

## PARTICLES BEYOND THE LIGHT BARRIER

Despite almost universal belief that particles cannot move faster than light, one can think of negative-energy particles traveling backward in time whose speed exceeds that of light. Experimenters are looking for these faster-than-light particles.

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FOR MANY DECADES now the view has prevailed that no particle could possibly travel with a velocity greater than the velocity of light in vacuum,  $c = 3 \times 10^8$  m/sec. It is generally held that this limitation is a direct consequence of the special theory of relativity. Albert Einstein himself has said so in his original paper on relativity.

Some time ago we reexamined this point<sup>1</sup> and concluded that existence of superluminal particles is in no way precluded by Einstein's theory. On the contrary, it is this very theory that suggests the possibility. Other physicists, notably Yakov P. Terletskii<sup>2</sup> and Gerald Feinberg,<sup>3</sup> have reiterated this same conclusion.

Around the turn of the century, shortly before Einstein had published his revolutionary paper on the special theory of relativity, Arnold Sommerfeld<sup>4</sup> examined the problem of accelerating particles to velocities greater than  $c$ . He concluded that at such velocities particles would have to behave in a patently absurd fashion: Upon loss of energy they would have to accelerate! Einstein's theory has remedied this seemingly inadmissible state of affairs. It predicted that the mass of a particle would get infinitely large upon approaching the velocity  $c$ . Thus it became obvious that no

particle could be accelerated past the "light barrier."

This argument still stands. To assail it is a futile task. Yet it is possible to circumvent it by asking the following question: Is the acceleration process the only way by which fast particles are produced? Certainly not! Take photons or neutrinos. They *do* travel with a velocity equal to  $c$  without ever having been accelerated from a slower speed. In fact there

are no slow photons or neutrinos. When they are created in atomic or nuclear processes they take off right away with the velocity of light. Conversely, the only way to slow them down is to make them disappear.

### *A third class?*

For this reason photons and neutrinos must be regarded as a class of objects different from "normal" particles such as electrons or nucleons. Let us



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henceforth refer to the normal ones as Class I, and to photons and neutrinos as Class II. Whereas Einstein's theory encompasses both of these classes, only for Class I does it require  $c$  to be the unattainable limiting velocity. Following this line of thought, we have inquired whether Einstein's theory could possibly accommodate yet a third class of objects, that is, superluminal particles.

Would existence of such particles really violate any basic maxims of physics, such as conservation of energy or causality? If so, it would indeed be senseless to speculate further about such particles. But if their existence would not lead to any contradictions, one should be looking for them.

There is an unwritten precept in modern physics, often facetiously referred to as Gell-Mann's totalitarian

principle, which states that in physics "anything which is not prohibited is compulsory." Guided by this sort of argument we have made a number of remarkable discoveries, from neutrinos to radio galaxies.

Several such searches are in progress now. Because theory does not exclude the possibility that a magnetic analog to the electric charge can exist, physicists persist in their quest for the magnetic monopole.<sup>5</sup> A similar search is on for the "quark," a fundamental particle having 1/3 of the electronic charge, whose existence is suggested by recondite symmetries of elementary particles.

In each of the above cases, the possible existence of the new particle was first suggested by the logical extension of the regularities or symmetries governing the known physical world. The special theory of relativity pro-

vides for just such an extension. We have called it "meta-relativity."

#### Geometrical representation

Consider a particle having energy  $E$  and momentum components  $p_x$ ,  $p_y$  and  $p_z$ . According to special theory of relativity, the quantities must obey:

$$E^2 - p_x^2 c^2 - p_y^2 c^2 - p_z^2 c^2 = m_0^2 c^4$$

If the same particle is observed from another frame of reference its energy and its momentum components will be different, but their values will still satisfy the above equation. This property is called invariance of the energy-momentum four-vector under a Lorentz transformation. Without loss of generality, we may assume that the particle moves along the  $x$  axis, so that  $p_y$  and  $p_z$  are both zero. It now becomes possible to represent the situation graphically. The equation

$$E^2 - p_x^2 c^2 = m_0^2 c^4$$

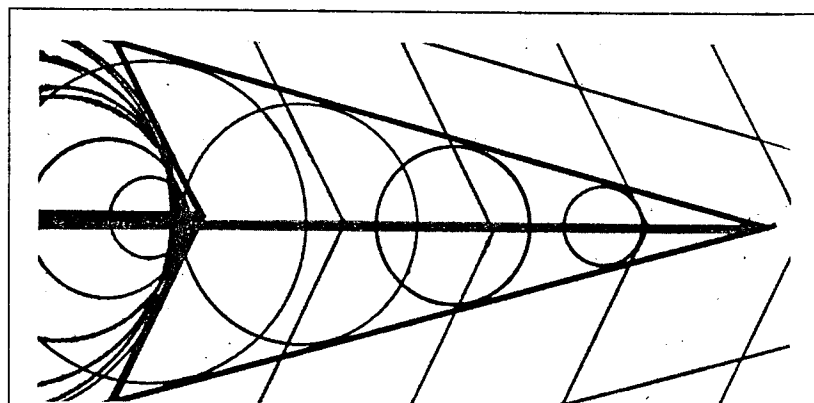
describes a hyperbola in the coordinate system of  $p_x$  and  $E$  (black curve in figure 1). Each point on the upper branch of the black curve furnishes the energy  $E$  and the momentum  $p_x$  that the particle will have in a given frame of reference. It can be shown that the slope of the hyperbola at that point gives the velocity of the particle in the corresponding reference frame,

$$v_x = dE/dp_x$$

Because this slope is everywhere smaller than  $c$ , we see that even by choosing a frame in which the energy is incredibly large, its velocity will still not exceed the value of  $c$ . This means, conversely, that even if we could supply a particle with an arbitrarily large amount of energy, its velocity with respect to us would still be bounded by the value of  $c$ . Let us also note that transform as we may, we will not succeed in getting onto the lower branch of the black hyperbola. So much the better, as a particle with negative energy is not observable.

A point of particular interest on the upper black curve is that for which  $p_x = 0$ . This point corresponds to a frame in which the particle is at rest. Even though its momentum vanishes we see that the energy of the particle remains at a finite value of  $E = m_0 c^2$ . We call it the proper energy, or rest energy, of the particle;  $m_0$  is its proper mass.

In the special case in which  $m_0$  is



#### A TARDYON'S POCKET DICTIONARY TO THE WORLD OF TACHYONS

**Subluminal**—slower than light

**Superluminal**—faster than light

**Ultraluminal**—faster than  $c^2/V$ , where  $V$  is the relative velocity of two laboratory systems

**Tachyon or meta-particle**—a faster-than-light particle

**Tardyion**—any slower-than-light particle

**Luxon**—photon or neutrino

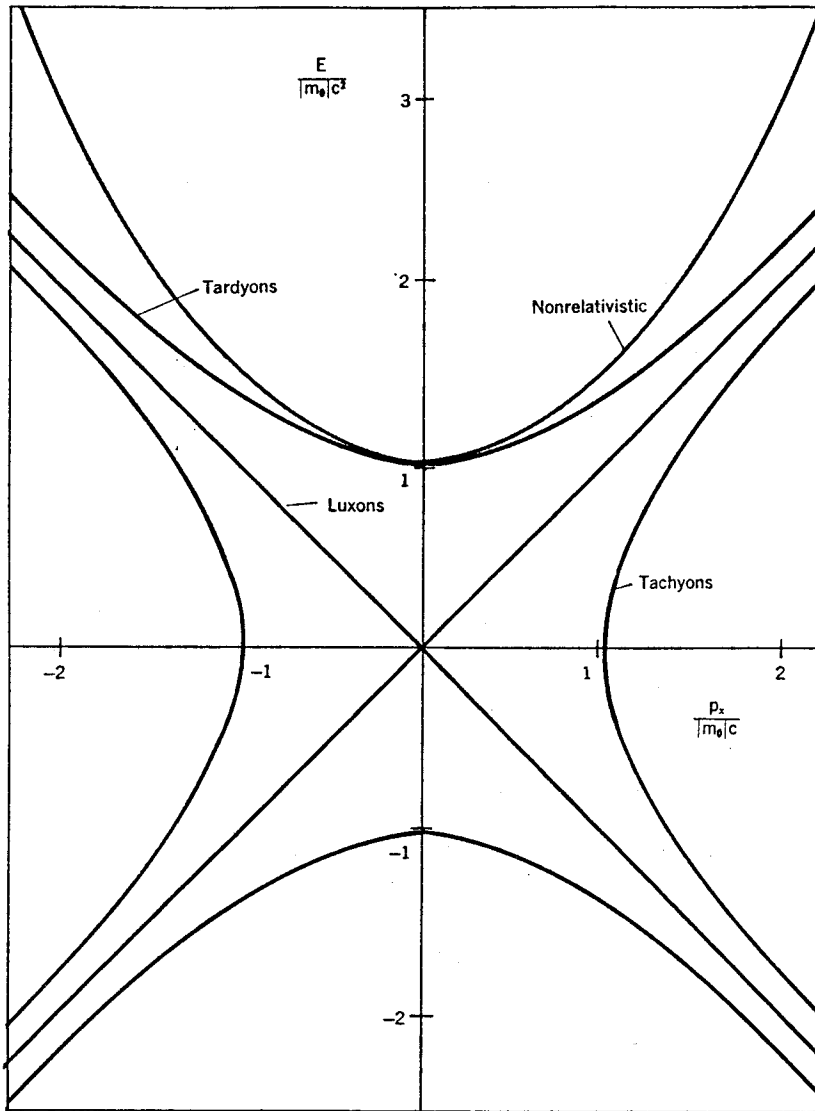
**Meta-relativity** — special-relativity theory of tachyons

**Proper mass ( $m_0$ )**—In analogy to proper length and proper time, this term should be used instead of the term "rest" mass. The term proper mass is appropriate for all classes of particles, including luxons, whose proper mass is zero, and tachyons, whose proper mass is imaginary. (It does not make sense to speak of the "rest" mass of a tachyon.)

**Meta-mass ( $m_*$ )**—absolute value of the proper mass of a tachyon ( $m_0 = im_*$ )

**Reinterpretation principle**—interpretation of negative-energy tachyons propagating backward in time as positive-energy tachyons propagating forward in time. This reinterpretation invalidates causality objections to the possibility of existence of faster-than-light signals and permits construction of a consistent theory of tachyons.

**Transcendent tachyon**—infinite-velocity tachyon having finite momentum ( $p = m_* c$ ) and zero energy. Such a tachyon is everywhere on the supercircle of its trajectory. A transcendent state of a tachyon is analogous to the quantum-mechanical state of rest, in which a definite value of momentum implies total uncertainty of position.



RELATIVISTIC-ENERGY ( $E$ ) VS. MOMENTUM ( $p_x$ ) dependence for three classes of particles. Slope of a curve at any given point gives the velocity of the particle whose energy and momentum are furnished by the coordinates of the point. Because the slope of the red curve is, in absolute value, everywhere greater than  $c$ , this curve represents the as-yet-undiscovered tachyons. The gray curve depicts the nonrelativistic dependence where energy is simply  $E = p^2/2m_0$ . It has been shifted up to show that for small velocities it coincides with the black hyperbola. —FIG. 1

zero the two branches of our hyperbola degenerate into two intersecting lines,

$$(E + p_x c)(E - p_x c) = 0$$

drawn in pink in figure 1. Take a point on the pink line in the upper right-hand quadrant. The coordinates of this point give us the energy  $E$  and the momentum  $p_x$  of a photon in the corresponding reference frame. When we change to another frame the energy and momentum of the photon will assume new values, as in the case of normal particles. But the velocity will

not; the slope of the line is everywhere  $c$ . This geometrical representation shows clearly that there can be no vantage point with respect to which the photon would appear to be at rest.

Now we are almost ready for our generalization. But before we proceed with it, let us take a look at the relativistic dependence of energy on velocity. Because in relativity theory the energy of a particle is given by

$$E = mc^2 \quad (1)$$

and  $c$  is a universal constant, the ve-

locity dependence is contained in the expression of the relativistic mass,

$$m = m_0[1 - (v/c)^2]^{-1/2} \quad (2)$$

Here  $m_0$  is the proper (or rest) mass of the particle and  $v$  is its velocity in our frame of reference. Because energy is a measurable quantity, the expression for  $m$  must yield a real number so that the value that  $mc^2$  gives for  $E$  remains itself a real number. As we have already seen, the velocity of particles whose behavior is described by the black hyperbola is always smaller than  $c$ . This means that the expression under the square-root sign above is always positive for these particles. Inasmuch as  $m_0$  is also given by a real number, the relativistic mass  $m$ , and hence the total energy  $E$ , are also real. (Note that the square root provides a plus as well as a minus sign for the energy. These signs correspond to the upper and the lower branch of the hyperbola, respectively. So far we consider only the upper branch of the curve to have physical significance.)

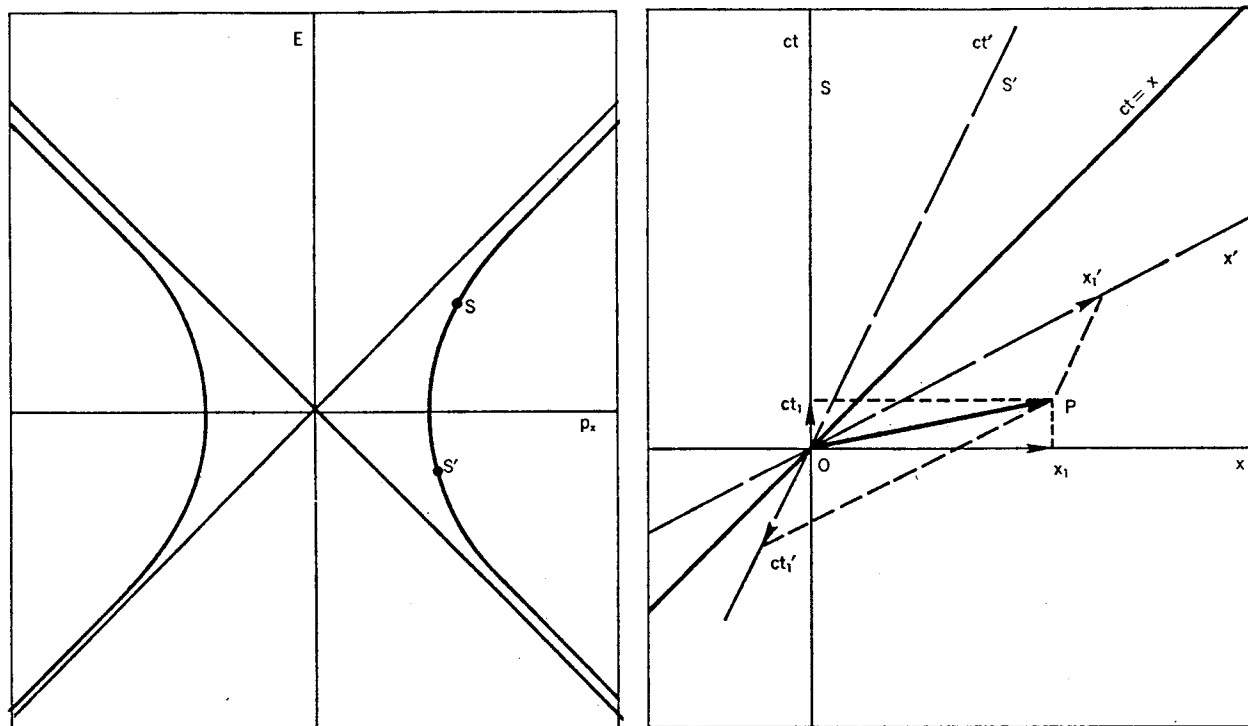
Equation 1 has general validity; so it must also hold for photons. If we know the energy  $E$  of a photon, we can compute its relativistic mass as  $m = E/c^2$ . But we have just seen that the relativistic mass is also given by equation 2. In the case of photons  $v$  is equal to  $c$  and we seem to be in trouble; we are dividing by zero. The only way out is to require that particles traveling with the velocity of  $c$  have zero proper mass. We know this conclusion to be in full accord with experimental observations.

We have just seen again that particles traveling at subluminal and those traveling at luminal velocities are two entirely distinct kinds of objects. The former can never reach the velocity of  $c$ , the latter can have nothing but  $c$ . Yet even though these two kinds of particles are so drastically different, they are governed by the same relativistic laws.

#### A hypothetical situation

Let us for a moment imagine a hypothetical (and highly improbable, but not inconceivable) situation in which the entire formalism of the special theory of relativity is based solely on observations of slower-than-light particles, that is normal (Class I) particles having a nonvanishing proper mass  $m_0$ .

One could imagine that under such circumstances some nonconforming



**REINTERPRETATION OF NEGATIVE ENERGIES.** An objection to tachyon existence points out that a superluminal particle, given by  $S$  in one frame will be given by  $S'$  in another, in which it would appear to carry "negative energy" as shown at left in the  $E$  vs.  $p_x$  diagram. The space-time diagram (right) reveals however that in such a system the sequence of events involving this particle would also appear as "negative" ( $ct'$ ). Thus the event corresponding to the point  $P$  takes place before the event corresponding to the point  $O$ , when the events are referred to the  $ct'$  axis. So one can think of "negative-energy" particles that have been "absorbed first and emitted later" simply as positive-energy particles that have been emitted first and absorbed later—a perfectly normal situation. —FIG. 2

physicist might start reasoning as follows. Although the theory of relativity excludes the possibility of accelerating particles to the velocity of  $c$ , does it also preclude the emission, during some as yet unknown process, of a new kind of particle (Class II) having the velocity of  $c$ ?

He would next take a closer look at relativistic laws and would discover that such particles are indeed admissible, but only under the condition that they possess no proper mass. To some of his colleagues such a condition may appear rather far fetched.

What if one imagines a laboratory attached to such a particle, traveling with the same velocity  $c$  as the particle? In this lab the particle would be at rest. But then it ought to vanish because its proper mass (rest mass) is required to be zero.

How can it be? Our imaginary physicist would answer: The situation is simple, no lab can travel relative to us with the velocity of  $c$ . All

observers are Class I objects and as such are restricted to subluminal velocities. Conditions under which such a conceptual difficulty appears can never arise.

After this introduction the reader may have guessed which question we are about to ask next. Although relativity precludes acceleration of particles to velocities greater than  $c$ , is it not possible that a new kind (Class III) of particle having a velocity greater than  $c$  is emitted during some as yet undiscovered process?

#### Imaginary proper mass

To answer this question we must first look at equations 1 and 2. In order for the energy  $E$  to be given by a real number the expression for  $m$  must again furnish a real number. But how can it when a negative number is under the square-root sign? The only way  $m$  can be made real is by requiring that the proper mass  $m_0$  be imaginary; so it is expressed as some real

number  $m$  times the square root of minus one,

$$m_0 = im_*$$

Now the expression for relativistic mass may be rewritten as

$$m = m_* [(v/c)^2 - 1]^{-1/2}$$

As long as  $v$  remains greater than  $c$ , the new expression for  $m$  will remain real as required. The price we had to pay for having  $E$  remain real was to require the proper mass of the hypothetical faster-than-light particle to be imaginary. Let us refer to its absolute value  $m_*$  as the *meta-mass*.

Because no physical significance can be attached to an imaginary number, skeptics may wish to reject the notion of an imaginary proper mass right off. They should not be so hasty. As we have already seen, all observers are confined to subluminal velocities. Consequently there are no observers in whose frame of reference a superluminal particle would be at rest.

Proper mass of a superluminal particle is not an observable physical quantity; it is a parameter devoid of any immediate physical significance. As such this meta-mass may well be denoted by an imaginary number. Physics abounds in such parameters. What must remain real is the energy and the mass of the particle *as they appear to an observer*. Both these quantities will be real if we assume the meta-mass to be an imaginary parameter.

Next we must inquire if our generalization is in accord with the required invariance of the energy-momentum vector discussed earlier. In our simplified two-dimensional version this invariance is expressed as  $E^2 - p_x^2 c^2 = m_0^2 c^4$ . We have seen the graphical representation of this expression both for subluminal particles for which  $m_0^2$  is a real positive number, and for photons for which  $m_0^2$  is zero (figure 1). How do our hypothetical superluminal particles, with their imaginary proper mass, fit into the picture?

#### Making the picture complete

It is a remarkable aspect of the generalization that we not only find the concept of an imaginary mass consistent with the energy-momentum equation and its graphical representation, but that we actually need it to make the picture complete. We know from analytic geometry that the family of hyperbolas described by the equation

$$x^2 - y^2 = \text{constant}$$

includes not only those curves for which the constant is positive, and the degenerate case where the constant is zero, but also all those curves for which the constant is negative. By admitting the possibility of existence of particles with imaginary proper mass, we provide physical meaning to the red hyperbola in figure 1. This curve corresponds to our superluminal meta-particles. Because their proper mass  $m_0$  is given by  $im_*$ ,  $m_0^2$  becomes  $-m_*^2$ , which is a real negative number. The red hyperbola is thus a graphical representation of the energy-momentum invariance of the hypothetical superluminal particles,

$$E^2 - p_x^2 c^2 = -m_*^2 c^4$$

Let us note that the slope of this curve is everywhere greater than  $c$ . This is another way of saying that if particles with an imaginary proper mass

do exist, their velocity could never be less than  $c$ . Let us henceforth refer to these particles as *tachyons*, a name suggested in 1967 by Feinberg and derived from the Greek word  $\tau\alpha\chi\upsilon\omega$ , meaning swift. (In contrast, let us refer to all subluminal particles as *tardyons*. So as not to leave lightlike particles—photons and neutrinos—nameless, let us call them *luxons*.)

Our skeptic friends cannot be expected to give up that easily though. They may point out that  $[1 - (v/c)^2]^{1/2}$  turns up not only in the expression for mass but also in expressions for length, time interval and so on. Because these quantities are all physically measurable, they must be given by real numbers. The only way to make these numbers real is again to postulate that *proper* lengths and *proper* lifetimes of tachyons are imaginary parameters, just as their *proper* mass. Because none of the quantities that have to be symbolized by imaginary parameters are accessible to measurement, there can be no quarrel with their imaginary character.

#### The reinterpretation principle

A much more serious objection to the possible existence of tachyons is that for certain observers these particles appear to have negative energy. This is so because the red hyperbola in figure 1 crosses over into the region of  $E < 0$ . Because the explanation of this question provides the key to the resolution of other even more serious objections, let us examine this problem in some detail.

Suppose that we are at rest in a system  $S$ . We are observing a tachyon that has been emitted by a source and absorbed a while (and many miles) later by a sink. While in transit the tachyon had a velocity  $v$  relative to us. This same particle has a different velocity, say  $u$ , relative to another system  $S'$  that travels with respect to  $S$  with a velocity  $w$ .

It can be shown that the point representing the state of the tachyon in the system  $S'$  will pass into the negative energy region when the product  $w$  becomes greater than  $c^2$ . But under these very circumstances another remarkable thing happens. To the observer in the  $S'$  system the "negative-energy" particle will appear to have been *absorbed first and emitted later*. This can be seen at right in figure 2.

In this graph two sets of reference

axes are drawn, the black unprimed axes of the system  $S$  and the gray primed axes of the system  $S'$ . Each of the primed axes makes an angle  $\varphi = \tan^{-1}(w/c)$  with the corresponding unprimed axis, as required by the theory of relativity. Points  $O$  and  $P$  represent the coordinates (position and time) at which the tachyon is emitted and absorbed. In the unprimed system the event at  $P$  takes place after the event at  $O$ . In the primed system the sequence is reversed.

Such sequence reversal will take place every time the point  $P$  falls below the  $x'$  axis. We were intrigued when we noticed that this occurs under exactly the same conditions under which the energy turns negative, that is, when the product  $w$  becomes greater than  $c^2$ . As we shall see in the following, it is the interpretation of this coincidence of sign reversals that provides the key to a consistent theory of faster-than-light particles.

It is precisely by putting together the two quizzical concepts of "negative-energy" particles traveling "backward in time" that the resolution of the difficulty is found. We call it *the reinterpretation principle*. A "negative-energy" particle that has been absorbed first and emitted later is nothing else but a positive-energy particle emitted first and absorbed later, a perfectly normal situation. (In a sense, this line of reasoning is "antiparallel" to the Stückelberg-Feinman interpretation of positrons as negative-energy electrons running backward in time.<sup>6</sup>)

The two observers will disagree on the direction in which the particle travels but there is nothing disquieting about this disagreement. Classical relativity is full of examples of similar disagreements, notably with respect to simultaneity. The chief requirement of the theory is for the laws of physics to remain the same from system to system. There is no requirement whatever that events should have the same appearance.

#### Now you see it, now you don't

Keep in mind that events need not have the same appearance, particularly when collisions of tachyons with normal particles (tardyons) are envisaged. Depending on the reference frame from which the collision is viewed, the process may look completely dissimilar although in each system the collision is governed by

the same basic laws of conservation of energy and momentum.

To one observer the tachyon may appear to approach the target particle, collide with it and then bounce off it. To another observer this same process may appear as two tachyons approaching the target, colliding with it simultaneously and vanishing by transmitting all of their energy and momentum to the target particle.

Such a difference in appearance of the same event will result every time the collision leads to a "negative-energy" tachyon. Because such a tachyon travels "backward in time," the collision looks like a simultaneous fusion of two tachyons with the target particle, rather than like a "billiard-ball" collision where we have two particles before and two after the collision. In other words, the number of tachyons before and after a collision need not be the same. They may appear or disappear, depending on the relative motion of the observer.

#### *Infinite-energy source?*

What we have just said can be used to refute another major objection to the existence of tachyons. That the hyperbola describing the energy-momentum invariance of tachyons (red curve in figure 1) passes into the region of negative energy has been held to imply the existence of an infinite source of energy. The argument goes like this. Two tachyons of zero energy collide simultaneously with a target particle having energy  $E_0$ . In the collision process each tachyon acquires an amount of negative energy  $-E_1$ . For energy to be conserved, the target particle must now have an energy  $E_0 + 2E_1$ . Tachyons are thus viewed as vehicles for "pumping" energy into an ordinary particle by themselves acquiring negative energy. Because there is no limit to the amount of negative energy they could assume, there should then be no limit, according to the argument, to the positive amount of energy that could be obtained from them.

This objection is fallacious because it ignores the sequence reversal that invariably accompanies the appearance of negative energies. In the above collision we would not see two tachyons approaching the target and then two tachyons receding. The two "receding" tachyons would also appear as approaching, each carrying positive energy  $+E_1$ . By taking sequence reversal into account, the ob-

jectionable source of infinite amounts of energy disappears.

#### *No communication with the past*

The most subtle of all objections against faster-than-light particles was raised as early as 1917 by Richard C. Tolman in his book *The Theory of Relativity of Motion*.<sup>7</sup> This objection is quite basic.

In a simplified form the argument goes as follows. Suppose an observer A in a reference system S has a source of infinitely fast particles. At a time  $t = t_0$  he sends out a burst  $\tau_1$  of these particles to an observer B in a system S' that is receding from S at a uniform rate  $w$ . Let us assume that the reception of the signal in S' triggers a similar burst  $\tau_2$  of particles that now travel with infinite velocity relative to S'. Signal  $\tau_2$  will arrive in S at a time  $t_1$  that is earlier than  $t_0$ .

This sequence of events is a causal loop: The effect (reception of signal  $\tau_2$  by A) takes place before the cause (sending of signal  $\tau_1$  by A). It can be shown that the same argument applies not only to infinite velocities, but to all velocities greater than  $c^2/w$ , where  $w$  is the relative velocity of the two observers.

It must have been this argument that provided inspiration for Reginald Buller's limerick:

*There was a young lady named  
Bright  
Whose speed was far faster than  
light  
She went out one day  
In a relative way  
And returned the previous night.*

This objection, although in principle quite profound, still suffers from the same defect as the preceding one. It fails to take into account the relative sequence reversal accompanying propagation of ultraluminal signals whose velocity is greater than  $c^2/w$ . When this effect is introduced into the argument, the causal circle breaks down. There is no more back and forth exchange of signals. In each case the observer believes that he is sending out both signals. Similar reinterpretation invalidates the difficulties encountered by Helmut Schmidt<sup>8</sup> in his investigation of the causality objection against waves propagating at superluminal velocities.

Nonetheless, there are more sophisticated versions of the causality argument that can be resolved only by a close scrutiny of the hypotheti-

cal process of tachyon emission and absorption. Such considerations lead from macrocausality to microcausality where thermodynamic fluctuations and quantum-mechanical uncertainties play a decisive role. The relevance of the second law of thermodynamics to causality arguments regarding the possibility of existence of superluminal signals was analyzed by Terletski<sup>9</sup> in 1960. Because he ignored the possibility of reinterpreting "antisignals" propagating backward in time as positive-energy signals propagating forward in time, he concluded that any superluminal signals could only arise to the extent of stochastic entropy fluctuations. This same flaw mars his otherwise most valuable monograph *Paradoxes in the Theory of Relativity*.<sup>2</sup>

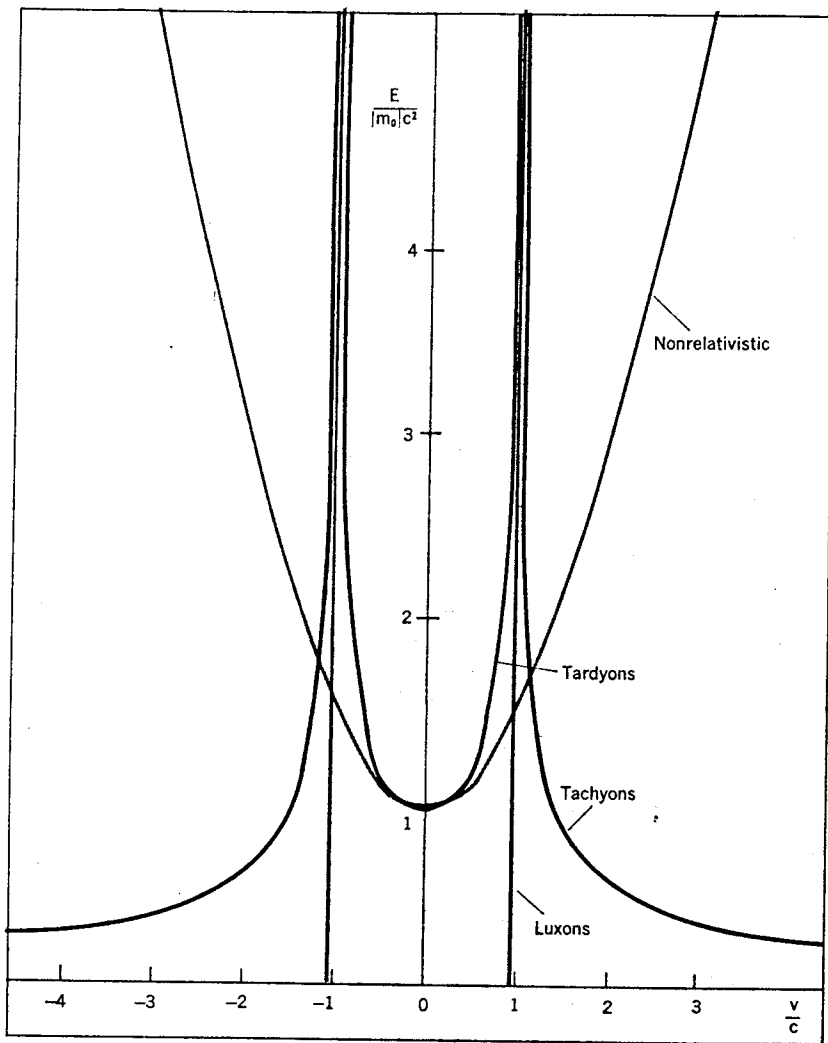
Summing up, the causality objections against the logical consistency of the tachyon hypothesis are at best not compelling, and possibly altogether unfounded. Still, much room for thought remains.

#### *Accelerate upon loss of energy*

Soon after we had shown that the arguments against the possibility of existence of superluminal particles are either flawed or inconclusive, several enterprising physicists initiated a search for these particles.<sup>10</sup> To get an insight into some of the avenues of approach open to experimenters, and to be able to appreciate the difficulties they are facing, let us take a closer look at some of the surmised properties of tachyons.

Let us start by plotting the energy  $E$  and the momentum  $p$  of a particle as a function of its velocity. In this way we shall be able to get a comparative view of properties of each of the three classes of particles, the subluminal, the luminal and the hypothetical superluminal particles. In the energy graph of figure 3 we first note the black U-shaped curve bounded on both sides by the pink lines at  $v = c$ . This black curve corresponds to tardyons (normal particles) whose energy tends to infinity as they approach the velocity of light. Because these particles are also observable at rest, their proper mass is given by a real number. These are the particles we are all made of.

The two vertical lines represent the luxons (photons and neutrinos) with zero proper mass whose velocity in free space is confined to the value of  $c$ . The domain of the tachyons begins beyond the pink lines. Variation



**RELATIVISTIC ENERGY VS. VELOCITY.** Tardyons have energy even at rest. Their energy is seen to increase indefinitely as the limiting velocity of  $c$  is approached. The vertical pink lines, which represent luxons, tell us that no matter what energy one of these particles may have, its speed will be  $c$ . The red curve reveals the singular behavior of the tachyons. Upon loss of energy they would accelerate; when energy is imparted to them they would slow down. To retard them to their lowest possible speed, which is  $c$ , an infinite amount of energy would have to be provided. —FIG. 3

of energy with velocity is described by the red curve. Inspection of this curve leads to some rather uncommon conclusions. Because the red curve rises monotonically as the velocity of  $c$  is approached, we are forced to conclude that energy must be supplied to a tachyon, rather than taken away from it, if it is to be slowed down. If it is to be decelerated to its lowest possible velocity, which is the velocity of light, an infinite amount of energy would have to be imparted to it. Conversely, upon loss of energy a tachyon will accelerate. This is a corroboration of the result deduced by Arnold Sommerfeld<sup>4</sup> around the turn of the century. This

conclusion, which seemed so absurd at that time, is seen here to be a natural consequence of the relativistic theory.

#### "Transcendent" tachyons

It was also Sommerfeld who, at that early stage, had inferred from Maxwell's electromagnetic theory that electrically charged faster-than-light particles would spontaneously radiate electromagnetic waves.<sup>4</sup> This means that soon after their emission charged tachyons are likely to dissipate all of their energy. In so doing they would attain in the limit the state of infinite velocity. Because the red curve goes to zero as the velocity  $v$  approaches

infinity, we are led to another remarkable result: Infinitely fast tachyons carry no energy.

To better comprehend the features of this "transcendent" state, let us compare the energy-velocity curve of figure 3 with the corresponding curve in the momentum-velocity graph of figure 4. As the velocity increases, the momentum tends to a finite nonzero value. This can also be seen in figure 1 where the point corresponding to the state of zero energy falls on the apex of the red hyperbola. In a sense, we have here an analog to the state represented by the apex of the black hyperbola, which denotes the state of rest (zero momentum) of a normal particle. In a closed universe this analogy goes even further. The infinitely fast tachyon is present everywhere on the supercircle of its trajectory, which corresponds to the quantum-mechanical situation of a particle at rest, with the ensuing total uncertainty as to its position.

For all we know, the world may be crisscrossed by tachyons, just as it is swarming with the elusive neutrinos. If and how these meta-particles may be detected no one can say; much more work regarding possible tachyon interactions is needed if the search for tachyons is to become less fortuitous.

A transcendent (infinitely fast) tachyon should be particularly difficult to detect, as it has no energy or momentum to spare. It may appear that it could signal its previous existence by giving all of its momentum to a stationary particle whose recoil would then be observed. But this process is forbidden because to recoil the absorbing particle needs not only momentum but also energy.

The requisite of energy and momentum conservation can be met only under very restricting kinematic conditions when the absorbing particle is itself in motion as shown in figure 5. In this case the absorption of a single neutral zero-energy tachyon would look very much like an elastic collision of the absorbing particle with an infinitely massive object: The energy of the particle would remain unaltered, but the direction of its motion would abruptly change. Should the tachyon have been carrying an electric charge, its absorption would be accompanied moreover by a corresponding change in the charge of the absorbing particle.

Notice that in the above process the transfer of momentum occurs at in-

finite speed. In classical physics such instantaneous "action-at-distance" has a simple model: a rigid body! Hence tachyons, in a sense, reintroduce the concept of rigid bodies into relativistic quantum mechanics.

#### *First experimental search*

It appears that a natural place to look for tachyons is the immediate vicinity of possible sources of these particles. Radioactive beta decay is one such source. Although a satisfactory theory exists, that accounts for most of the details of this process, there is still room for conjecturing that, to ever so small a degree, tachyons may be participating in it, along with beta rays (nuclear electrons) and neutrinos. Prompted by our 1962 paper,<sup>1</sup> Torsten Alväger and Peter Erman, physicists at the Nobel Institute in Stockholm, carried out in the years 1963-65 an extensive search for charged meta-particles using a strong thulium-170 beta source. A first object of their search was a particle whose meta-mass would equal the mass of a normal electron. To separate such "meta-electrons," should any be emitted, from the normal electrons, they deflected the charged radiation by means of a magnet (a double-focusing beta spectrometer) onto a semiconductor counter. The magnet selected particles of a definite momentum, and the counter recorded their energy. At equal momentum, electrons and meta-electrons are expected to carry different amounts of energy. It was hoped that this difference could be used to detect the presence, if any, of the meta-electrons. The results of this investigation were negative.<sup>11</sup>

#### *Cerenkov radiation*

Another experiment, again broached by Alväger, and carried out together with Michael Kreisler at the Princeton-Pennsylvania Accelerator, follows the approach that we suggested in our first paper on meta-relativity.<sup>1</sup> Charged meta-particles are to be detected by recording the electromagnetic waves they are expected to emit. This Cerenkov radiation is analogous to the bow wave of a ship, or to the shock wave of a supersonic airplane. The direction of propagation of this radiation relative to the particle trajectory is uniquely determined by the particle velocity. Moreover, in a vacuum only tachyons can travel faster than light; hence they emit Cerenkov

radiation. Thus an unambiguous identification of electrically charged superluminal particles should be possible.

An essential improvement on our original idea was the introduction by Alväger of a strong electric field at the presumed tachyon source. This field is directed so as to supply emitted tachyons with energy and thereby enable them to radiate over a longer portion of their trajectory. A first series of measurements, in which the attempt was made to produce tachyons in lead by bombarding it with gamma rays from a 5-millicurie cesium-134 source, was recently concluded.<sup>12</sup> Again no trace of tachyons was found. Further experiments along these lines are under way with improved apparatus.

Because no Class-II particles (photons and neutrinos) carry a charge, it is quite possible that Class III particles are also all electrically neutral. A neutral particle can be detected only indirectly, and the difficulties which experimenters face in trying to spy neutral meta-particles are formidable. Notwithstanding, a project whose aim is to ferret out neutral tachyons is being carried out by Alväger at Indiana State University. His setup is ingeniously simple. It parallels the early work by Irène Joliot-Curie and Frédéric Joliot on the "very penetrating" gamma rays that later turned out to be neutrons. Working below the threshold for neutron production, Alväger is looking for a penetrating radiation component other than neutrons.

Another type of experiment, one which does not rely on the interaction of tachyons with matter for their detection, may soon be undertaken at Argonne and Brookhaven by a group of seasoned high-energy experimenters using their powerful missing-mass spectrometer.<sup>13</sup> High-energy protons striking a deuteron target produce (among other things)  $\text{He}^3$  plus something else. If that "something else" is a tardyon or a luxon,  $\text{He}^3$  recoils are restricted to a limited forward range of angles. Should  $\text{He}^3$  nuclei be detected in the spectrometer when it is set at a larger angle, the missing reaction product can only be a tachyon.

#### *Quantization*

The hypothesis of faster-than-light particles must also be approached on another plane. It is important to

make sure that meta-particles are consistent not only with relativity theory but also with quantum theory. In other words, we must ask the question if there is room for tachyons in the existing theories of the subatomic world.

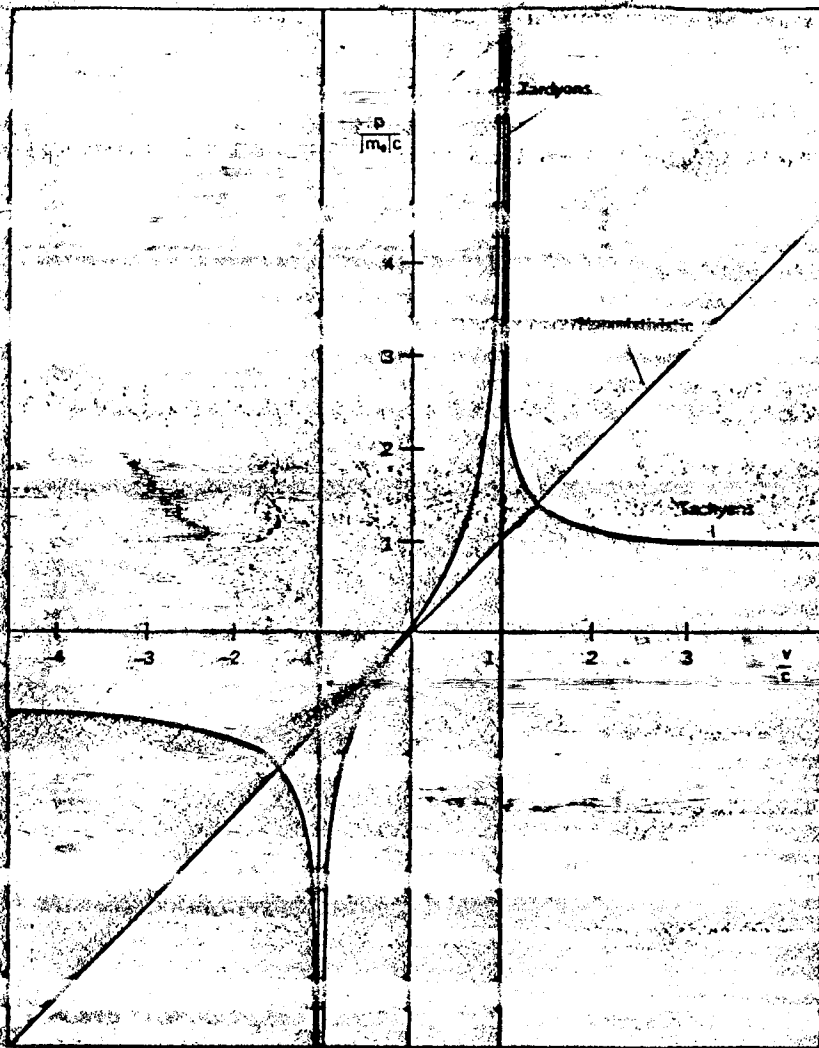
None of these theories carry a restriction on particle velocity as such. In fact they provide for the possibility of propagation of microscopic disturbances with arbitrarily high speeds, or admit solutions involving spacelike quanta. If these solutions are rejected, this is done solely on grounds of their alleged incompatibility with relativity theory and the causality principle. We hope to have shown that these reasons are not compelling and hence that it is reasonable to try to devise a quantum theory of superluminal particles. The apparent paradoxes of faster-than-light particles will reappear in any such attempt and they must be satisfactorily resolved. Such a quantum theory would be expected to parallel our classical theory of tachyons.

The first one to have attempted to work out the details of a relativistic quantum theory of faster-than-light particles was Sho Tanaka at Kyoto University.<sup>14</sup> Because he was not aware of the possibility of reinterpreting negative-energy particles as positive-energy particles propagating forward in time, he conceived of faster-than-light particles as virtual objects only. Moreover, the energy and momentum of the tachyon field in his theory do not transform like components of a four-vector, which makes his interesting work unacceptable as a relativistic theory of tachyons.

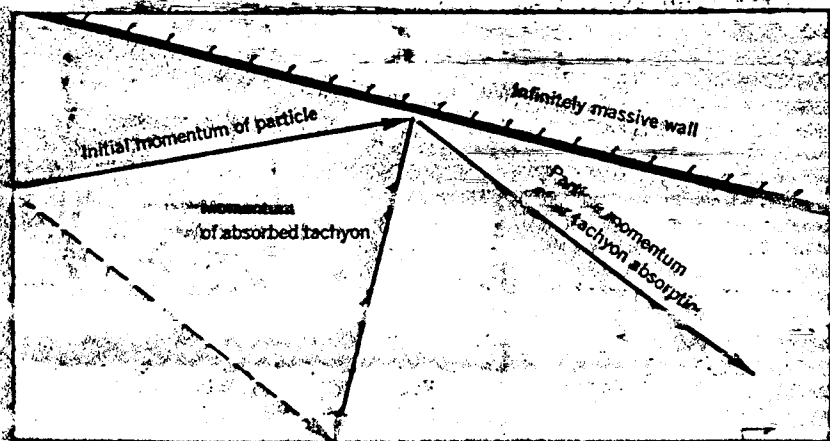
More recently, using our reinterpretation of negative energies, Feinberg has modified and imaginatively innovated Tanaka's work.<sup>3</sup> Nonetheless, some questions as to the invariance of the energy-momentum four-vector remain. Michael Arons of the City University of New York and one of us (Sudarshan) have proposed a novel approach that appears to obviate these difficulties.<sup>15</sup> This approach has been used to construct a quantum field theory of interacting tachyons.<sup>16</sup>

Still, much exploratory theoretical work remains to be done, particularly on the interactions in which tachyons may participate. The question of the existence of faster-than-light particles is closely linked with the possibility that we may find new, as yet undis-





**RELATIVISTIC MOMENTUM VS. VELOCITY.** The momentum of a tachyon tends to infinity as particle velocity approaches  $c$ . Laxons may have any momentum value, but their velocity will always remain at  $c$ . As the velocity of a tachyon increases indefinitely, its momentum approaches the limiting value of  $p = m_0 c$ . —FIG. 4



**TACHYON ABSORPTION.** To satisfy energy and momentum conservation when a transcendent tachyon is absorbed by an ordinary particle, the vector diagram representing the process must be isosceles (because the transcendent tachyon can only change the direction, and not the magnitude, of the momentum of the absorbing particle). Such an absorption would look very much like an elastic collision between the absorbing particle and an infinitely massive object. —FIG. 5

covered interactions characteristic of superluminal particles.

Although we think that superluminal particles do exist, the only unequivocal way to ascertain that they do is by actually detecting them. So far experimenters must grope very much in the dark, as nothing is known about the interactions in which tachyons are likely to participate. Further work on the part of experimenters is needed to make the task of the experimenters more manageable.

We find the question of existence of the hypothetical superluminal particles to be a challenging new frontier. Regardless of the outcome of the search for tachyons, investigations in this field most invariably lead to a deeper understanding of physics. If tachyons exist, they ought to be found. If they do not exist, we ought to be able to say why not.

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