How to Recover Causality for Tachyons
Even in Macrophysics (*).

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Summary. — The postulate that negative-energy particles do not exist (travelling forward in time) leads automatically to the "Reinterpretation Principle" by Stückelberg and by Feynman. It has been already shown that such a "principle", assumed as the Third postulate of special relativity, ensures the validity of the law of (retarded) causality both in standard relativity and in (extended) relativity with tachyons and with Superluminal inertial frames. Our Third postulate, moreover, allows predicting antiparticle existence in a purely relativistic context. In this paper we show that the Third postulate is enough to implement the law of causality even in macrophysics, when usual macro-objects interact with micro-tachyons and macrotachyons. To that aim, some tachyon kinematics is further developed, which can be useful even in understanding elementary-particle interactions (and may be hadron structure). Many other related problems are discussed.

1. — Introduction.

It has been known that special relativity (SR) can be extended (*) to faster-than-light inertial frames (²) and objects (tachyons) without leaving open any

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(2) For a generalized definition of equivalence (with recourse to some symbolic logic) see ref. (1), p. 249. See also E. Fabri: Nuovo Cimento, 14, 1130 (1959); A. Agodi: unpublished.
causality problem. For instance, all the proposed (3) «causality paradoxes» have been easily solved (1, 4), on the basis of the Dirac-Stückelberg-Feynman Reinterpretation Principle (RIP) (1, 4).

Namely an Extended Relativity (1), free of any causal violation, can be derived from the three following postulates (4):

I) Principle of relativity (PR). Laws of mechanics and electromagnetism are covariant (= invariant in form) when passing from one inertial frame to another frame in uniform, straight relative motion (with speeds \(-\infty < u < +\infty\)).

II) Space-time is homogeneous and space isotropic (notice: light speed invariance needs not to be postulated, since it can be derived from postulates I and II, as known since 1910 (7)).

III) Third postulate. «Negative-energy particles moving forward in time do not exist and, for every observer, physical signals are transported only by the objects that appear as carrying positive energy» (5). Careful investigation of SR, in the light of such a postulate, together with the observation that we «explore» space-time only forward in time (i.e. in the time direction fixed by macro-object behaviour), automatically leads us to the (5) «RIP»:

(8) The meaning of this postulate is self-clear within information theory; it is supported by thermodynamics and by all physical experience. Furthermore, it allows us to predict (1)—merely from relativity—the existence of antiparticles.
Any negative-energy particle $P$ does also travel backwards in time (and vice versa); it can, and must, be reinterpreted as its antiparticle $\bar{P}$ travelling, with positive energy, forward in time $\text{(*)}$.

As shown in ref. (1-4) and partly in this paper (10), our Third postulate, i.e. the "RIP", is equivalent to postulating the principle of (retarded) causality, since it ensures (1-5,6) that every observer will always see "causes" (11) to happen chronologically before their own "effects" (11).

The important point is that SR requires only physical laws (12) (and not "descriptions" (13)) to be covariant. For instance, in ref. (1) it has been shown that in (extended) relativity the "principle of (retarded) causality" is a law, whereas the assignements of the names "cause" and "effect" are description details. Therefore, according to the "RIP" (cf. fig. 16 at p. 239 of ref. (1)), we are forced (1-4) to abandon the old conviction that the judgement about what is cause and what is effect is independent of the observer (13).

2. Macro-objects, entropy and information transmission by tachyons.

We want to stress here that our "Third postulate" of SR recovers causality for tachyons (14) not only in the case of elementary processes—as mostly considered, till now—but also in macroscopic processes (15), in which entropy considerations are in order (15); even if many physicists are still unaware of these facts.

Let us consider two bodies, $A$ and $B$, for simplicity at rest one with respect to the other. Then, let us consider—in their rest frames (i.e. in the lab)—the exchange of a tachyon $T$ along the positive $x$-direction, with speed $+V$, from $A$ (source) to $B$ (detector). Now the frame with speed $u = u_v = c^2/V$ will see the tachyon $T$ travelling at infinite speed (1), and (as illustrated, e.g., in fig. 12 of ref. (1), p. 236) any frame with speed $u > c^2/V$ would "see" $T$ as going backwards in time and bearing negative energy; that is to say, it will

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(9) For a rigorous treatment of the RIP, and for details, see ref. (1), and E. Recami and G. Zino: Nuovo Cimento, 33 A, 205 (1976). See also ref. (1-4).


(11) For definitions of causes, effects, causal connections, see, e.g., ref. (1), pp. 261-262.

(12) Suitable analysis and definitions of law, description, etc., can be found in ref. (1), p. 242.

(13) Cf. p. 258 in ref. (1).

(14) Recall, however, that the "third postulate" (RIP) must be introduced even in standard relativity in order to avoid (1-4) energy transmission into the past by usual particles (bradyons), and in order to better understand the connection particles/anti-particles (and the whole subluminal physics as well). See also footnote (9).

actually observe an antitachyon $\overline{T}$ \textsuperscript{(1)}. In other words, if we consider a (subluminal) boost along the positive $x$-direction with speed $\frac{c^2}{V} < u < c$, then the new observer $s'$ will see \textsuperscript{(1,3)}—because of the «RIP»—an antitachyon $\overline{T}$ emitted by $B$ (source) and absorbed by $A$ (detector), and carrying of course positive energy \emph{forward} in time. See fig. 1.

![Fig. 1](https://example.com/fig1.png)

**Fig. 1.** The figure represents the exchange from $A$ to $B$ of a particle $P$ with negative energy (and «charges») and travelling backwards in time ($t_2 < t_1$). From the \textbf{third postulate} of special relativity («negative-energy particles travelling forward in time do not exist») and from the fact that we necessarily «explore» Minkowski space-time going «forward in time», it follows that such a process appears as the exchange from $B$ to $A$ of a particle $Q$ endowed with positive energy (and «charges») and moving \emph{forward} in time. Particle $Q$ results then to be—see the text—the \textit{antiparticle} of the initial particle (except for the helicity, in this case): $Q = -P$. As well known, the «Third postulate» of SR—while solving in nuce all the (apparent) paradoxes, which seem to imply an information transfer into the past, both with usual particles (bradyons) and with tachyons—furthermore predicts, for any particle, the existence of its \textit{antiparticle}.

The \textit{point} is that, while $s$ observes, \textit{e.g.}, the energy of $A$ \textit{decreasing} in that process, on the contrary $s'$ observes the energy of $A$ \textit{increasing} \textsuperscript{(14)} in the same process. (We shall use these results in sect. 5.) However, for each observer the \textit{law} of energy conservation is \textit{satisfied} in the observed process. Again, only the \textit{description} «details» are not invariant, in full accord with special relativity (SR), that does not require their invariance. For suitable definition and analysis of «law», «description», etc., see, \textit{e.g.}, p. 248 of ref. \textsuperscript{(1)}. To clarify the situation, let us recall that SR (and Doppler) taught us that, for exam-

\textsuperscript{(14)} This \textit{sign} dependence on the considered observer takes place for energy, as we are seeing, but not for «charges» (in this case). In fact, «charges» change their sign only when the «generalized Lorentz transformations» (see ref. \textsuperscript{(1)}) bring $A$ (or $B$) into $\overline{A}$ (or $\overline{B}$). The «generalized Lorentz transformations» (GLT) are the elements of the new group $G$ of extended relativity, containing both usual, subluminal Lorentz transformations (LT) and Superluminal Lorentz transformations (SLT). In ref. \textsuperscript{(1)} it has been shown that, if $L \in G$, then $-L \in G$. 
ple, the colour of an object is not Lorentz invariant (even if nothing prevents any observer, who knows SR, from calculating out the real colour, i.e. the proper colour displayed by the object in its rest frame). The necessary requirement of SR is that each observer puts forward a self-consistent description containing the same (covariant) physical laws (1,12).

These simple observations will help us in the following, and apply also to the previous case. They teach us that we must not be too surprised if A appears as increasing its energy to s', but as decreasing its energy to s. Still, all observers can transform their observations to the proper frame, where \( A, B \) are at rest (if \( A, B \) are at rest one with respect to the other), or—more generally—can agree to transform their observations to a (conventionally chosen) privileged frame. Nevertheless, all observers—in any case—will put forward a self-consistent description, in agreement with SR.

At this point, we have nothing to do but noticing that in fig. 1 we can have (instead of a tachyon exchange) a tachyon signal transmission by means of a modulated tachyon beam. Then, entropy changes and information exchanges behave—when passing from one frame to other ones—exactly as the energy exchanges of the previous example (fig. 1); so that, e.g., an information increase observed by s can become an information decrease as regarded by s'. And so on.

We shall illustrate the arising, possible problems by considering two examples, i.e. by proposing two apparent paradoxes, and then solving them (10).

3. Can a tachyon observer inform us about our future? (No).

First, let us consider the case of a subluminal frame \((x, t)\) and of a Superluminal frame \((x', t')\) boosted along the (positive) x-direction with relative speed \( U > c \). See fig. 2. And let us choose as common origin \( O \) the event

![Fig. 2. - The first apparent paradox here discussed. It seems that a Superluminal observer \((x', t')\), while overcoming at \( O \) the observer \((x, t)\) at rest, can tell the latter informations about a future—for the latter event \( E \), if tachyon signals exist travelling at (almost) infinite speed. The paradox is immediately solved on the basis of the third postulate of SR, when one remembers that SR requires only laws (and not description details) to be invariant. The important point, here, is that causal paradoxes with tachyons can be easily solved even in macrophysics (see the text). Notice that \( \tan \alpha = \beta = U/c \).](image-url)
in which both frames coincide. To $s'$, the $x$-axis represents all the events contemporary with $O$; whilst, to $s$, all the events contemporary with $O$ are represented by the $x'$-axis. If information can be carried by (almost \textsuperscript{(17)}) infinite-speed tachyons, then observer $s'$—when near $O$—can receive signals from an event $E$ (see fig. 2) and can give this information to $s$. It seems, therefore, that $s'$ can communicate (when near $O$) to $s$ information about the possible future of $s$.

However, it is clear that the «RIP» teaches us \textsuperscript{(1.4.8)} the following: the signal $E \rightarrow O$ will appear to the observer $s$ as a signal (or better «antisignal» \textsuperscript{(18)}) sent by $s'$ from $O$ towards $E$ (since, with respect to $s$, it would be a «negative signal going backwards in time»), which must \textsuperscript{(4.8)} be reinterpreted according to the «RIP»). In conclusion, according to $s$, the observer $s'$ is predicting to him nothing but what can be actually «forecast»—on the basis of our physical operations and of the physical laws—; i.e. the observer $s'$, to $s$, is merely «predicting» the obvious effects on $E$ of the (anti)signals sent by himself from $O$ towards $E$, to influence it physically \textsuperscript{(19)}.

Even in this case, each observer puts forward a different description of the same chain of events, but the law of (retarded) causality holds in all descriptions, for all observers.

Now let us pass to a more «subtle» example involving tachyon mechanics a little more deeply, and spend some more words in solving the relative (apparent) paradox \textsuperscript{(19)}.

4. — Tachyons, free will and entropy.

Now let us consider a process like the one in fig. 1, but with the body $B$ moving with respect to the body $A$. Let us, therefore, consider two usual, inertial observers (fig. 3) moving along the $x$-direction relative to each other with speed $u < c$, and let us suppose that (according to the frame $s \equiv (x, t)$) the observer $s$ sends

\textsuperscript{(17)} Infinite-speed tachyons carry zero energy (but 3-momentum magnitude equal to $m_0$), and their direction along their motion line is not definite. As «bradyons» at rest are points in space, extended in time along a line, so transcendent tachyons are «points» in time, extended in space along a line: cf. R. Mignani and E. Recami: Lett. Nuovo Cimento, \textbf{16}, 449 (1976). Infinite-speed tachyons will be dealt with elsewhere, also due to their possible role in hadron structure (recall, e.g., the «instantons», the quark «bilocal functions», besides «pomeron»). Cf., e.g., R. Mignani and E. Recami: Nuovo Cimento, \textbf{30} A, 533 (1975); Phys. Lett. (to appear); and quotations (87)-(89) in ref. \textsuperscript{(1)}.

\textsuperscript{(18)} From ref. \textsuperscript{(1)}, p. 239, it is clear that an «antisignal» is related to its «signal» as antiparticles to their particles: an «antisignal» is carried by antiparticles as the signal is carried by (their) particles. Of course, they both carry positive energy (and positive information)! See also the following. In the case of photons, they \textit{coincide} with antiphotons.
a signal to \( s' \equiv (x', t') \) by means of a tachyonic beam with speed \( V > c^2/u \). According to \( s' \), however, the "tachyon beam" would actually appear as an antitachyon beam emitted by \( s' \) himself towards \( s \).

Fig. 3. - The second apparent paradox here discussed; it deals, as the previous one, with *macrophysics with tachyons*. It seems that, if the "at rest" observer \((x, t)\) sends information from \( A \) by a modulated tachyon beam to another subluminal observer \((x', t')\), boosted along the positive \( x \)-direction with speed \( u < c \), then heavy paradoxes arise when the beam tachyons have speed \( V - V > c^2/u \) (in fact, in this case the latter observer should see the tachyon beam emitted by \( B \), i.e. by himself). The paradox is solved by the fact that, in macrophysics, tachyon mechanics allows \( B \) to absorb only tachyons with speed \( V < c^2/u \), in which case no paradoxes arise (where the above speeds are all measured in the \( A \) rest frame). Notice that \( \tan \alpha = \beta = u/c \).

Now, we can well imagine that—when overcoming \( s' \) at \( O \)—the observer \( s \) told \( s' \) about his intention of transmitting to him (i.e. to \( s' \)) a tachyonic signal (with speed \( V > c^2/u \)) at time \( t \), whose Lorentz-transformed value is time \( t' \). Then, it seems that the observer \( s' \) will be compelled—at a certain instant \( t' - \Delta t' \)—to emit an (anti)signal towards \( s \), in order ... to save the validity of the classical theory of tachyons in four dimensions. But this would of course violate the "free will" of the observer \( s' \), who can, on the contrary, decide to send no signal (or antisignal) towards \( s \). *A fortiori*, the observer \( s' \) can be in the impossibility of sending that signal, being lacking in information about it (for instance, \( s \) told \( s' \)—at \( O \)—that, at time \( t \), he, \( s \), will send to \( s' \) one piece of music by a tachyon beam with \( V > c^2/u \); and \( s' \) may have no record of that music, so that he cannot send to \( s \) any antimusic, i.e. any music by antitachyon beams). The situation seems self-contradictory. The solution of the apparent paradox is merely in the —previously ignored—fact that *mechanical laws of tachyons do not allow the observer \( s' \) (the moving body \( B \)) to absorb any tachyon with speed \( V > c^2/u \). In other words, \( s' \) can get information from \( s \) through such process (tachyon beam emission by \( A \) and tachyon beam absorption by \( B \)) only by means of tachyons with speed \( V \) smaller than \( c^2/u \) (in which case no causal problems arise) (10).

We explain this fact in the following section.
5. – Some (further) kinematics for tachyons.

Let us first emphasize that a body cannot emit or absorb any whatever tachyon momentum, but only definite values of it. For instance, a body $A$ at rest (with respect to the observer $O$) cannot emit or absorb tachyons endowed with infinite speed (with respect to $O$), unless it suitably decreases its rest mass. This is a trivial consequence of four-momentum conservation (17).

For simplicity, we shall start by considering (moving) bodies $B$ that do not change their rest mass in the process of tachyon absorption. Namely, in the beginning,

i) if $B$ is a nuclear or subnuclear particle, we shall assume that the absorbed tachyon does not carry enough energy for allowing $B$ to shift to another (discrete) rest mass level;

ii) if $B$ is a macroscopic body (as in the following), then we shall assume that the modulated tachyon beams are associated—as usually assumed in the information-transmission processes—to energies very small as compared to the rest energy of the body (detector) $B$; so that the possible change in the rest mass of $B$ is completely negligible.

Assumption ii) is equivalent to neglecting also the possible internal energy associated to tachyon absorption or (inelastic) scattering.

It must be stressed that in this paper we are essentially considering only tachyon emission or absorption, i.e. we are investigating only information transmission by tachyon beams that are merely either emitted (by the «apparent» source) or absorbed (by the «apparent» detector), and not scattered. In fact, we still do not even know how tachyons behave when interacting with matter (19) even if extended relativity can help us to guess it. For instance, would the phenomenon corresponding to «bradyon thermalization» be the one of having tachyons going approximately to infinite speed?

Now let us consider a macro-object $B$, with rest mass $M_B$, moving with (subluminal) speed $u$ in the positive $x$-direction and absorbing tachyons moving (with respect to the same reference frame $s_b$) along the positive $x$-axis, as well. Let the tachyons be emitted by a body $A$, with rest mass $M_A$, at rest (see the following) in the origin of $s_b$. Then, in the process of tachyon absorption by $B$ we shall have (in natural units)

\[ \sqrt{p^2 - m_A^2} + \sqrt{P^2 + M_B^2} = \sqrt{(p + P)^2 + M_A^2}, \]

(19) We warn the reader from drawing naive conclusions when analysing information transmission by tachyon beam scattering.
where $m_0$, $p$ are the tachyon proper mass and 3-momentum, respectively, and where $P$ is body $B$ initial 3-momentum. One immediately gets $p$ as a function of $m_0$ and $P$:

$$|p| = \frac{m_0}{2M^2_a} \left[ |P|m_0 + \sqrt{(P^2 + M^2_a)(m_0^2 + 4M^2_a)} \right] ,$$

so that, for every $m_0$, the body $B$ can absorb only tachyons with a definite (discrete) value of $p$.

After having considered the absorption process (by $B$), let us turn our attention to the emission process by $A$. The tachyon mechanics is such that the body $A$ (at rest in $S_0$) can emit tachyons (of any proper mass) only by lowering its rest mass ($2^0$). Thus, in this case, we cannot neglect $\Delta M_A = M'_A - M_A$; some trivial kinematics tells us that, in this case,

$$\Delta(M^2_A) = M'^2_A - M^2_A < - m^2_0 .$$

If $\Delta(M^2_A)$ is not quantized (as we may expect when dealing with a macro-object $A$), the energy balance for the emission process,

$$M_A = \sqrt{p^2 + M'^2_A} + \sqrt{p^2 - m^2_0} ,$$

will not yield any definite constraint on the value of $m_0$ (in terms of $p^2$ and $M_A$ ($2^1$)). Therefore, under the previous assumptions, we are left with eq. (2), corresponding to fig. 4a), b).

From eq. (2), it is straightforward to derive the important relation

$$V < c^2/u ,$$

($2^0$) See ref. (1), p. 264; and R. Mignani and E. Recami: to appear in Phys. Lett., B. Here and in the following natural units ($c = 1$) will be used when convenient.

($2^1$) However, we will immediately get such a constraint when $A$ is a subnuclear or nuclear particle, e.g. when considering the process $\Delta m(1232) \rightarrow p + t$, in the rest frame of the $\Delta m$-resonance. Such considerations are useful if we consider the probable role of tachyons in elementary-particle interactions (e.g. dual theories, strings, Higgs mechanism, besides virtual particles) ($2^0, 2^1$). Moreover, hadrons might be considered as strong black holes ($2^1$), so that tachyons—by crossing their horizon—might transform into bradyons, and vice versa. Tachyons, then, may even be the strong-field quanta (compare e.g. the electromagnetic excited-atom decay $A^* \rightarrow A + \gamma$ with the previous, possible process $\Delta m \rightarrow p + t$).


Fig. 4. – a) Relation \(|p| \text{ vs. } m_0\) holding for the tachyons that—due to their kinematics—can actually be absorbed by a body \(B\) moving with various speeds along the \(x\)-axis (where \(0 < u_1 < u_2 < u_3 < c\)) and having a fixed rest mass \(M_0\) (i.e. that does not change its rest mass in the tachyon absorption process). b) The same case as before, but showing now \(|p| \text{ vs. } |P|\), and using now \(m_0\) as parameter. The quantity \(|P|\) is the three-momentum magnitude of body \(B\).

where we should recall that \(u \equiv u_x\) is the relative speed between \(A\) and \(B\), and \(V \equiv V_x\) is the beam tachyon speed.

As a conclusion, if \(A\) wants to transmit information to \(B\) by tachyon beams, he cannot use tachyons with speed \(V > c/|u|\), i.e. he can use only tachyons that will appear even to \(B\) as travelling from \(A\) to \(B\).

Now, this conclusion will be generalized to the case in which also the detector \(B\) is allowed to change its own rest mass. Let us notice that tachyon mechanics is such that a body at rest can absorb tachyons both when changing its mass and when conserving it.

Here we are going to assume that, if a moving, macroscopic body \(B\) does change its rest mass while absorbing signal beam tachyons, then it increases its rest mass. In other words, we are assuming that tachyons absorbed by \(B\) have rest mass \(m_0\) small in comparison with the rest mass \(M\) of the macro-object \(B\), and are endowed (with respect to \(s\), that is to the rest frame of \(A\)) with not too small energies—i.e. with speeds not almost infinite—, so as to be actually able to carry information (17).

Furthermore, let us refer to fig. 3: if we want (as usual in macrophysics) that body \(B\) does not appreciably change its speed when absorbing the tachyon beam, then its rest mass must logically be assumed to increase (and, if this increase is negligible, we are left with the case already considered earlier). Then, for macro-objects \(B\), we have (see fig. 5)

\[
M'_B > M_B, \quad \Delta^2 = M'_B^2 - M_B^2 > 0,
\]

and now eq. (2) reads

\[
|p| = \frac{m_0}{2 M_B} \left[ m_0 |P| + \sqrt{(P^2 + M_B^2)(m_0^2 + 4 M_B^2)} + M_B \Delta^2 \right],
\]
The tachyons that (owing to their mechanics) can actually be absorbed by a body $B$, with initial rest mass $M_B$ and moving with a fixed speed $u = u_0$ along the positive $x$-axis, must satisfy the relation $V$ vs. $m_0$ shown in the figure. The quantities $V = V_0$ and $m_0$ are speed and rest mass of tachyons, respectively. Now body $B$ is allowed to change its rest mass during tachyon absorption: line 1 refers to $A^2 = M_B^2 - M_0^2 = 0$, and line 2 to $A^2 > 0$. Remember that $u$ is fixed.

thus yielding a $|p|$ value larger than the one yielded by eq. (2). This means that, even in this more general case, the speed $V$ of beam tachyons possibly exchanged from $A$ to $B$ is, a fortiori, constrained to values

\[ V < c^2/u , \]

in the initial rest frame of $A$, in which case no causal paradoxes arise.

We can again conclude that every time that (the macro-object) $A$ transmits information by a modulated tachyon beam to the (moving) macro-object $B$, which absorbs the beam (either by conserving its rest mass, or by increasing it), then tachyon dynamics ensures us that also $B$ will always see the beam as going from $A$ to $B$. So that neither the free will of observer $B$ will be jeopardized, nor we shall actually meet any contradictory situation (of the kind hypothetically proposed in sect. 4) (15).

In connection with eq. (4), let us notice that—in four dimensions—the relevant quantity will be, instead of $V$, the tachyon speed component along the direction $B-A$.

In connection with eq. (2bis), let us notice that, for every $m_0$, the body $B$ can absorb only tachyons with discrete values of $|p|$ whenever $A^2$ can assume only discrete values (or, in particular, when it is zero) (21-22).

6. Some science fiction.

In the previous section, we have been considering macro-bradyons essentially absorbing beams made of micro-tachyons. Here we want to give a hint about
how proceeding when dealing also with macro-tachyons. At this point, let us take the liberty of using some science fiction. Namely, let us assume (24) that a reader $R_1$ seats on a chair and that an author $A_1$ switches on, around him, a (rotating) Kerr or Kerr-Newman black hole (25) $K_1$, so that $R_1$ finds himself inside the ergosphere, near its internal boundary horizon. Then, the chair starts receiving angular momentum, so that $R_1$ crosses the external ergosphere boundary, transforming into a tachyon (cf. p. 879 of the first of ref. (25)). Afterwards, $R_1$ travels e.g. along the positive $x$-direction with speed $V > c$ until he reaches—in a very short time—another, very far planet, where a pioneer (author $A_2$) had already arrived and switched on a second, analogous Kerr (or Kerr-Newman) black hole $K_2$. Then, $K_2$ captures $R_1$ who, crossing the external limit of $K_2$ ergosphere, transforms again into a bradyon. At last, the $R_1$-chair angular momentum is slowed down until $R_1$ approaches the internal horizon of $K_2$ ergosphere, and eventually $A_2$ switches off $K_2$ (so that $R_1$ can leave his chair and walk on the new planet). Of course, $K_1$ and $K_2$ are practically considered at rest one with respect to the other (for simplicity).

At this point, if we consider a second reader $R_2$, travelling (along the positive $x$-direction) with subluminal speed $u = c^2/V$, he will not see the reader $R_1$ going from $K_1$ to $K_2$, but, on the contrary, the antireader $R_1$ going from $K_2$ to $K_1$. Or, better, he will observe $K_2$ creating a pair $R_1$, $R_1$ (the fact that in this case the traveller $R_1$ is tachyonic and the walking-on-the-new-planet $R_1$ is bradyonic is not essential in this respect: it is due to the internal action of $K_2$).

You are ready to accept micro-object pair creation (provided some energy is supplied), but perhaps you are not eager to accept macro-object (reader-antireader) pair creation. Therefore, if you know (extended) relativity, we have a simple recipe (for orthodox persons): through the suitable Lorentz transformation, go from your description to the description in the $K_2$ rest frame; and you shall find a more orthodox description (i.e. the reception of tachyonic $R_1$, his slowing down and the emission of bradyonic $R_1$).

Naturally enough, however, we expect that the reader $R_2$ will operate an analogous Lorentz transformation whenever he observes the dress colour of the (subluminal) reader $R_1$ as shifted by the standard «Doppler effect».

Fiction aside, let us remember that always the descriptions will become more orthodox in some suitable frames (e.g. in the detector or in some rest frames, etc.). The same applies, for instance, also when the body $B$ of fig. 3 has a complicated internal structure, so as to contain moving constituent objects:

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(24) It will be soon clear that our relevant assumption on this respect is that the set $\{E\}$ of readers contains $n > 2$ elements.

in this case, $B$ can practically absorb even tachyons with the "prohibited" speeds $V \geq c^2/u$ in the overall c.m. of $B$ (where $u$ is the c.m. speed of $B$).

7. - Miscellaneous, further remarks.

i) Any standard (e.g. electron-positron) pair creation can appear to a Superluminal frame $S$ as a unique, travelling tachyon-electron (or tachyon-positron), which emits or absorbs a couple of photons at a certain time instant. Since, for $S$, one law of the very particular phenomenon under examination seems to be that "rest mass is an additive, conserved charge", then the same law (28) should hold for subluminal observers $s$ (observing the pair creation). We conclude that $m_0(e^+) = -m_0(e^-)$, as already claimed in ref. (9) and references therein; that is to say, antiparticles—in the usual formalism (28)—ought to be formally associated to negative rest masses (but to positive relativistic masses and energies, of course!) (9).

ii) Infinite-speed tachyons (17) carry no energy (even if they carry a minimal momentum $m_0c$) and should not be able to transmit information. But, then, why is it not possible to modulate their spins (or helicities), to enable them to transmit information? (27)

Let us recall, first, that "transcendent" tachyons are not associated to any definite direction along their motion line: they can be considered (28) as "outgoing" tachyons as well as "incoming" antitachyons; or even we can consider them as pair created (28,29) in any intermediate point between $A$ and $B$: see fig. 1. In the quantum-mechanical formalism, we could write, for example,

\[ |t(v = \infty)\rangle = a|t(v = +\infty)\rangle + b|t(v = -\infty)\rangle, \quad |a|^2 + |b|^2 = 1. \]

For the consistency of our descriptions, however, when we pass from considering, e.g., $A \rightarrow B$ tachyons to considering $B \rightarrow A$ antitachyons, the associated, transported quantities must either change sign, or be zero. For instance, the

(26) The stated assertion is of course a "law" of that particular phenomenon (12) in the sense that it remains true under a certain, large class of (subluminal) Lorentz transformations (e.g. from $S$ to suitable $S'$); if we assume that it is actually a "$G$-covariant" (16) law, then we get as a consequence that antiparticles must be formally attributed a negative rest mass. But nothing will prevent us from reformulating "extended relativity" in a slightly different way (so as to define, for instance, a "rest mass", that changes sign when going from particles to antiparticles, and a "proper mass", which, on the contrary, is $G$-invariant).

(27) W. Zacharias and J. Grodsky: private communication.


charges do change sign and, therefore, can be—as they are—different from zero (in fact, even transcendent tachyons seem to be able to transport charges (29)). On the contrary, e.g., energy (bound to be positive, both for tachyons and for antitachyons) would not change sign and, therefore, transcendent tachyons must carry zero energy (as they do).

Now, helicity too does not change sign (see, e.g., fig. 16b) in ref. (1) in the case above and, therefore, helicity for infinite-speed tachyons should be zero. Consequently, it seems that at least helicity cannot be modulated for transcendent tachyons (29), so as to allow information transmission. (This is true at least for the spin component along the motion direction of infinite-speed tachyons.)

Of course, now one could ask why we cannot modulate the (electric) charge (29) of transcendent tachyons. All these problems will be dealt with elsewhere. Here, we can «solve» that problem simply by recalling that, if a macro-object $B$ is assumed, as before, not to decrease its rest mass when absorbing tachyons, then $B$ will never be able to absorb transcendent tachyons (neither when moving, nor when at rest). It can be shown, through some easy kinematics, that—under the previous conditions—$B$ will not be able even to scatter infinite-speed tachyons (31).

iii) Another (possibly important) consideration is the following. Let us consider, e.g., a process like the following:

$$a \rightarrow b + \bar{t},$$

where $\bar{t}$ is an antitachyon. Then, under a suitable Lorentz transformation (LT), a new observer can describe the same process as (1)

$$a + t \rightarrow b.$$

If, in eq. (6), $\bar{t}$ was emitted and then had travelled until it has been absorbed (32) by a (near or far) (32) detector, then in eq. (7) $t$ must be of course considered as emitted by a (near of far) source.

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(29) We have shown, however, that an (electric) charge, when going at infinite speed, builds up only a magnetic field: see, e.g., ref. (1), and E. Recami and R. Mignani: Lett. Nuovo Cimento, 9, 367 (1974).

(31) Notice that transcendent tachyons (17) can only take energy from the scatterer. Therefore, if $B$ (for instance at rest) scatters transcendent tachyons, it should utilize its rest mass energy to supply energy both to tachyons and to itself (for its recoil motion). This would be contrary to the assumptions, about the rest mass behaviour of macro-objects, adopted in this paper.

(32) Our philosophy—similar to the one by Wheeler and Feynman (33)—is that no object can be emitted if detectors do not exist, in the Universe, that will be able to absorb it soon or later. In fact, this philosophy is a must (42) in (extended) relativity with tachyons (1), since tachyon physics cannot be done without taking always into account
It should then be clear that the matter emission power of tachyons must be connected with the tachyon cosmic flux (as expected also from other, obvious considerations). For instance, if $\Delta \tau$ is the mean life of particles $a$ for the decay in eq. (6), then

$$[\Delta \tau]^{-1} \propto \varphi(t) \sigma(a, b),$$

where $\varphi(t)$ is the tachyon (cosmic) flux density and $\sigma(a, b)$ the invariant cross-section of process (7). In other words, $\Delta \tau$ is the Lorentz-transformed value of the average time $\Delta \tau'$ that particle $a$ has to spend before being struck by a cosmic tachyon $t$ and transforming into $b$:

$$[\Delta \tau]^{-1} = [L(\Delta \tau')]^{-1}.$$

iv) Finally, let us mention that one of us (M.P.) thinks that causal paradoxes could even better be solved in the context of 5-dimensional relativity (34). In any case, considering SR in five dimensions already resulted to be a useful tool for attributing the correct role to proper mass and proper time and for giving extended relativity a more elegant form (34,35).

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the proper sources and detectors (because of the fact that the roles of tachyon sources and tachyon detectors can invert under a standard LT). Any couple of bodies connected through tachyon exchange are realizing a symmetrical, instantaneous connection according to suitable observers. And it is not without meaning that in ref. (35) the same philosophy was shown to be adoptable in the limiting case of photons.


● R I A S S U N T O

Il postulato che non esistano particelle ad energia negativa (che viaggino avanti nel tempo) conduce automaticamente al «Principio di Reinterpretazione» di Stückelberg e di Feynman. Si è già mostrato che tale «principio», una volta assunto come terzo
postulato della relatività ristretta, assicura la validità della legge di causalità (ritardata) sia nella usuale relatività, sia nella « relatività estesa », con tachioni e con sistemi inerziali superluminali. Inoltre il nostro terzo postulato permette di prevedere l’esistenza delle antiparticelle in un contesto puramente relativistico. In questo lavoro si mostra che il terzo postulato è sufficiente a salvaguardare la validità della legge di causalità (ritardata) anche in macrofisica, quando gli usuali macrooggetti interagiscono con microtachioni o con macrotachioni. A questo scopo si sviluppa ulteriormente la cinematica dei tachioni, la quale potrebbe essere utile anche per la comprensione delle interazioni tra particelle elementari (e forse della struttura degli adroni). Si discutono infine anche molti altri problemi connessi.

Как восстановить причинность для тахионов даже в макрофизике.

Резюме (*). — Постулат, что частицы с отрицательной энергией не существуют (которые движутся в прямом направлении по времени) автоматически приводит к «Принципу Реперпертации», предложенному Стюкелбергом и Фейнманом. Также было показано, что такой «Принцип », принимаемый как Третий Постулат специальной теории относительности, обеспечивает справедливость закона (защемляющей) причинности, как в обычной теории относительности, так и в (протяженной) теории относительности с тахионами и с суперлюминальными инерциальными системами. Наш Третий Постулат, кроме того, позволяет предсказать существование античастиц в чисто релятивистском контексте. В этой статье мы показываем, что Третий Постулат является достаточным, чтобы обеспечить выполнение закона причинности даже в макрофизике, когда обычные макро-объекты взаимодействуют с микро-тахионами и макро-тахионами. С этой целью развивается кинематика тахионов, которая может быть полезной для понимания взаимодействий элементарных частиц (и, может быть, структуры адронов). Обсуждается большое число родственных проблем.

(*) Переведено редакцией.
How to Recover Causality for Tachyons Even in Macrophysics.

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(Nuovo Cimento, 36 A, 171 (1976))

In this paper we considered in particular a macro-object \( B \), with rest-mass \( M = M_\gamma \) and 3-momentum \( \mathbf{P} \), moving with (subluminal) speed in the positive \( x \)-direction and absorbing tachyons, with rest-mass \( m = m_\circ \) and 3-momentum \( \mathbf{p} \), moving along the positive \( x \)-axis as well. From the four-momentum conservation law in the case when \( M \) does not change during the absorption, we correctly derived eq. (2). In the case, however, when we have a nonzero \( \Delta \equiv M^2 - M' \), then eq. (2 bis) was trivially miscalculated. It should rather read

\[
2M' |\mathbf{p}| = (m^2 + \Delta) |\mathbf{p}| + E \sqrt{(m^2 + \Delta)^2 + 4m^2 M^2}, \quad E \equiv \sqrt{P^2 + M^2}.
\]

(Notice that the present \( \Delta \) was called \( \Delta^2 \), since in this paper we assumed \( \Delta > 0 \).)

Notice, however, that the physical conclusions—and actually the whole paper—remain totally unchanged. Even fig. 5 still holds, since the physics was not affected at all by that miscalculation.

Let us take advantage of the present occasion for repeating that—as already (1) remarked—lines 14 and 15 (and the first eight words of line 16) ought to be eliminated at page 178.

For further details about the subjects of this paper, see for instance ref. (1,2).

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