On Two Conflicting Physical Interpretations of the Breaking of Restricted Relativistic Einsteinian Causality by Quantum Mechanics.

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The present trend of experimental results on the E.P.R. paradox (which seems at present (1) to favour the predictions of the measuring theory of quantum mechanics) will find its final issue in Aspect's (2) scheduled experiment. The aim of the present letter is to stress the contradictory aspects of the two conflicting interpretations which have been proposed (3,4) in the case (believed by the authors) that Aspect confirms the quantum mechanical predictions.

To clarify this conflict let us first discuss the particular case of Aspect's experiment if the coïncidences of the two correlated photons λ_A and λ_B emitted with opposite spins at the source S (fig. 1) are first measured with an angle θ between the polarizers. If θ is different from $\pi/2$ (cf. fig. 1) for a time $t < t_0$ one observes coïncidences since if photon λ_A passes through A photon λ_B (according to QM) places itself in a state of polarization at an angle θ with the axis of A and there exists a probability ($\propto \cos^2\theta$) to see the photon λ_B passing through B. As one knows this prediction (which is different from the prediction deduced from the existence of local hidden variables at S) can only be measured when one compares the arrival of measurements made at A and B. Indeed from the observation at A or B only one cannot deduce anything on the correlated arrival of λ_A and λ_B: one only observes an unsignificant stochastic arrival of isolated photons *i.e.* no information on correlation. However the observation in C of $\lambda_A \lambda_B$ correlations

(1) J. P. VIGIER: *Lett. Nuovo Cimento*, **24**, 258 (1979).
(2) A. ASPECT: *Phys. Lett.*, **54** A, 117 (1975); *Prog. Sci. Culture*, **1**, 439 (1976); *Phys. Rev. D*, **14**, 1944 (1976).
(3) O. COSTA DE BEAUREGARD: *Phys. Lett.*, **67** A, 171 (1978); *Ann. Fond. de Broglie*, **2**, 231 (1977).
(4) J. P. VIGIER: *Lett. Nuovo Cimento*, **24**, 265 (1979).

is sufficient to establish the meaning of the EPR paradox. As a consequence of the correlated wave field (5) in QM there is no definite direction of the polarization of λ_B for example before the measurement, but a polarization measurement of λ_A puts λ_B in a precise polarization state in which it has there a precise probability ($\propto \cos^2 \theta$) to be measured in B. As one knows QM predicts (6,7) a spacelike interaction which produces an effect in B when a measurement is performed in A.

Of course one could still claim that this superluminal interaction between the two polarizers does not truly imply an exchange of information and/or energy since we are only dealing with probabilistic events.

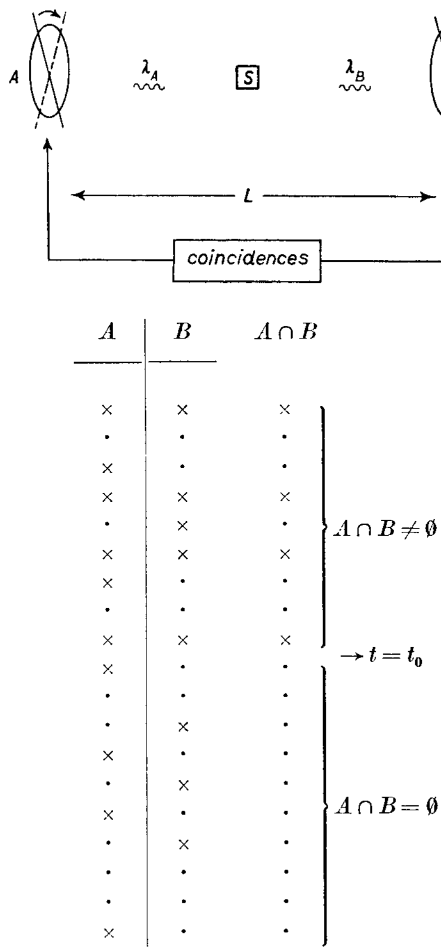

Fig. 1.

As we shall now show this is not true and one can utilize Aspect's experiment to send superluminal signals in the particular case where $\theta = \pi/2$. First one remarks that one can in principle send a signal from A to B through a brusque modification

(5) V. AUGELLI, A. GARUCCIO and F. SELLERI: *Ann. Fond. de Broglie*, **1**, 154 (1976).
(6) H. P. STAPP: *Nuovo Cimento*, **40** B, 191 (1977).
(7) D. BOHM and B. J. HILEY: *Found. Phys.*, **5**, 93 (1975).

(at a time $t = t_0$) of the orientation of the polarizer A while the photons λ_A and λ_B have left source and are still in flight. Let us then assume that for $t < t_0$ the axis of the polarizers A and B are parallel. In that case when a photon λ_A passes through A we are sure that λ_B will pass through B and we will observe a coïncidence. If at $t = t_0$ we then turn the axis of the polarizer A to a position where its angle with B is $\pi/2$ then, according to quantum theory the coïncidences will instantaneously vanish independently of the overall orientation of the polarizers: a situation summarized in fig. 1.

According to QM the coïncidences must vanish because if a photon λ_A passes through A the correlation of the two photons forces photon λ_B into an orthogonal polarization which is orthogonal to B; so that its probability of passing through it is exactly zero *i.e.* this constitutes nonprobabilistic information.

Of course this signal cannot be perceived by an external observer instantaneously, but must be checked by a delayed test. Indeed an observer in A (B) cannot deduce anything about B (A) from its observations since he will still observe a random photon arrival which is not different (see fig. 4) from the distribution at $t < t_0$. In order to acquire knowledge this observer must compare his results with those of B (A) so that he must wait for the information of B (A) which can only propagate with a velocity $v \leqslant c$. However the singal which arrives from B (A) in A (B) is built from two parts *i.e.* a superluminal part along AB (BA) and a subluminal part from B (A) to A (B). Thus even if one cannot utilize this EPR type of device to propagate instantaneous signals from A (B) to B (A) one can deduce *a posteriori* from this observation the existence of past superluminal interactions between A and B. After the passage of a time $\Delta t \geqslant L/2c > 0$ an observer in C can check that coincidences have vanished after $t = t_0$ so that photons λ_B which have started at $t = 0$ and arrive in B have «realized» after that time that the polarizer A has turned to the $\theta = \pi/2$ orientation for $t = t_0$, an operation which henceforward prevents them to pass through B and «forbids» coincidences with the photons λ_A.

The origin of this property lies in the existence of a closed material space-time loop which brings the photons λ_A and λ_B which started at $t = 0$ to A and B from which information is carried in $\Delta t \geqslant L/2c$ to the point C where we can check coincidences... a loop which contains a spacelike link between A and B.

This clearly contradicts macroscopic Einsteinian causality.

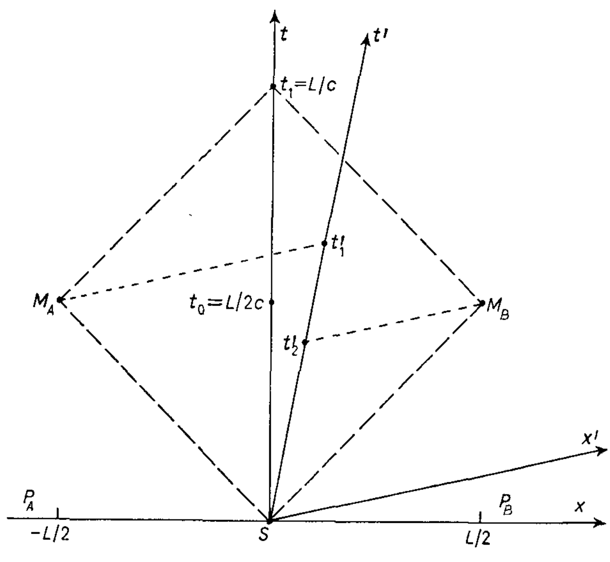

Fig. 2.

To check this, we can draw fig. 2 which describes the spatio-temporal sequence of events. The axis Ox, Ot describe the rest frame at the source S with respect to the polarizers A and B. The points M_A and M_B describe the detection of the photon arrival at A, B and C the minimal point where an observer can check the existence of coincidences. If $t = 0$ two photons λ_A, λ_B leave S they reach M_A and M_B at $t_0 = L/2c$ and inform C (supposedly at the velocity of light) at $t_1 = L/c$. Let us then assume that at the time $t_0 = L/2c$ one turns the polarizer A so that we have as discussed before an angle $\pi/2$ with the axis of P_B. According to QM the coincidences then vanish in C at $t \geqslant t_1 = L/2$ with 100% probability while they still existed before t_1. At $t = t_1$ C stands within the forward light cone of M_A *i.e.* in its absolute future, so that it is tempting and coherent to assume a causal determination of this coincidence vanishing through the act of turning A at M_A. This however neglects the essential fact that the observer in C cannot deduce anything about coincidences unless he compares the signals coming from M_A and M_B which are both influenced by the act of turning A at M_A, so that C is determined by a double causal chain *i.e.* $M_A C$ and $M_A M_B C$.

Such a situation implies a modification of Einstein's causality. To show this it is sufficient to observe this experiment in a Lorentz frame which move with a velocity $v < c$ along the axis with respect to the preceding frame. The Lorentz transform between both frames is just a complex rotation in xSt (see fig. 2) and one sees that in this new frame M_B occurs before M_A so that the chain $M_A M_B C$ cannot be a causal chain.

If Aspect's experiment confirms the quantum mechanical prediction *i.e.* the existence of spacelike interactions two different interpretations have been proposed until now.

I) The first essentially defended by C. de Beauregard preserves the idea that no information and/or energy travels faster than light and obtains spacelike vectors as a combination of two timelike vectors which represent a sum of retarded and advanced potentials. Taking advantage of the formal invariance of Maxwell's equation under time reversal information travels in the past from M_A to S and back to M_B as a retarded potential. Inverse cases of telegraphing into the future, then back into the past, have also been proposed for the Mandel-Pflegor experiment [8]. The authors personally reject this interpretation for two main reasons:

a) it destroy's any ordered sequence between cause and effect in nature, so that there is no real reason to reject superluminal propagation [9];

b) it abolishes in fact any physical distinction between past, present and future since they can physically be linked by advanced potentials.

II) The second possible interpretation [1,4] lies on an extension of the model of the causal interpretation of QM in terms of a fluid with irregular stochastic fluctuation proposed in 1958 by Bohm and one of us (J.P.V.) [10]. Indeed if one adds to it; *a*) the assumption that its elements are built from extended structures which can propagate at their interior superluminal interactions; *b*) the assumption that these stochastic jumps occur at (or very close to) the velocity of light one can:

1) demonstrate Nelson's equations;

2) show that the Klein-Gordon equation describes this stochastic relativistic motion;

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(8) R. L. Pflegor and L. Mandel: *Phys. Rev.*, **159**, 1084 (1967); *Journ. Opt. Soc. Amer.*, **58**, 946 (1968).

(9) W. Pauli: *Theory of Relativity* (Oxford, 1958); C. Møller: *The Theory of Relativity* (Oxford, 1960).

(10) D. Bohm and J. P. Vigier: *Phys. Rev.*, **109**, 882 (1958).

3) demonstrate that the stochastic medium propagates superluminal collective motions despite the fact that all its elements move individually within the light cone and that the causal sequence of causes and effects in time is always locally preserved in the fluid's local drift rest frame.

Point 3) of course is in complete contradiction with C. de Beauregard's proposal. We will show it here in a new different more complete way than the general demonstration given in ref. (1).

Let us start from the equation

$$\frac{1}{\sqrt{-g}}\,\partial_\mu g^{\mu\nu}\sqrt{-g}\;\partial_\nu\psi = \frac{m_0c^2}{\hbar^2}\,\psi$$

with

$$\psi(\boldsymbol{x}, t) = R(\boldsymbol{x}, t)\exp\left[iS(\boldsymbol{x}, t)/\hbar\right] \qquad \text{with } R \text{ and } S \text{ real}.$$

According to relativistic fluidodynamics (11), we can write the energy tensor for a Klein-Gordon fluid as

$$t_{\mu\nu} = \varrho M_0 u_\mu u_\nu + \varrho\frac{\hbar^2}{2M_0}\left[2\partial_\mu\log R\cdot\partial_\mu\log R - \delta_{\mu\nu}(2\,\partial_\lambda\log R\cdot\partial^\lambda\log R + \Box\log R)\right], \tag{1}$$

where, starting from the current vector j_μ for Klein-Gordon fields, the density ϱ and the velocity u_μ are defined as

$$\varrho = \frac{1}{c\hbar}\sqrt{-j^\mu j_\mu}\,, \qquad u_\mu = \frac{1}{\varrho\hbar}\,j_\mu \qquad \text{with } u_\mu u^\mu = -c^2 \tag{2}$$

and the total proper mass M_0 is defined as

$$M_0^2 = m_0 - \frac{\hbar^2}{c^2}\frac{\Box R}{R}\,, \tag{3}$$

where m_0 is the ordinary mass of the particle. We can now decompose this tensor in its orthogonal and colinear components (11). We get

$$t_{\mu\nu} = \mu_0 u_\mu u_\nu - p_\mu u_\nu + q_\nu u_\mu + \theta_{\mu\nu} \tag{4}$$

with

$$p_\mu u^\mu = q_\mu u^\mu = 0 \qquad \text{and} \qquad \theta_{\mu\nu}u^\nu = u_\mu\theta^{\mu\nu} = 0\,,$$

where p_μ and q_μ are, respectively, the transverse-impulse density and the heat current density, μ_0 the proper mass density and $\theta_{\mu\nu}$ an internal tension tensor. We will observe at once that the vectors q_μ and p_μ are spacelike vectors indicating that in this relativistic fluid there is something propagating faster than light.

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(11) F. HALBWACHS: *Théorie relativiste des fluides à spire* (Paris, 1960).

The authors are of the opinion that this is the physical basis of information transmission between correlated particles in a spacelike direction. More: we are in a position to define the heat current on the basis of a temperature gradient. Starting from the explicit form [11] of q_μ *i.e.*

$$q_\mu = \varrho \cdot \frac{\hbar^2}{M_0 c^2} D \log R \cdot \eta_{\mu\nu} \partial^\nu \log R \tag{5}$$

with

$$D = u_\lambda \partial^\lambda \qquad \text{and} \qquad \eta_{\mu\nu} = \delta_{\mu\nu} + \frac{u_\mu u_\nu}{c^2} ,$$

we can try to put it in the form [12] given by Eckart, *i.e.*:

$$q_\mu = -K(\partial_\mu \theta + \theta \cdot D u_\mu) \tag{6}$$

which is the relativistic generalization of the classical Fourier equation $\boldsymbol{q} = -K \boldsymbol{\nabla} \theta$, where θ is the fluid temperature. Indeed if we define $\theta = G \log R$ and $K = -(1/G) \cdot \varrho (\hbar^2/M_0 c^2) D \log R$ where G is a function satisfying the equations $\partial^\mu \log G = -Du^\mu$ we can immediately transform (5) into (6). Moreover, we can see immediately that

$$DG = u_\mu \partial^\mu \log G = -u_\mu D u^\mu = 0 \tag{7}$$

(that is $\dot{G} = 0$) so that G is a function, constant along current lines. Moreover $\dot{\theta} = GD \log R$ and

$$K = -\frac{1}{G^2} \varrho \cdot \frac{\hbar^2}{M_0 c^2} \dot{\theta} \tag{8}$$

which is obviously positive, as it should. Because θ decreases in general along current lines (for free particles we must consider the wave diffusion process) we thus respect the second principle of thermodynamics.

This second interpretation, of course, cannot completely eliminate the main problem posed by quantum predictions. The fluid model implies that beyond a certain distance the random stochastic motion destroys any correlation between the wave packets so that Bell's inequalities could reappear when measurements M_A and M_B are made too far apart. Moreover as will be discussed in a subsequent publication effects incompatible with QM (such as interference of isolated photons coming from independent sources) should appear in our model contrary to Dirac's famous statement that a photon can only interfere with itself.

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[12] C. ECKART: *Phys. Rev.*, **18**, 919 (1940).