On the Physical Nonexistence of Signals Going Backwards in Time, and Quantum Mechanics (*).

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A growing number of experiments have been recently performed to test the paradoxical, seemingly nonlocal predictions of quantum mechanics (QM) in Einstein-Podolsky-Rosen's conditions. Recent experiments by CLAUSER and FREEDMAN [1], for instance, confirmed QM and seemed to disagree with Bell inequality (which follows from Einstein locality). New experiments, *e.g.* by ASPECT [2], are moreover going on or being performed [2].

In such a situation, careful attention should be paid to the theoretical interpretations put forth to explain the experimental results. In this letter we would like to comment on a recent series of theoretical papers [3], which are essentially characterized

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(1) See *e.g.* J. F. CLAUSER: *Phys. Rev. Lett.*, **36**, 1223 (1976); S. J. FREEDMAN and J. F. CLAUSER: *Phys. Rev. Lett.*, **28**, 938 (1972).
(2) See A. ASPECT: *Phys. Rev. D*, **14**, 1944 (1976); *Prog. Sci. Culture*, **1**, 439 (1976); *Phys. Lett. A*, **54**, 117 (1975); and (work in progress). See also V. RAPISARDA: private communication.
(3) O. COSTA DE BEAUREGARD: *Nuovo Cimento B*, **54**, 267 (1979); **42**, 41 (1977); *Phys. Lett. A*, **67**, 171 (1978); *Ann. Fond. de Broglie*, **2**, 231 (1977).

by the rôle attributed to the *advanced solutions* for the sake of explaining (within the orthodox Copenhagen interpretation of QM) the possible nonlocal interaction between the measuring apparata, which detect pairs of *correlated* photons emitted in the singlet state. Namely, in ref. [3] those advanced solutions have been interpreted as actually associated to motion into the past, so that recourse to an « anti-telephone » mechanism has been substantially made there [3] (and even over macroscopic distances [2]), in order to render reason of the experience.

Let us briefly summarize that model [3]. One utilizes as initial source an atom 0 which emits at the time $t = 0$ in a cascade 0-1-0 two correlated photons γ_A and γ_B that start to move in opposite directions along the x-axis. One then measures the polarization of γ_A at time $t_A > 0$ (in the direction $+ x$) by the apparatus A, and the polarization of γ_B at time $t_B > t_A$ by the apparatus B (in the direction $- x$).

As is well known, some *doubts* may be cast on the fact that the quantum-mechanical correlations between the results of these two measurements can actually be interpreted within the concept of locality, *i.e.* in terms of ordinary signals travelling from one apparatus (A) to the other (B).

In order to overcome this problem within the usual Copenhagen interpretation of QM, they assumed in ref. [3] that at the time t_A of the measurement performed by A on γ_A a signal—corresponding to an advanced potential—starts from the apparatus A and travels backwards in time along the light-cone, and thus supposedly carries information (about the result of that measurement) back to 0 at $t = 0$. A second signal, then, carries information forward in time to B at $t = t_B$: therefore arriving at the apparatus B simultaneously with the photon γ_B.

Before criticizing that possible mechanism, we want to premise that there is nothing formally wrong from the mathematical point of view with that proposal. It is evidently compatible with the Copenhagen interpretation expressed in the relativistic S-matrix formalism. It is also formally compatible with the time-reversible formalism of quantum theory. Indeed, if $\varphi(t, x)$ is a wave solution of the Laplace-Beltrami equation, also $\varphi(-t, x)$ is a solution as well: a point that we shall touch upon again at the end of this letter.

The troubles apparently lie with its physical consequences; what is at stake in such an use of the advanced potentials is the existence of causality in real phenomena. Let us recall that such an approach (contrary to the usual practice in electrodynamics [4] which mix advanced and retarded potential solutions) implies the use of *isolated* advanced solutions in « isolated » space-time regions. Then, following ref. [3], one could utilize those advanced solutions for an « anti-telephone » mechanism (*i.e.* for communicating with one's past!), even over macroscopic distances ... Evidently, that possibility would raise new theoretical problems since—following Einstein—one usually, implicitly assumes that: i) positive energy can be associated only with particles moving forward in time; ii) actual signals and/or information can only be carried by positive-energy objects (an assumption which appears to be consistent with information theory).

Indeed, in the present understanding of physical reality, negative-energy objects (travelling forward in time) cannot exist for many known reasons. For istance, did they exist, a « bubble » of vacuum could then suitably decay into a couple of particles (*e.g.* nucleons), one bearing negative energy and the other positive energy [5].

Such spontaneous vacuum instabilities would have the tendency to possess divergent probabilities (*unless* the vacuum decays into zero-energy tachyons, which is not the

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[4] See *e.g.* F. RÖHRLICH: *Classical Charged Particles* (Reading, Mass., 1965).

[5] R. MIGNANI and E. RECAMI: *Phys. Lett. B*, **65**, 148 (1976).

case here considered [5]), leading immediately to *unphysical* situations. Even if one supposed the negative-energy particles to be devoided of any interactions except the gravitational one, nevertheless a diagram of the type depicted in fig. 1 (where two vacuum-bubbles become unstable under the mutual exchange of a graviton) would yield—for any kind of ordinary particles a, b—a « cosmic » flux as big as the one actually observed *only* for neutrinos. This shows that negative energies (for objects moving forward in time) do not seem to be actually allowable.

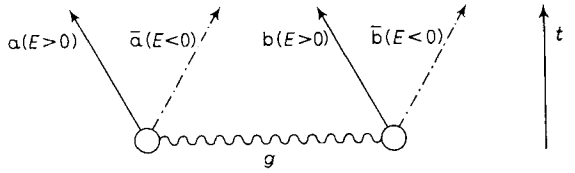

Fig. 1. – A diagram helping to show that negative-energy particles cannot exist in relativistic physics Symbols $a, \bar{a}, b, \bar{b}$ represent positive-energy (negative-energy) particles. See the text.

Our aim is to stress once more that the advanced potentials are actually to be associated to (orthodox) motions of suitable positive-energy anti-objects forward in time. To show this, let us notice that advanced solutions are got from the retarded ones by the simple (and only) application of a nonorthochronous Lorentz transformation $L^{\downarrow} \in \mathscr{L}_4^{\downarrow}$ (*). The Lorentz transformations $L^{\downarrow}$, which change (among the others) the sign of *time*, have the obvious property of changing also the sign of *energy* and of *all* the fourth components of all four-vectors associated to the same observed object. In fact, any advanced solution (*e.g.* in the electromagnetic case) refers also to negative energy, whenever it refers to negative time; this can be verified by direct inspection of the relevant propagators [6] ($t > 0$; $\hbar = 1$):

$$G_{\mathrm{ret}}(\boldsymbol{r}, t) = -i(2\pi)^{-3}\int \exp[i\boldsymbol{p}\cdot\boldsymbol{r} - iEt]\,\mathrm{d}^3\boldsymbol{p}\,, \tag{1a}$$

$$G_{\mathrm{adv}}(\boldsymbol{r}, t) = i(2\pi)^{-3}\int \exp[i\boldsymbol{p}\cdot\boldsymbol{r} - iEt]\,\mathrm{d}^3\boldsymbol{p}\,, \tag{1b}$$

and agrees with the general fact that, when connecting the two *dual* (four-position and four-momentum) spaces through Fourier-type transformations ($\hbar = 1$):

$$f(\boldsymbol{p}, E) = (2\pi)^{-2}\int F(\boldsymbol{r}, t)\exp[i\boldsymbol{p}\cdot\boldsymbol{r} - iEt]\,\mathrm{d}^4x\,, \tag{2a}$$

a change of the t-sign in the first space implies a change of the E-sign in the second, dual space

$$f(\boldsymbol{p}, -E) = (2\pi)^{-2}\int F(\boldsymbol{r}, -t)\exp[i\boldsymbol{p}\cdot\boldsymbol{r} - iEt]\,\mathrm{d}^4x\,. \tag{2b}$$

(*) For simplicity, let us confine ourselves to the proper, homogeneous Lorentz groups: $\mathscr{L}_4^{\uparrow}$ (orthochronous) and $\mathscr{L}_4^{\downarrow}$ (nonorthochronous).

(6) See *e.g.* R. FIESCHI (Editor): *Elementi introduttivi di fisica dello stato solido* (Torino, 1968).

The previous considerations allow us to conclude that—in relativistic physics—if an object moves backwards in time, then it is endowed also with negative energy; and, *vice versa*, negative-energy objects can exist only when travelling backwards in time.

At this point, as is well known [7], it is enough to apply the celebrate Stückelberg-Feynman « *reinterpretation principle* » [7] in order to obtain that a « negative-energy particle travelling backwards in time » will show up as an (orthodox) antiparticle travelling forward in time and bearing positive energy. As shown in ref. [7,8], the reinterpretation principle (RIP) not only *can* but *must* be applied in such cases. It is essentially based on the following two points [7,8]: i) any observer, being a macroscopical system, does move *forward* in time; ii) any emission (absorption) of a negative quantity is equivalent to absorption (emission) of the corresponding positive quantity, since $(-)\cdot(-) = (+)\cdot(+)$. For details, let us again quote ref. [7,8].

All what precedes finds its proper settlement within the (enlarged) theory of special relativity (ESR), founded on the group $\mathscr{L}_4^{\uparrow} \cup \mathscr{L}_4^{\downarrow}$ instead that on the group $\mathscr{L}_4^{\uparrow}$. The ESR formulation of special relativity thus includes into a unique scheme both particles and antiparticles [7,8] (where the latter can be defined and introduced *in purely relativistic terms*!). The ESR, as is now intuitive, is based on the two ordinary postulates of special relativity and on a « third postulate » [7,8] which implements, briefly speaking, the « RIP ». This « third postulate » enforces the validity of the principle of (retarded) causality, and simultaneously allows the « prediction » (*)—for each particle or object considered—of existence and correct properties of its antiparticle or antiobject.

Mathematically, we thus *conclude* [9] that the advanced solutions (**) (*e.g.*, in A at time t_A) describe entering *anti-objects* (in the case of photons, entering *photons*) endowed with positive energy and motion forward in time, rather that *outgoing* objects endowed with an « unphysical » motion backwards in time.

We have also seen, on the contrary, that *if* they were by hypothesis to be associated to actual motion backwards in time, *then* the « objects » supposedly described by those advanced solutions could find no room within the realm of present-time relativistic physics (even if such solutions could go on maintaining their rôle in the mathematical elaborations) (***).

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(7) See *e.g.* E. RECAMI: *Found. Phys.*, **8**, 329 (1978); P. CALDIROLA and E. RECAMI: in *Italian Studies in the Philosophy of Science*, edited by M. DALBA CHIARA (Boston, Mass., 1980); E. RECAMI: in *Albert Einstein 1879-1979: Relativity, Quanta, and Cosmology in the Development of the Scientific Thought of A. Einstein*, edited by F. DE FINIS, Chap. 16 (New York, N. Y., 1979); in *Centenario di Einstein: astrofisica e cosmologia, gravitazione, quanti e relatività negli sviluppi del pensiero scientifico di A. Einstein*, edited by M. PANTALEO, Chapt. 18 (Firenze, 1979). See also ref. (3).

(8) E. RECAMI and R. MIGNANI: *Riv. Nuovo Cimento*, **4**, 209-290, 398 (1974); E. RECAMI (Editor): *Tachyons, Monopoles, and Related Topics* (Amsterdam, 1978).

(*) In the sense that it would have allowed to predict the existence of antiparticles even since 1905 (in purely relativistic terms): cf. ref. (7,8).

(9) R. MIGNANI and E. RECAMI: *Lett. Nuovo Cimento*, **18**, 5 (1977).

(**) *A priori*, to be associated to « negative-energy particles travelling backwards in time ».

(***) At last, let us briefly go back to the « reversibility » problem. As one knows, classical stochastic processes are fundamentally irreversible, being associated with continuous, increasing loss of information on the place where the particle came from. This can be directly shown, *e.g.* by an argument of R. THOM [10], which states that any stochastic *set* of intitial parameters, influenced by an infinite number of degrees of freedom, corresponds to a measure of dimension zero (*i.e.* to a negligible probability) in the space of the infinite many possible states; so that time always flows in the « forward » direction. Now, as one knows, Nelson stochastic law [11] recovers reversibility by taking a different sign in Newton (dynamics) fundamental equation. This can be and has been [12] interpreted by means of the argument that quantum stochastic mixtures contain both particles *and* anti-

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particles. The latter always move (so as the particles) in the forward time-direction, but are mathematically equivalent to negative-energy motion backwards in time; so that one gets an *apparently* reversible process. (The word « apparently » is essential, since of course the alternative, stochastic, causal quantum-mechanical model of the EPR paradox [11] implies only motions in the forward time-direction).

[10] R. THOM: private communication.

[11] E. NELSON: *Phys. Rev.*, **450**, 1079 (1966).

[12] Cf. also N. CUFARO PETRONI and J. P. VIGIER: *Lett. Nuovo Cimento*, **26**, 149 (1979); J. P. VIGIER: *Lett. Nuovo Cimento*, **24**, 265 (1979).

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