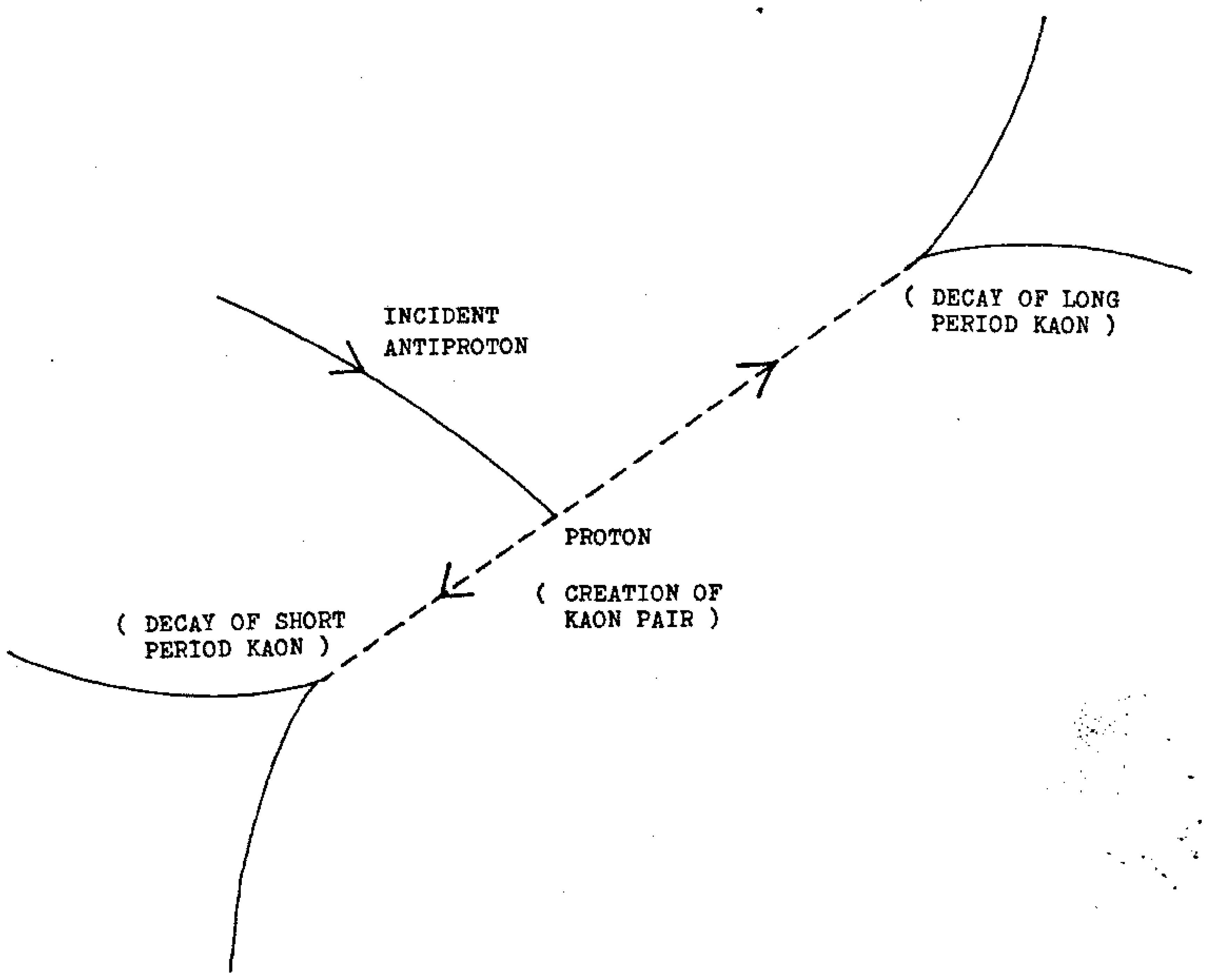

FIGURE 2 Proton-antiproton annihilation creating two correlated kaons. This example is taken from R. Lestienne (1973).

whose behaviour is only determined by factors in its local vicinity. Each photon is in some kind of immediate connection with the other, even though they are observed in regions widely separated in space.

Another phenomenon, similar to that described above, occurs in the field of high energy physics. Antiprotons coming to rest in liquid hydrogen associate with protons and form electrically bound pairs. These subsequently annihilate via strong interactions and create two kaons, both of which eventually decay into pions (Figure 2). Even though the kaon decays are widely separated in space, they are not independent of one another. One decay occurs within a short period of time, and the other takes a longer period. Which kaon will decay within the short period is not predetermined. Whichever is first forces the other to take the longer period. According to quantum theory, as soon as one decays, the state of the other instantaneously becomes that which will take the longer period to decay. The instantaneity of this transition precludes interpretation in terms of any transmission of influence at finite speed between the two kaons. Furthermore, Bell's theorem proves that the correlation of the decays cannot be explained in terms of any as yet unknown, internal properties of the kaons which become correlated when they are together at the moment of their creation, and preserve this correlation when they separate in space. Hence, in order to explain the correlation of the decays, we must regard each kaon as in some kind of immediate contact with the other, even though they are widely separated in space at the time.

At the macroscopic level, the phenomena of superfluidity and superconductivity are now known to be due to the nonlocality of microphysical objects. In a superfluid, such as helium II, a macroscopic number of microphysical objects occupy the same quantum state, and consequently, the unfamiliar quantum properties of this state can be observed at the macroscopic level. For example, the phenomenon of superfluid flow in helium II, which explains the rapid "creeping" of thin films of the fluid, reveals at the macroscopic level the nonlocality of the individual helium atoms. Unlike an ordinary fluid, where the motions of the individual atoms are uncoordinated, the atoms in helium II behave as a coordinated whole, and consequently avoid the energy losses in random collisions that give rise to frictional resistance and viscosity. Consequently, helium II flows frictionlessly and without internal viscosity. If, for example, a quantity of helium II is set in motion in a straight channel, it does not gradually slow down as an ordinary fluid would due to the continual slight energy losses of the atoms in their collisions with one another and the walls of the channel, but instead, it maintains its original velocity indefinitely. The atoms of the superfluid are in a form of immediate connection, and cannot gain or lose energy individually. Hence, to change the velocity of the fluid, the magnitude of the collisional disturbances must be sufficient to change simultaneously the velocity of *all* the atoms of the fluid. Such disturbances are unlikely to occur, and consequently, the fluid flows with constant velocity, not subject to the usual, gradual loss of energy. Thus, superfluidity reveals at the macroscopic level the immediate interdependence of the behaviour of the individual atoms of the fluid. Superconductivity is explained in a similar way. The conducting electrons are regarded as a special kind of fluid moving as a coordinated whole which, consequently, avoids the random collisions which give rise to electrical resistance. These effects are described in more detail in W.F. Vinen (1968).

The phenomena discussed above are not exceptional cases. Rather, they are particular manifestations of a most general characteristic of microphysical objects. According to quantum theory, if two objects, A and B, interact, then, after the interaction, their behaviour will generally exhibit instantaneous interdependence of the kind illustrated above. If ψ^{A} and ψ^{B} are the state descriptions of the two objects before the interaction, quantum theory requires that after the interaction their combined state be described by a function with the general form

$$\psi^{\mathrm{A+B}} = c_1\psi_1^{\mathrm{A}}\psi_1^{\mathrm{B}} + c_2\psi_2^{\mathrm{A}}\psi_2^{\mathrm{B}} + \ldots = \sum_{i=1}^{\infty} c_i\,\psi_i^{\mathrm{A}}\,\psi_i^{\mathrm{B}}\,, \tag{1}$$

where the c_i are complex numbers. The ψ_i^A and ψ_i^B are functions describing A and B respectively after the interaction. Thus, each term in the sum describing the combined system after the interaction consists of a factor describing object A correlated with a factor describing object B. A function with this form cannot in general be expressed as a product of two factors, one involving only the ψ_i^A, and the other only the ψ_i^B. Thus, the states of the two objects after the interaction are in a form of immediate connection; the possible results of observations on A are immediately correlated with the possible results of observations on B, even though the observations may be performed in regions separated by macroscopic orders of distance. If, as a result of its observation, the state of A becomes ψ_a^A then the state of B immediately changes to ψ_a^B, even though A and B may be widely separated in space at the time. More generally, quantum theory implies that in general the state function describing a system of n objects is not factorizable into n components, each describing a separate object. Each object is in immediate connection with the others.

In order to understand quantum phenomena, we are forced to abandon the classical idea of simply located particles. The observed behaviour of microphysical objects cannot be explained if we assume that they are localised entities which can only be influenced by factors in their immediate neighbourhood. Typically, their behaviour is nonlocal, immediately influenced by events occurring in spatially separated regions. Thus, microphysical objects cannot be described as being simply "there", in some spatial region, without reference to any other regions. Connections with other regions are essential to their mode of being.

Though physical theory may change radically as a result of future discoveries, it is unlikely that there will be a return to theories of a local type. Bell's theorem proves that current experimental evidence cannot be explained by any theory involving, exclusively, local parameters. Any future physical theory, which, obviously, must also explain the current evidence, must therefore retain the element of nonlocality. Thus, nonlocality must be regarded as an essential characteristic of the physical world.

Nonlocal microphysical objects can be pictured intuitively as rudimentary "centres of perception". Here, the term "perception" is used in its original sense of "to grasp" or "to take account of", without any suggestion of conscious apprehension. To perceive something, in this sense, means simply to take account of it. As shown above, microphysical objects are nonlocal entities whose behaviour immediately takes account of events in distant spatial regions. Hence, they may reasonably be described as having an immediate perception of those events. Furthermore, the observable interactions of microphysical objects are generally confined to some particular small region of space. Thus, whilst not "completely contained" in a particular region, they are generally "centred" in a particular region.

Human sense perception is usually understood as a causal process, involving

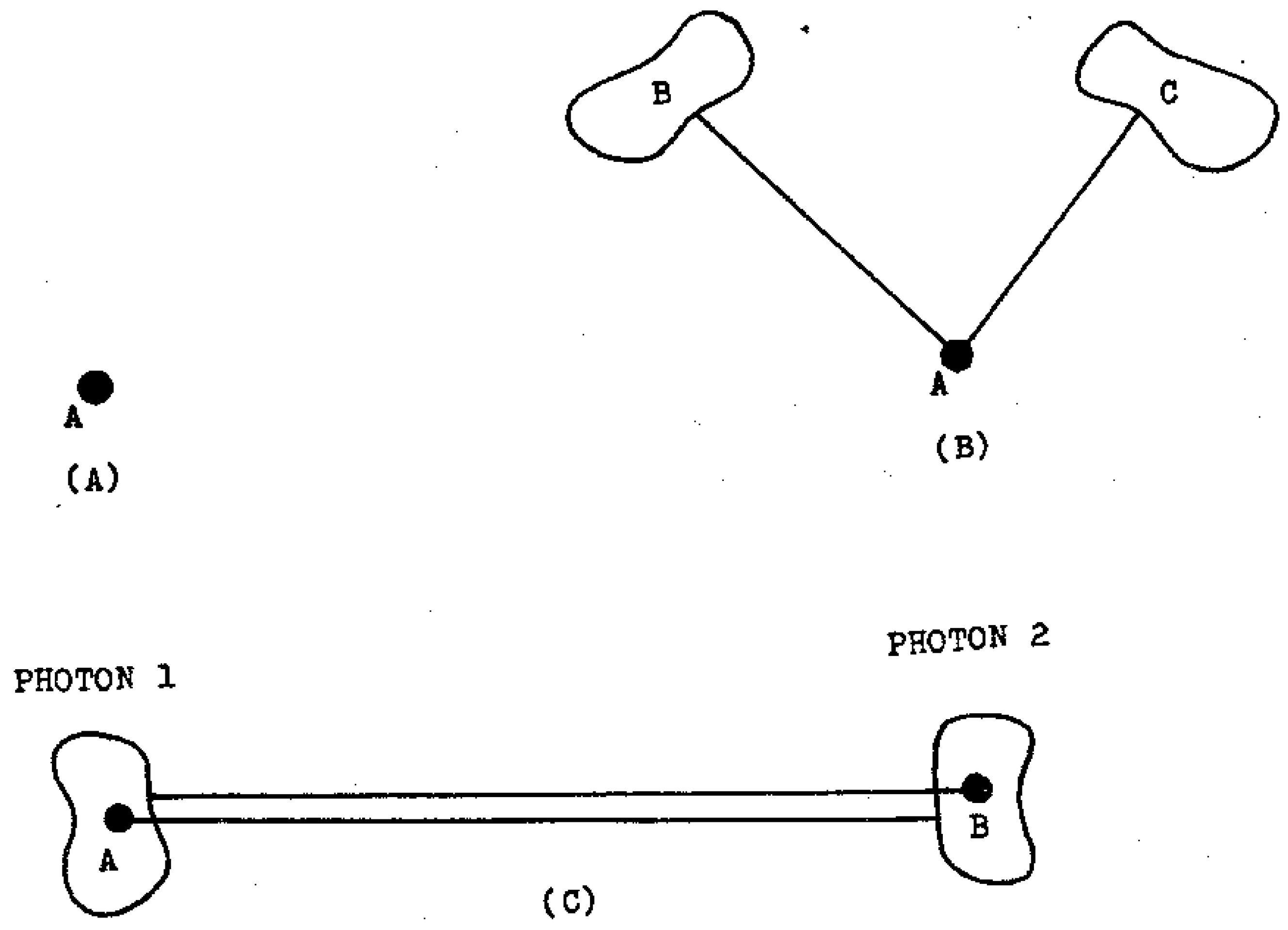

FIGURE 3 Schematic representations of (A) a simply located material particle, (B) a nonlocal microphysical object, and (C) the correlated photons in Freedman and Clauser's experiment.

transmission of influence, at finite speed, between the thing perceived and the percipient. By contrast, the perceptions of microphysical objects are not mediated by any kind of causal process, but rather, are forms of immediate interconnection.

Nonlocal microphysical objects, conceived as centres of perception, may be represented schematically as in Figure 3 (B). Figure 3 (A) shows a classical material particle, completely contained in region A, instantaneously isolated from all other particles. These particles are often described as being like minute billiard balls. Figure 3 (B) shows a microphysical object centred in region A but having immediate connections with distant regions B and C. Microphysical objects are centres of perception, centred in some particular finite region but having immediate perceptions of events in distant regions. Figure 3 (C) represents the situation in the experiment of Freedman and Clauser, described above. At the time of the measurements, photon 1 is centred in region A with immediate perception of events in region B, and photon 2 is centred in region B with immediate perception of events in region A. It is by virtue of these immediate perceptions that their interactions with their respective polarizers are correlated.

A quite different intuitive interpretation of quantum nonlocality has been proposed by D. Bohm and B. Hiley (1975). They suggest that physical reality be conceived as one, unbroken, or indivisible whole. This monistic view of nature involves denying the real existence of individual microphysical objects. Physical reality is one indivisible entity. Individual microphysical objects are temporary appearances, brought about by our means of observation, like the eddies or vortices which form temporarily in the unbroken medium of a stream.

The alternative suggestion presented above, to conceive microphysical objects as centres of perception, has the advantage that it remains consistent with the pluralistic view of nature traditionally maintained by physics, according to which physical reality consists of a multitude of real individuals interacting with one another.

The idea that the ultimate constituents of nature are a multitude of elementary centres of perception is not new. Such a conception was already presented by G.W. Leibniz (1714). The fundamental constituents of nature, called "monads" by Leibniz, were conceived as each perceiving all the others in a unique perspective. However, the perceptions of the monads were conceived as internal representations. Monads had no direct contact with one another. Their perceptions were internal images in which they mirrored one another by virtue of a pre-established divine harmony, in spite of being separate and "windowless". By contrast, if we conceive microphysical objects as centres of perception, their perceptions are their immediate connections with one another, not internal representations or images. Microphysical objects, unlike monads, are in immediate contact with one another. Their perceptions are the particular forms of this immediate contact.

The phenomenon of quantum nonlocality may have important implications for our understanding of psychical phenomena such as telepathy and psychokinesis. These phenomena seem to involve an acausal correlation between spatially separated events which is, superficially at least, very similar to that now observed in the microphysical world. Much of the evidence for psychical phenomena takes a precisely similar form to that for nonlocality, i.e. a statistical correlation between related sets of data obtained in spatially separated regions. Perhaps it has been the influence of classical physics which has led much of the theorizing about psychical phenomena to be concerned with transmission processes, often involving the electromagnetic field. Nonlocality suggests that the alternative approach based on the acceptance of acausal connection, as proposed, for example, by C.G. Jung (1952), may prove more fruitful. It is possible to hope that a detailed consideration of nonlocality and its role in macrosystems such as the brain may lead to new hypotheses concerning the physical basis of psychical phenomena. At the very least, the physicist can no longer lightly dismiss the psychical researcher's postulation of acausal connection, for such connections are now known to exist even between physical objects themselves.

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