Faster-Than-Light Phenomenology

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Aug 2009

A hundred years after the invention of relativity theory, popular writers seem to have convinced everybody that we live in a relativistic world, where no material body can move faster than light. To support this statement, the formal scheme of Einstein's relativity theory is called up, with Lorentz transform used to derive the formulas relating all the physical quantities obtained in one frame of reference to their values in another. Then we are told that the obvious singularity in the transformation law for the relative speeds approaching the speed of light is an indication of utter impossibility of faster-than-light motion. Any speculations about the "tachyon" world have nothing to do with serious physical research essentially limited to the under-light movements. Of course, there are collective effects in various media that can (and sometimes even must) propagate faster than light. However, such phase waves do not carry any physical meaning; they do not mediate any interactions and are not related to energy flows. Yet another case of unphysical "tachyons" is due to the non-inertial nature of the reference frame; when the transition to such a coordinate system lacks continuity, some points may seem to move infinitely fast, like, for instance, for a rotating observer. Since there is no actual motion, the restriction of any physical signal exchange to the light cone is never really violated.

This impressive picture is, however, entirely due to a *logical fallacy*. Even accepting relativity theory as a final truth beyond any doubt, one could observe that the presence of singularity in the coordinate transform does *not* imply the impossibility of penetrating through the light barrier. In this respect, one needs to clearly distinguish the velocities of material bodies in a particular reference frame from the velocities of one observer moving relative to another. It is only *the latter* that appears in the formulas of Lorentz transform and its derivatives; the theory says nothing about the observable velocities of material bodies in a given frame. That is, we cannot formally switch to a reference frame moving faster than light; but we still can speak about infinitely fast movements within the current frame. The weak objection that, in this case, we cannot associate a reference frame with a moving particle is out of topic, since there is no physical reason why we should generally be able to do that. There is no conflict with the relativity principle, since a point moving faster than light in one frame will move faster than light in any other frame moving slower than light relative to the first one. This qualitative invariance may mean a dawn of a new physics.

The existence of the maximum limit on the speed of a material particle is in no way an experimental fact, as some popular books tend to say. The only experimental result we have is that no traces of such fast movements have been observed so far. However, this may entirely be due to that we do not look for them the right way. Quite probably, such traces are already suggested by many some well-known facts, but we do no pay attention to this evidence.

Moreover, logically, the singularity in the Lorentz transform does not mean that there is no such thing as a faster-than-light reference frame. The only correct conclusion forbid *directly transforming* physical quantities between the frames if their relative velocity is greater than the speed of light. First, nothing prevents us from considering alternative transforms specially adjusted to link the frames with fast relative movement; second, when two frames of reference are moving faster than light relative to us, they still can be slowly moving relative to each other, with the usual Lorentz transform applicable in a straightforward manner. That is, the Lorentz transform simply splits the whole set of reference frames into an infinity of space-time "cells" isolated from each other by the light barrier. Within each cell, the standard relativistic physics holds in full, while transitions between the cells are forbidden.

But is the light barrier as impenetrable as in seems to be? Mathematical singularities are all unphysical; they do not mean anything but the necessity to adjust a physical theory when it runs across phenomena beyond its scope of applicability. The singularity in the Lorentz transform is no exception. The standard relativism may be valid up to speeds very close to the light barrier, but not infinitely close. At some speed, we will need to account for additional considerations that did not influence the original development of the theory. For instance, when the mass of an electron (which, as we know, increases with speed) becomes greater than the mass of the whole universe, the present theory is bound to fail, and a new paradigm will be needed. Indeed, in a quantum theory, such a super-heavy electron could not exist; it would rather produce many other particles (including hard radiation), thus effectively distributing the excess of energy. Still, in principle, quantum field theory allows infinitely approaching the light barrier and hence is not entirely free from unphysical behavior.

On the other hand, leaving aside the details of near-threshold physics, one could find that crossing the light barrier is already possible within the traditional paradigm. The singularity in the Lorentz transform becomes an impenetrable barrier for *continuous* velocity changes, but it does not say anything against *discrete* transitions, which abound in quantum theory. A quantum leap from one side of the barrier to another is not only possible, but also virtually inevitable, in view of the uncertainty principle. Basically, the idea is to rewrite the traditional equation

$$\Delta x \Delta p \geq \hbar / 2$$

as

$$v \cdot F \geq \hbar / 2\tau^2 ,$$

with the right hand side steeply increasing for $\tau \to 0$ (which can always be made to overweigh the relativistic slowdown of time); considering nearly inertial motion with $F \sim 0$, we obtain infinitely high velocities v. Of course, this is a very rough outline, but it can be used as an illustration of the way of thought.

The standard vision of the tunnel effect assumes that a general quantum state is to be composed of a number of components with definite velocities, both under the light barrier and above it. Such states do not need to be orthogonal, and this accounts for spontaneous cross-barrier transitions. Additionally, the transitions induced by various physical interactions may mix the states from different velocity cells. Theoretically, it is possible to adjust the model so that such transitions were forbidden by construction. But do we really need to impose this *ad hoc* restriction for no practical reasons? Quantum physics may require certain modifications near the relativistic singularity, in accordance with the similar revision of the notions of macroscopic mechanics. However, one would always prefer a minimal extension enough to remove the formal contradictions rather than a drastic change in the physical content of a theory.

Now, that the principal compatibility of faster-than-light motion with the standard apparatus of relativistic and quantum mechanics is intuitively acceptable, it would be quite logical to collect, without too much pretense, a few qualitative traits of this supposed area of experience. Of course, reasoning in the currently available notions may be inadequate in certain respects; still, in any case, it will bring forth some of the issues overlooked by the traditionally educated physicists, and the development of the physical theory may eventually need to cope with the related questions, albeit in a manner one can hardly anticipate today.

The fundamental difference between classical mechanics and special relativity, as well as between special and general relativity, is in the idea of inertial motion. Basically, all physicists agree that certain features of motion do not depend on the frame of reference, provided the different frames do not move relative to each other in some peculiar manner. There are different opinions on the degree of peculiarity. In classical physics and special relativity, we admit that the possible inertial frames of reference move relative to each other with a constant speed; in the general relativity theory, all kinds of smooth relative motion are equally admissible. With all that, we believe that, in either approach, the character of physical motion does not depend on the chosen reference frame, and the laws of dynamics can be formulated in a covariant way, that is, their mathematical form is to be the same for all observers.

However, the covariant formulation of the physical laws cannot ensure the same *qualitative* behavior of the physical system in different reference frames; on the other hand, we need to agree on the level of changes that would still keep us within our practical notion of "the same". Thus, for a pre-Galilean philosopher, spatial motion was obviously different from being at rest; in this cultural context, admitting that uniform straight-line motion is physically equivalent to the state of rest has been quite a revolutionary step. Similarly, the transition from classical to relativistic mechanics introduced a number of ideas very inconvenient for a classically minded person. Even with the dependence of lengths and durations on the motion of the observer accepted as a mere quantitative change, the relativity of simultaneity and locality is a much more challenging demand. In special relativity, apparently different physical phenomena have become the manifestations of the same motion. For instance, electrical and magnetic fields can be transformed into each other by simply moving to a different inertial reference frame. This breach in the qualitative determinacy of physics has initiated the race for absolute unification, reducing all the physical forces to a unique fundamental entity. So far, this development, despite all the promises and preliminary demonstrations, has not yet come to anything satisfactory, and, instead of a dynamic unified field theory, we have a family of almost numerological "theories of everything".

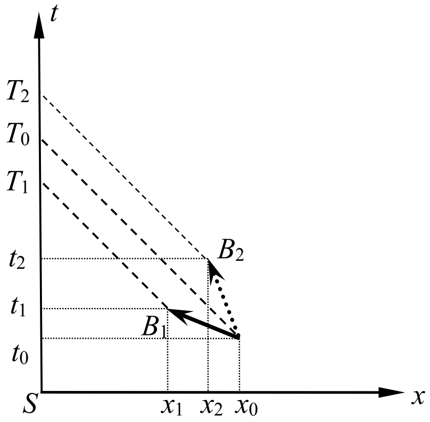
General relativity considers accelerated motion on the same footing with uniform rectilinear motion, and the notion of an inertial frame of reference has become absolutely spurious. In a way, the very idea of a reference frame has thus been eliminated from physics, as the transition from one observer to another is no longer formally distinguishable from mere coordinate transform. A couple of attempts to restore the physical significance of a reference frame in general relativity have ended as mere technical tricks similar to any other variable substitution. The presumed identity of physical and inertial forces brings in an absolute confusion, as we no longer need the ideas of interaction, physical state, physical system, and so on; that is, we can no longer speak of *motion* in physics. Entire dynamics has been reduced to mere geometry. Well, if the world is designed that way, we only have to accept it as it is. Personally, I would prefer something more animated.

But let us get back to superluminal phenomenology. For a while, let there be frames of reference and the idea of inertial motion. There is still a wide conceptual tolerance, since it is only the relative motion of reference frames that can be considered, and one can never tell whether the forces within a given frame are real. However, switching from one reference frame to another should not change the observable behavior, provided the new frame moves relative to the original with a constant velocity. We still cannot be sure, which aspects of reality should be called "physical" (and hence frame-independent), and which properties could freely mutate from one manifestation to another. In the relativistic world, the notion of a physical event is rather vague, as the very occurrence of certain events may be relative. Thus, let an observer at rest S send a light signal along the X-axis of his reference frame; let another observer S' have a positive coordinate x_0 relative to S on the moment of signal emission, while moving along the X-axis of S with some velocity V. If $|V|< c$, observer S' will register the emission event regardless of the direction of velocity V. However, if $|V|> c$, S' will only receive the signal for negative velocities V; otherwise, the emitted photon will never catch up with the moving observer, and the event of signal emission will never occur in the frame S'. On the contrary, for negative x_0, the signal sent by S in the positive direction of the X-axis will be registered by S' moving with a superluminal positive velocity V, while any negative velocity will prevent S' from registering the emission event. In special relativity, such a dependence of the very occurrence of a physical event on the relative positions of the reference frames S and S' and the direction of their relative motion is deemed to be impossible, contradicting the homogeneity and isotropy of space and the principle of relativity. This is not exactly true, since there is still anisotropy expressed by the condition $\operatorname{sgn} x_0 \cdot \operatorname{sgn} c > 0$ required to ensure that the signal c emitted by S will be received by S'. The admission of faster-than-light motion just extends this condition. But is this apparent violation of isotropy due to the motion of observer any different from the violation of isotropy in an accelerated reference frame, as introduced in the general relativity theory?

One could argue that the speed of light is the same in all the frames of reference, and the photons emitted by S will move towards S' with the same speed c in both S and S', so that both observers will see them anyway. This logic works fine for $|V| < c$ and $\operatorname{sgn} x_0 \cdot \operatorname{sgn} c > 0$, when the emission event is indeed observed in the both reference frames. However, if there is no such event at all for the moving observer, talking about the same propagation speed is entirely void, as there is nothing to compare. Anyway, having a light signal to catch up with an observer moving faster than light is a logical contradiction that does not seem more intuitively acceptable than mere violation of spatial isotropy.

On the other hand, space is not entirely isotropic in special relativity as it is pictured in popular renditions. The very presence of a moving observer means the presence of a preferred direction, so that the longitudinal and transversal components of any structure are no longer treated on the same footing. That is, the dependence of geometry on the relative motion is a normal feature in the standard relativistic physics; there is no reason why it could not be extended to the superluminal domain, with obvious specifications.

As indicated, the superluminal observer S' moving in the positive direction along the X-axis still can receive a signal sent by the observer at rest S in the same direction, provided the emission time is far in the past, when S' was somewhere at a negative coordinate. In this case, S' will catch up with the photon emitted by S; but for S', this would look like meeting a photon moving in the *negative* direction. Here, we come to the relative nature of spatial direction once again; the *sign* of the photon's velocity does not need to be the same for all observers (though we do not say anything about the *speed* of light).



In general, faster-than-light motion may also mean the relativity of sequential order (as shown in the figure). Indeed, let body B_1 move from point x_0 in the reference frame S to $x_1 < x_0$; the body's velocity

$$V = \frac{x_1 - x_0}{t_1 - t_0}$$

will then appear to be negative. Now, let the body emit two photons, at time instants t_0 and t_1; these photons will reach the observer S (presumably situated in the point $x = 0$) at time moments T_0 and T_1 respectively. For $|V| > c$ and $t_1 > t_0$, we obtain $T_1 < T_0$, so that the initial sequence of events becomes reversed. This is an obvious consequence of the fact that the second photon has been emitted from the point x_1 where the first photon has not yet come (which is exactly the meaning of B_1 moving faster than light in the S frame). For a body B_2 moving slower than light, the order of photon reception by S is always the same as the order of their emission. This order preservation is implicitly involved in the derivation of Lorentz transform, thus essentially restricting the domain of its applicability to $|V| < c$.

It should be stressed that this kind of inversion does not mean any violation of causality. This is a purely kinematic effect that is quite compatible with causal dynamics. One could compare it with the apparent faster-than-light wave propagation in plasmas, which is indeed a mere collective effect produced by subluminal physical interactions.

Observer S could try to measure the speed of B_1 detecting the emitted photons (which is the way we judge about the movements of the distant stars). Taking the sequence of events at $x = 0$ for the true sequence of photon emission, one can compute the observable velocity as

$$\tilde{V} = c\frac{T_0 - T_1}{t_1 - t_0} > 0$$

If the body B_1 emits photons with a standard frequency (which is equivalent to detecting the phase of the signal), and with observer S assuming the validity of the time contraction formulas of the special relativity theory, we obtain

$$\tilde{\omega} = \frac{2\pi}{t_1 - t_0} = \omega\sqrt{1 - \frac{\tilde{V}^2}{c^2}}$$

and finally,

$$\tilde{V} = c\frac{\tilde{\omega}}{\Omega} = c\frac{\omega}{\Omega}\Bigg/\sqrt{1 + \frac{\omega^2}{\Omega^2}}$$

That is, for the observer at rest, the body B_1 seems to move with a *subluminal* velocity $|\tilde{V}| < c$, and the apparent direction of motion is reversed compared to the true direction.

Now, let the same observer S be able to somehow distinguish one spatial point from another by the parameters of the signal received. For instance, the axis X could be thought about as some active medium reacting on the passage of the bodies by emitting light with the frequency (or phase) dependent on the distance from the origin. The motion of the superluminal body B_1 will then reveal some strange features; for instance, the observer might think that the body B_1 moved “back in time”, just like in Dirac’s picture of a positron.

Finally, let us admit that any coordinates are measured in the reference frame of S with a finite resolution, so that the points of the axis X could be pictured as separated from each other with a finite space interval Δx. The signals from the neighboring points will then be separated by the time interval

$$\Delta t = \Delta x / c\,,$$

which provides the natural measure of the discreteness of time. All the signals coming within the interval Δt will be considered by S as simultaneous. For a slowly moving body, signals indicating the passage of successive special points will be separated by many temporal quanta Δt, which can produce the impression of smooth movement. On the contrary, if the body is moving faster than light, the observer may receive several signals within the same interval Δt; this can be readily interpreted as the presence of several moving bodies. For very high speeds, one gets the impression of some distribution of bodies over the axis X, a kind of wave. This is how we come to something resembling a quantum picture of motion. Einsteinian mechanics and quantum mechanics could be naturally unified in this way, to provide a logically consistent basis for quantum field theories.

To summarize, the apparent movement of a superluminal body may be very different from its real motion. Some of the effects we ascribe to the regular movements of the observable bodies in our frame of reference might rather be the manifestations of faster-than-light motion. So far, we do not have a sound theoretical background for discriminating such peculiar cases with regular subluminal objects. Since standard physics can be differently extrapolated into the superluminal region, we need several such extensions to start hunting tachyons disguised as ordinary particles.

One of the most important test points for extended kinematic theories is related to velocity addition. It is difficult to tell, in which way the usual relativistic law should be modified to account for faster-than-light speeds; obviously, such a generalization must be nontrivial, concerning the very topology of space-time. As indicated, the existence of light barrier splits the whole velocity range into isolated cells, with subluminal relative movements within each cell and the necessity of extended treatment for inter-cell transitions (a kind of four-dimensional lattice structure). However, while the sum of a superluminal and a subluminal velocity will always be superluminal, belonging to the same cell as the original superluminal velocity, adding one superluminal velocity to another may produce almost anything. This is like indeterminate forms in mathematical analysis. The methods of evaluation for such indeterminate expressions for superluminal velocities will essentially depend on the adopted model of faster-than-light motion. In any case, a similar lattice structure is to be reproduced in any kinematic extension of relativity to comply with the correspondence principle.

The common ideas of geometry and time came from our everyday activities, and they reflect its overall structure. In physics, we only consider a definite class of measurement procedures compatible with that traditional structure extended to cover the regions of indirect experience. Probably, such measurement procedures are not well suited to determine the characteristics of very fast bodies and hence must be modified in some respects. Obviously, most modifications are to concern the methods of interpretation, as we observe anything at all within the same sensory limits, so that any indirect measurement is essentially dependent on the theoretical background.

The popular literature abounds with speculations around the formal interchange of spatial and temporal coordinates in the form of the relativistic interval, when the Lorentz transform is formally applied to velocities higher than the speed of light. Similar effects are also discussed for the (imaginary) inner areas of the (presumably existing) black holes. Though some effects like that could indeed take place, we should always keep in mind that the singular formulas like Lorentz transform or Schwarzschild solution are only valid as long as we keep far enough from singularity. Directly extrapolating them into the singular region and beyond may be inadequate. Numerous alternatives and the inevitable indeterminacy issues reduce the value of far-reaching conclusions almost to zero. Still, there are no principal objections to the possibility of faster-than-light motion, and its experimental discovery may be a matter of the nearest future.