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Particles That Go Faster than Light

Efforts to detect such particles, named tachyons, have yielded only negative results. Contrary to common belief, however, their existence would not be inconsistent with the theory of relativity

by Gerald Feinberg

Since the formulation of the special theory of relativity by Einstein in 1905 and its subsequent verification by innumerable experiments, physicists have generally believed that the speed of light in a vacuum (about 300,000 kilometers per second) is the maximum speed at which energy or information can travel through space. Indeed, Einstein's first article on relativity contains the statement that "velocities greater than that of light... have no possibility of existence."

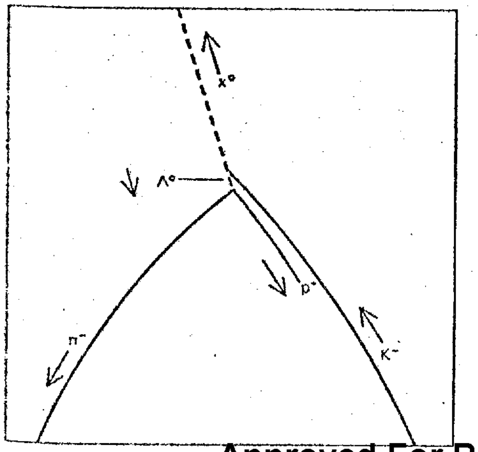
The basis of Einstein's conclusion was his discovery that the equations of relativity implied that the mass of an object increases as its speed increases, becoming infinite at the speed of light (which is usually denoted c). Since the mass of a body measures its resistance to a change of speed, when the mass becomes infinite the body cannot be made to go any faster. Stated somewhat differently, the relation between energy and speed implied by relativity is such that as the speed of a body approaches c its energy becomes infinite. Since this energy must be supplied by whatever is accelerating the body, an infinite source of energy would be needed to speed up a body to the speed of light from any lower speed. No such infinite energy source is available, and so it is impossible to make a body go from less than c to c.

Furthermore, if a body could somehow be made to go from a speed less than c to one greater than c, the same relativity equations imply that its energy and momentum would become imaginary numbers, that is, numbers containing a square root of a negative number. This situation does not seem to have any physical meaning. Objects with imaginary energy clearly cannot exchange energy with objects having real energy and hence cannot affect them. Accordingly, such objects could not be detected by real instruments, and can be said not to exist. Within the context in which Einstein worked, where the properties of objects varied continuously and where the creation of new objects was not considered, it therefore seemed a logical conclusion that no form of energy, and hence no matter, could travel faster than light.

With the development of subatomic physics, however, the context has changed considerably. We now know that the subatomic particles can easily be created or destroyed, and that in their mutual interactions their energies and other properties change discontinuously, rather than in the smooth way envisioned in classical physics. Therefore one can imagine the creation of particles already traveling faster than light, and so avoid the need for accelerating them through the "light barrier" with the attendant expenditure of infinite energy.

In addition, one can consistently require that such particles *always* travel at speeds greater than c, which obviously cannot be the case for known particles. If one assumes these conditions, there is no problem in satisfying the requirement that the particles carry real energy and momentum. This can be done mathematically by allowing a certain constant that appears in the relation between energy and speed to be an imaginary number, rather than a real number as it is for ordinary particles [*see top illustration on next two pages*]. This constant is usually known as the rest mass, because for ordinary objects, which can be slowed to rest, it gives the value of the object's mass when at rest.

For the hypothetical faster-than-light particles, which can never be brought to



SEARCH FOR TACHYONS led the author and his colleagues at Columbia University to scrutinize thousands of bubble-chamber photographs such as the one on the opposite page for indirect evidence of the occurrence of neutral tachyons among the by-products of certain subatomic interactions. The photographs, which were originally made at the Brookhaven National Laboratory for another experiment, were analyzed by means of the "missing mass" method. In this approach the energy and momentum of the charged particles in the reaction are measured directly from the configuration of the tracks they make in the bubble chamber. Although neutral particles are usually not observed directly, it is possible to tell from the values measured for the charged particles whether or not any neutral particles have been produced, and also what the missing mass of these particles is. In this case a negative K meson (K^-) was allowed to come to rest and be captured by a proton in the hydrogen bubble chamber (*see diagram at left*). One neutral particle, a lambda hyperon (Λ^0), was produced and was detected through its decay into two charged particles, a negative pion (π^-) and a proton (p^+). In order to conserve energy and momentum, another neutral particle (x^0) had to be produced in this reaction, but the experimenters were able to show that this particle was probably a neutral pion (π^0), not a neutral tachyon (t^0).

a

$$E = \frac{mc^2}{\sqrt{1-(v^2/c^2)}}$$

b

$$E_0 = mc^2$$

c

$$E = \frac{\mu c^2}{\sqrt{(v^2/c^2)-1}}$$

EQUATIONS OF RELATIVITY pertinent to a discussion of the possible existence of tachyons are shown on these two pages. The relation between energy and speed that must be satisfied by any object obeying the special theory of relativity is given by equation *a*, where E is the energy of the object, v is its speed and c is the speed of light. The quantity m is known as the rest mass of the object and is related to the energy E_0 that the object has at rest by equation *b*. For a body traveling faster than light v^2/c^2 is greater than one; consequently the quantity under the square-root sign in equation *a* is negative, and the denominator of the quantity that is equal to E in the same equation is an imaginary number (that is, a number containing a square root of a negative number). In order to make E a real number one must choose m to be an imaginary number, say $m = \mu\sqrt{-1}$. As long as the object always travels at more than the speed of light, its energy, which can be written in the form shown in equation *c*, will then be real, because $(v^2/c^2) - 1$

rest, this constant is not directly measurable, and there is no need for it to be real. The square of the rest mass, however, can be expressed in terms of the measurable energy and momentum of an object and hence can be directly measured. For ordinary objects the rest mass squared is found to be a positive real number. For faster-than-light particles it would be a negative number; indeed, this fact is the basis of one attempt to detect such particles. It should be mentioned that there is a third class of particles, including photons (light quanta) and neutrinos, for which the rest mass is zero and which always travel at c.

The possibility therefore seems to exist that there is a new kind of natural object: one that always travels faster than light. The latter statement is invariant, in the sense that if a body travels faster than light with respect to one observer, it will do so with respect to any other observer himself traveling in relation to the first at less than the speed of light. These are the only observers of which we have any knowledge. It must be stressed that all the considerations given here and below are consistent with the special theory of relativity, and assume the validity of its equations for describing particles, even if the particles travel faster than light.

In anticipation of the possible discovery of faster-than-light particles, I named them tachyons, from the Greek word *tachys*, meaning swift. In order to show how physicists have gone about searching for tachyons, I shall describe some of the properties that would distinguish them from ordinary particles.

One such property follows directly from the relation between energy and speed given in the equations of relativity. We have seen that for ordinary particles, as their speed increases, their energy also increases. For tachyons, in contrast, an increase in speed results in a decrease in energy. Hence a tachyon that was losing energy by interacting with matter or by radiating light would speed up, whereas a tachyon that was gaining energy from some outside source would slow down, and its speed would approach c from above rather than below. Thus c acts as a limiting speed for tachyons also, but the limit is a lower limit, rather than the upper limit that it is for ordinary objects.

In the limiting case of a tachyon moving at infinite speed its total energy would be zero, although its momentum would remain finite. It should be emphasized that for a tachyon at infinite speed it is the total energy that is zero and not just the kinetic energy. For an ordinary particle with nonzero rest mass the total energy can never vanish.

The condition of infinite speed is, however, not invariant but depends on the observer. If a tachyon were moving at infinite speed as seen by one observer, its speed as measured by another observer in motion with respect to the first would not be infinite but rather some finite value between c and infinity. This is another way of phrasing Einstein's discovery that simultaneity for events at different points in space has only a relative and not an absolute meaning.

A second property of tachyons that substantially distinguishes them from ordinary particles comes about from the way measurements of energy and time change with the relative motion of observers. For ordinary particles the energy is a number whose value will change from observer to observer but that will always be positive. A tachyon whose energy is positive for one observer, however, might appear to be negative to other observers in motion with respect to the first. This can occur for tachyons because of the equation of relativity that states that the energy of a tachyon is always less than its momentum multiplied by c; this ambivalence does not apply to ordinary particles. If negative-energy tachyons were emitted by the unexcited atoms of ordinary matter, this would cause the emitting atoms to be unstable, and hence the existence of such tachyons would contradict the known stability of ordinary matter.

The change in the sign of the energy of a tachyon from observer to observer is connected to another peculiar property of tachyons. If an ordinary particle is seen by one observer to be emitted (say by an atom A) at one time and absorbed elsewhere (by atom B) at a later time, then any other observer in relative motion will see this process in the same way—as emission by atom A followed at a later time by absorption by atom B—although the time interval will vary from observer to observer. Tachyons, however, because they would travel faster than light, would move between points in "space time" whose time-ordering can vary from observer to observer. Therefore if one observer saw a tachyon emitted by atom A at one time t_1 and absorbed by atom B at a later time t_2, another observer could find that the time t_1' that he measures corresponding to t_1 is later than the time t_2' that he measures corresponding to t_2. If this occurs, the latter observer would naturally want to interpret what happens in the following way: The tachyon is emitted by atom B at the earlier time t_2' and absorbed by atom A at the later time t_1'.

It can be seen that this interchange of emission and absorption also removes the problem of negative-energy tachyons, since the reversal between observers of the sign of the energy occurs if and only if the reversal in time-ordering occurs. Since the emission of a negative-energy particle and the absorption of a positive-energy particle traveling in the d

$$p = \frac{mv}{\sqrt{1-(v^2/c^2)}}$$

e

$$E^2 - p^2c^2 = m^2c^4$$

f

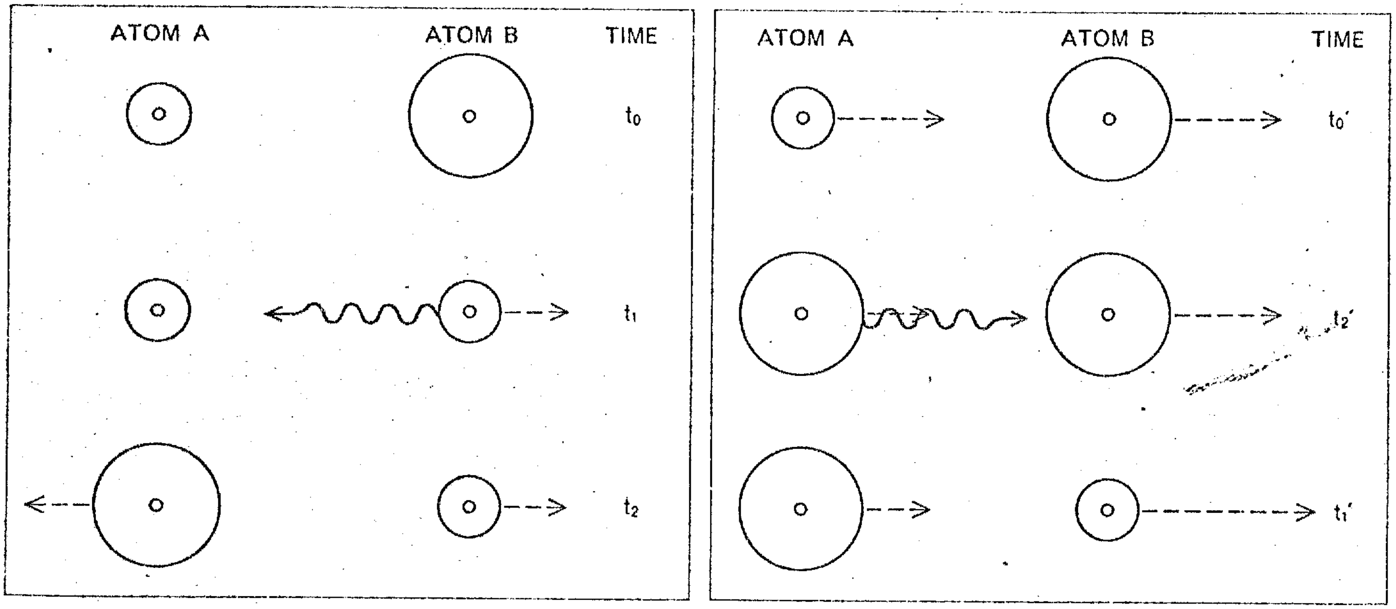
$$\frac{v}{c} = \frac{pc}{E}$$

will in this case be a positive quantity. The momentum p of any body obeying the special theory of relativity can be expressed in terms of its speed by means of equation *d*, in which m is independent of v. It follows from a combination of this equation and equation *a* that the quantity represented by equation e does not depend on v and hence is the same for all observers. The quantity m^2 (called the rest mass squared) is then a constant for each object, even for bodies such as photons (light quanta) or tachyons, which are never at rest. One can also deduce from these relations equation *f*, which implies that if v/c is less than one (as it is for ordinary objects), then pc/E is less than one, $E^2 - p^2c^2$ is greater than zero and hence m^2 is positive. On the other hand, for objects that go faster than light v/c is greater than one, $E^2 - p^2c^2$ is less than zero and hence m^2 is negative. In either case the rest mass squared should always have the same value for a given object and can be measured by measuring the energy and momentum for the object.

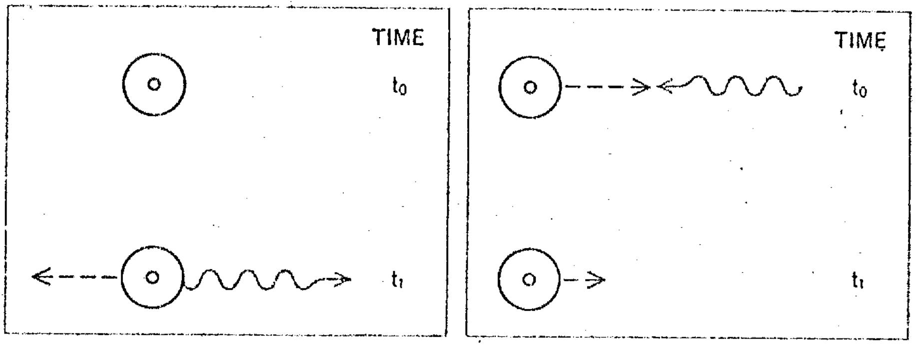
opposite direction produce the same effect on the energy of a system, it is always possible for any observer to insist that all tachyons have positive energy, and that emission and absorption take place in the familiar time-ordering, thus removing the instability problems that negative-energy tachyons would present. This interpretation of the negative-energy states of the tachyon was first proposed in 1962 by O. M. P. Bilaniuk, E. C. G. Sudarshan and V. K. Deshpande of the University of Rochester.

The description given above is in agreement with the principle of relativity requiring that any process that can be seen by one observer must also be a possible process for any other observer. The principle does not require, however, that different observers agree on the interpretation of any individual process. Hence there is no contradiction of the principle of relativity involved in the fact that one observer views as absorption what another views as emission, since both absorption and emission can be witnessed by either observer under suitable conditions. The novelty of tachyons is that emission and absorption must be converted into each other by a change in the observer's velocity, and this implies a closer connection between the two processes than exists for ordinary particles.

It also implies that the number of tachyons in some region of space must vary from observer to observer. Suppose one observer views the process of emission of a tachyon by an atom, with the subsequent escape of the tachyon to infinity. A second observer may view the same process as the tachyon's coming in from outer space and being absorbed by the atom. Hence the two observers will disagree on the number of tachyons present in the past and in the future. Again this situation differs from that for ordinary particles, where the number of particles present at any time is independent of the observer. A detailed theory of the interaction of tachyons with



PECULIAR PROPERTY OF TACHYONS arises from the fact that the time-ordering of points in "space time" between which a faster-than-light particle would move could vary from observer to observer. Thus a process that appears to one observer as emission of a tachyon by one atom followed by absorption of the tachyon by another atom could be reversed for another observer moving with respect to the first. In this schematic representation of such a phenomenon the first observer (*left*) sees atom A at rest in its ground state and atom B at rest in an excited state at time t_0. At t_1 atom B emits a tachyon (*color*), dropping to its ground state and recoiling (*broken arrow*). At t_2 this tachyon is absorbed by atom A, which jumps to an excited state and also recoils. In this situation the time-ordering would be t_0, t_1, t_2. To another observer (*right*), for whom emission and absorption have been exchanged, the same process would appear as follows: Atom A is now moving at time t_0' but is still in its ground state. It emits a tachyon at t_2' and jumps to an excited state, losing some of its translational energy. Atom B, which is moving and in an excited state at t_0', absorbs the tachyon at t_1', dropping to the ground state and gaining translational energy. For this observer the time sequence would be t_0', t_2', t_1'.



POPULATION OF TACHYONS in a region of space at any given time would also vary from observer to observer. One observer (*left*) would view the emission of a tachyon by an atom at rest, with the subsequent recoil to the atom and the escape of the tachyon to infinity. A second observer (*right*) would view the tachyon coming in from outer space and being absorbed by a moving atom, causing the atom to lose translational energy.

matter, which has not yet been worked out, would have to take these features into account.

Having convinced ourselves that the existence of faster-than-light particles does not imply any contradiction of relativity, we must nevertheless leave the determination of whether such objects really happen in nature to the experimental physicist. In the present state of theoretical physics there are few circumstances in which theories flatly predict that certain objects must exist. Instead these theories generally enable us to describe various hypothetical objects, and we must determine by experiment which objects exist in reality. For example, present theories allow for the description of particles with an electric charge equal to half the electron's charge and a mass six times the electron's mass, but we are fairly confident from experiments that no such objects are to be found in nature. We do not, however, know why this is so, and we may not know until we have more fundamental theories than we have now.

The situation with tachyons is similar; to settle the issue of their existence one turns to the experimentalist. This is not to say, however, that he must hope to stumble on them somewhere in the universe. One feature of all particle theories based on relativity is that they imply that if particles of some type exist at all, it must be possible to create them from other particles, provided that enough energy is available. For tachyons this condition of having enough energy is particularly easy to satisfy, because fast tachyons have very low energy. It is therefore easy to set up experimental conditions under which tachyons could be produced from other particles if tachyons indeed exist. The only unknown factor, apart from their existence, is the rate at which they would be produced. Among known particles the production rate varies by many orders of magnitude. Pions, for instance, are produced quite readily, whereas neutrinos are very difficult to produce. Therefore whereas an experiment with a positive result could establish the existence of tachyons, a negative result could at best establish an upper limit for the rate at which tachyons are produced from the particles involved. Only the demonstration that this rate, in all reactions studied, is much less than the rate of production of any other particles would lead to the conclusion that tachyons probably do not exist at all.

Two kinds of experimental attempt to produce and detect tachyons have been made so far. These experiments are sensitive to different types of tachyon and use very different methods, and so they will be discussed separately. The first experiment, which was done two years ago at Princeton University by Torsten Alväger and Michael N. Kreisler, was a search for electrically charged tachyons. It has been known for 35 years that electrically charged particles can be produced in pairs by the passage of high-energy gamma rays (photons) through matter. Many of the known types of charged elementary particle have been made in this way. It follows that if electrically charged tachyons exist, it should be possible to produce them from photons. As indicated above, the fact that tachyons can occur with zero total energy means that a pair of them can be produced by a photon of any energy, whereas a pair of ordinary particles can only be produced by a photon with an energy greater than twice the individual particle's rest energy.

Assuming that charged tachyons are produced, how can they be detected and distinguished from other charged particles that may be produced in the same way, such as an electron-positron pair? A convenient way to do this is to make use of the fact that charged tachyons would continuously radiate photons even when passing through empty space. This phenomenon, known as Cerenkov radiation after the Russian physicist who first observed it from electrons in 1937, occurs whenever a charged object moves through a substance at a speed higher than the speed of light in the substance. Thus an electron moving through glass at a speed greater than about .7 *c* will emit Cerenkov radiation, since the speed of light in glass is about .7 times its value in free space. Since the speed of a tachyon is greater than that of light in free space, one would expect the tachyon to emit Cerenkov radiation even in a vacuum, and a calculation confirms the expectation: The light would be emitted at a characteristic angle depending only on the speed of the tachyon [*see illustration on opposite page*]. Calculation also shows that a tachyon with the same charge as an electron would lose energy so quickly through Cerenkov radiation that even if it is produced with a very high energy, its energy will drop below one electron volt before it has traveled one millimeter. When this happens, the Cerenkov radiation will no longer include visible light, whose photons have energies of more than two electron volts. Instead the radiation will consist of infrared and longer wavelengths, which are a good deal harder to detect. In order to avoid this problem the Princeton experimenters used the ingenious scheme of allowing any tachyons produced to move through a region empty of matter but containing an electric field. The electric field would transfer energy to charged particles, but it would not cause ordinary particles to radiate detectable amounts of light. A tachyon passing through the region, on the other hand, would reach an equilibrium between gaining energy from the field and losing energy through radiation, and would therefore continue to radiate photons of about the equilibrium energy. By fixing the value of the field, the experimenters were able to make this equilibrium energy correspond to photons of visible light, thus making the radiation easy to detect.

In their experiment Alväger and Kreisler used gamma rays from a radioactive cesium source. These high-energy photons hit a lead shield that prevented them from reaching the detector directly. Beyond the shield was a high-vacuum region containing two parallel plates with an electric field between them [*see illustration on next page*]. Pairs of charged tachyons could be produced by the photons in passing through the lead, and some of these would escape (since they speed up while losing energy) into the region between the plates. A photomultiplier tube was used to detect any photons radiated by the tachyons passing through the region.

No positive indication of Cerenkov radiation, and hence no evidence for tachyon production, was found in this experiment. More precisely, the rate of production of tachyon pairs was found to be less than one ten-thousandth of the known rate for producing electron-positron pairs by photons of slightly higher energy. The mass-energy relation satisfied by tachyons makes it highly unlikely that this rate can depend very sensitively on either the photon energy or the tachyon mass. Therefore it seems, with one qualification to be discussed below, that tachyons with a charge approximately equal to the electron's charge simply do not exist. Tachyons with a charge differing from the electron's charge by more than a factor of two in the upward direction or .1 in the downward direction would probably not have been seen in the experiment. Of course, uncharged tachyons, which would not emit Cerenkov radiation, would not have been detected either.

The qualification that must be made to these conclusions is that it is uncertain whether or not tachyons might lose energy through processes other than Cerenkov radiation. One such possibility is that a single tachyon could decay into several tachyons, each of lower energy. If there were such other energy-loss mechanisms, the amount of Cerenkov radiation actually emitted might be smaller than the anticipated amount, and the value of the upper limit for the number of tachyons produced would be too low. For this reason, and because we are in general ignorant about possible interactions of tachyons with matter, it was thought desirable to search for tachyons in a manner independent of how they interact after being produced.

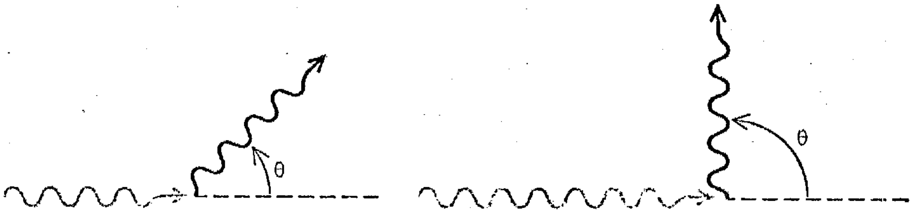
Such an experiment was performed recently by a group at Columbia University consisting of Charles Baltay, Ralph Linsker, Noel K. Yeh and myself. The method used was a well-known one for searching for new elementary particles; it is called the missing-mass method.

In this approach a large number of reactions among elementary particles are examined in a detecting apparatus (in our case a bubble chamber) in which the momentum and energy of the charged particles in the reaction can be measured. In some fraction of the reactions a number of neutral particles will be produced in addition to the charged particles observed. These neutral particles are usually not observed directly, and it is often not even known how many of them are produced. By applying the laws of the conservation of energy and momentum, however, it is possible to tell from the values measured for the charged particles whether or not any neutral particles have been produced, and also what the momentum and energy carried away by these particles are. The latter quantities, defined as the difference between the energy or momentum of the particles observed going into the reaction and the energy or momentum of the particles observed emerging from the reaction, are known as the missing energy and momentum. If there are no missing energy and momentum in a given event, it suggests that no other particles have been produced.

From the missing energy and momentum in a specific event one can calculate a "missing mass squared" for the event. If exactly one missing neutral particle has been produced, the missing mass squared is the actual mass of the particle squared. A number of elementary particles, such as the neutral eta meson, have been detected in this way. The obvious advantage of the method is that nothing need be assumed about what the missing particle does after being produced. Its presence is indicated simply by the mass it represents, which is inferred from measurements made on known particles.

If a single neutral particle of a specific kind is produced, the missing mass will have the same value in each event. When more than one neutral particle is produced, the missing mass will not have a unique value but will vary from event to event, depending on the angle between the directions of the two neutral particles, among other things. Hence those events containing several neutral particles will in general show a distribution in the missing mass squared over a range of values. Since there is no way of knowing a priori whether a given event contains one or many neutral particles, the experimenter must combine all events to obtain an overall distribution of missing mass squared [*see illustration on page 77*]. The production of single particles will usually stand out as a peak at a specific value in the distribution of missing mass. If there is no such peak, it usually means that the production of a single neutral particle is improbable compared with the production of several neutral particles.

In using the missing-mass method to search for neutral tachyons, we note that if a single neutral tachyon is produced, the missing mass squared is a negative number. Furthermore, if two or more neutral tachyons are produced, the missing mass squared can be either positive or negative depending on the configuration. If the missing mass squared is observed to be negative for any events, then necessarily at least one tachyon must have been produced among the neutral particles. In other words, a collection of ordinary particles cannot have a negative mass squared. Hence in order to investigate neutral-tachyon production by means of specific incident particles, one makes a plot of the missing mass squared for all events and looks for any events with a negative missing mass squared. The production of single tachyons would give a peak in the missing-mass-squared distribution at some negative value, whereas the production of two neutral tachyons would give a broad



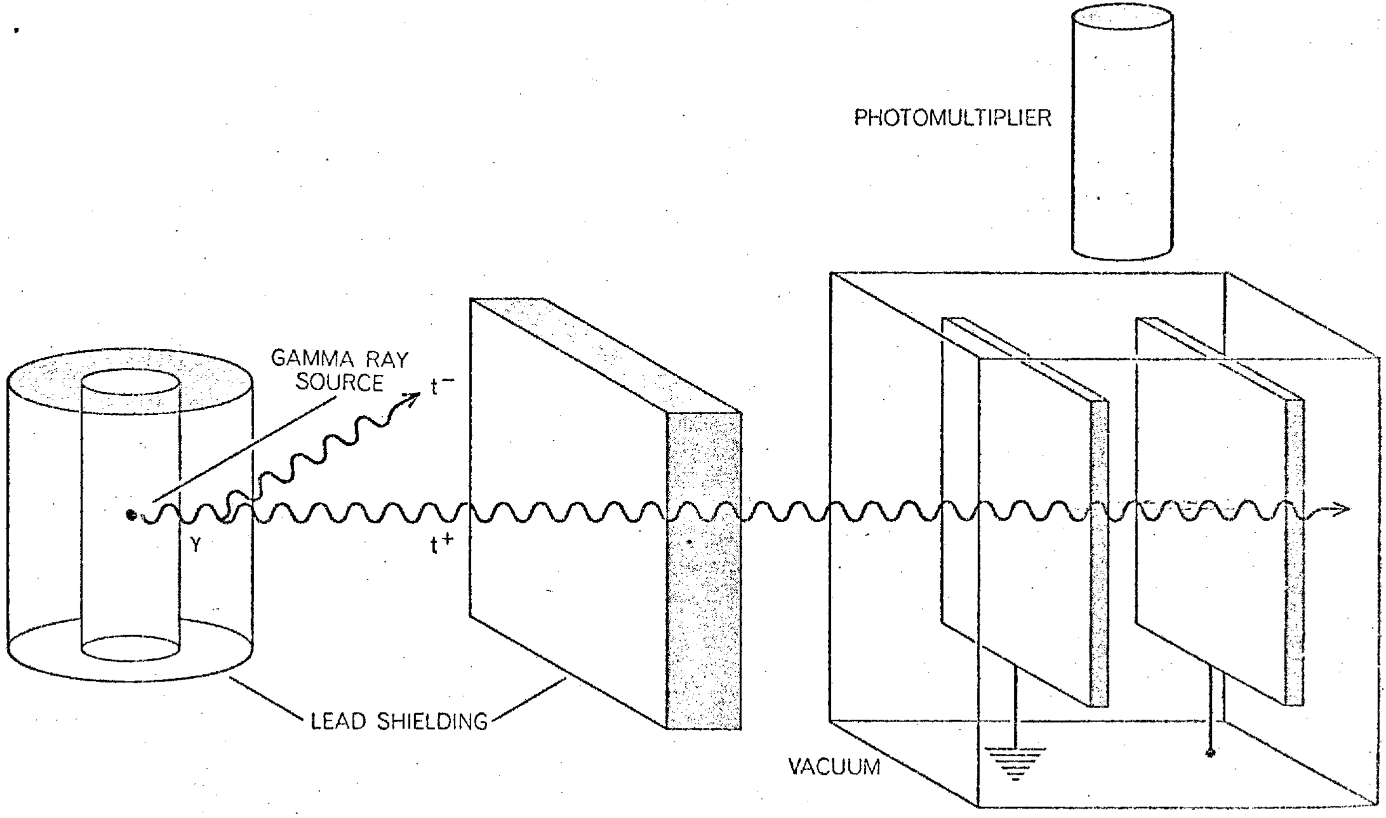
CERENKOV RADIATION would be emitted continuously by an electrically charged tachyon moving in a vacuum. The characteristic angle (θ) at which the photons (*black*) would be emitted would depend only on the speed of the tachyon: the faster the tachyon, the greater the angle. Ordinary charged particles, such as the electron, emit Cerenkov radiation only when they move through a substance faster than the speed of light in the substance.

distribution of the total missing mass squared, over both positive and negative values, without any sharp peaks.

In our experiment two reactions were studied. In one, negative *K* mesons were allowed to come to rest and be captured by protons in a hydrogen bubble chamber. One neutral particle, a lambda hyperon, was produced and was detected through its decay in the bubble chamber into two charged particles. (The momentum and energy of the lambda particle can then be inferred from the measured values for the charged particles.) In order to conserve energy and momentum other neutral particles had to be produced. These were usually a single neutral pion, or sometimes a neutral pion and a photon. The events had all been analyzed previously for other purposes, so that the momentum and energy of the charges were already measured. A plot of the missing mass squared was made for some 6,000 events involving the capture of a negative *K* meson. It should be realized that in this case the missing energy and momentum are defined as the difference between the sum of the initial values for the *K* meson and the proton, and the values for the emerging lambda particle, which, as indicated above, can be inferred from its decay products, even though it is neutral. In our first set of measurements a number of events were found with a negative missing mass squared, which suggested tachyon production. Caution, however, suggested that various tests be made before this conclusion could be accepted.

One test involved making sure that the *K* mesons were really at rest when captured. If this were not the case, the missing mass squared would be incorrectly calculated for a given event, since in the calculation it was always assumed that the meson was at rest when captured. If the direction of the lambda particle were nearly the same as the actual direction of a *K* meson captured in flight, then the missing mass squared could be measured as negative when it was really positive. Accordingly all events in which the angle between the *K* meson and the lambda particle was less than 60 degrees were removed from the sample. For true tachyon-production events this should only reduce the number by the ratio of remaining events to total events, whereas it should eliminate all spurious negative-mass-squared events due to capture in flight. When this test was carried out, the number of events with negative missing mass squared was reduced to 23 from an original total of 101, indicating that most of the supposed tachyon events were actually captures in flight, producing ordinary particles.

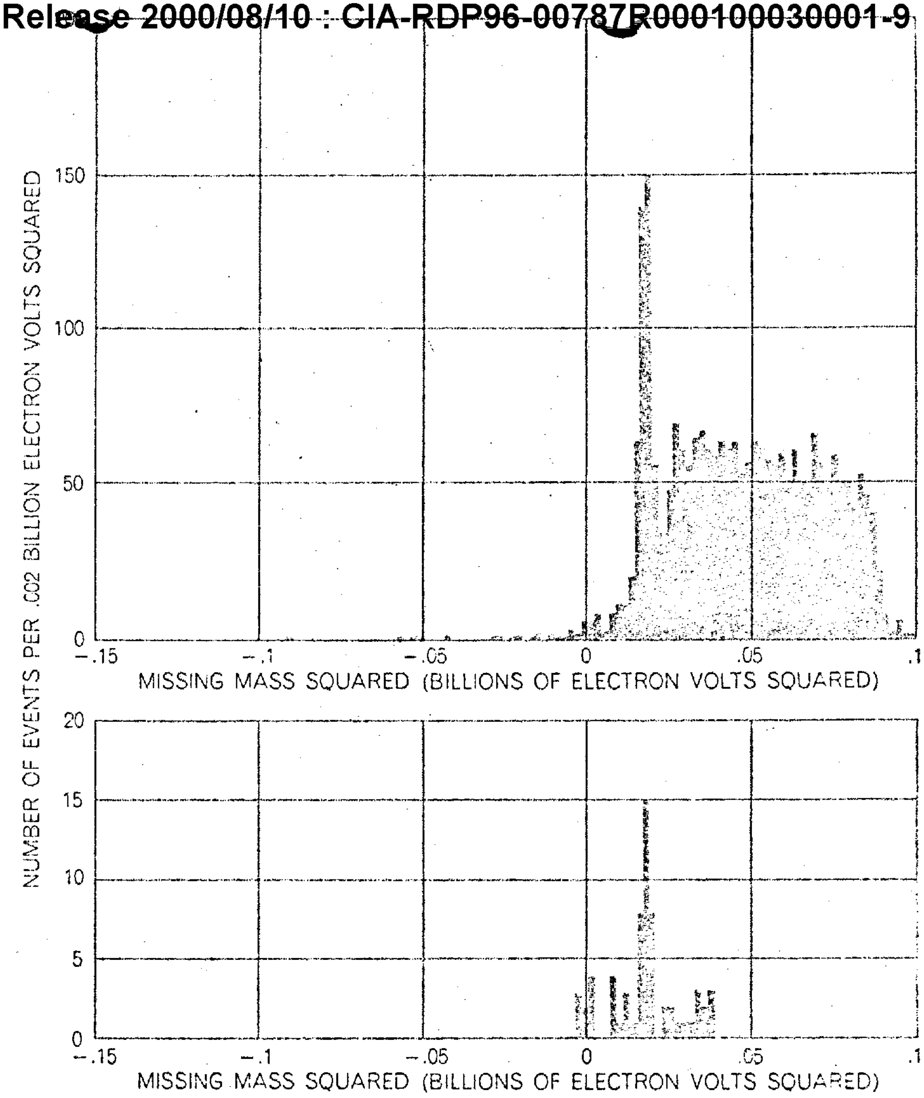
The remaining events were carefully remeasured to ensure that the missing mass squared had been correctly measured. It was found in each case that the true missing mass squared was positive or zero, within the precision of the measurements. Hence what was originally a substantial number of tachyon-candidate events was reduced, after careful study, to none at all. By comparing the limit on tachyon production (less than one) with the total number of events seen, most of which had a missing mass squared represented by a neutral pion, it can be inferred that the rate of tachyon production is less than one part in 400 of the



EXPERIMENT designed to detect charged tachyons by means of their Cerenkov radiation was carried out two years ago by Torsten Alväger and Michael N. Kreisler at Princeton University. They used a radioactive cesium source to provide high-energy gamma rays (γ), which were allowed to hit a lead shield that prevented them from reaching the detection apparatus directly. Pairs of charged tachyons could be produced by the gamma ray photons in passing through the lead, and some of these would escape into a high-vacuum region, which contained two parallel plates with an electric field between them. The purpose of the electric field was to transfer just enough energy to the tachyons to compensate for the energy they lost through radiation, thus enabling them to continue to radiate photons of visible light. A photomultiplier tube was used to detect any photons radiated by the tachyons passing through this region. No positive indication of Cerenkov radiation (and hence no evidence of tachyons) was found in this experiment.

pion production rate, which is typical of a strong production process. Of course, the tachyon production rate was also consistent with zero.

A similar search by the same group, carried out on the annihilation of antiprotons with protons, gave no examples of tachyon production and a similarly low limit for the rate of tachyon production in that reaction. In each of the experiments single tachyons could be produced only if their mass squared was within a specific range of values, and hence the experiment tested single-tachyon production only for particles in that mass range. There are reasons to believe, however, that single-tachyon production is forbidden anyway, just as single production of electrons without other similar particles is forbidden. Nonetheless, production of two tachyons, or of tachyon-antitachyon pairs, is not so forbidden. Such two-particle production could occur in either experiment no matter what the squared mass of the individual tachyons was, and so the experiments actually put rather sharp limits on the production of tachyons of any mass, except for values so near zero that they are within the experimental error of being positive.



RESULTS of the analysis by the author and his colleagues at Columbia of some 6,000 bubble-chamber events involving the capture of a negative K meson are presented here in the form of two curves representing the overall distribution of missing mass squared for all events in terms of its energy equivalent in billions of electron volts squared. The highest peak in each case corresponds to the production of single neutral pions. The production of single neutral tachyons would result in a similar peak at some negative value of missing mass squared, whereas the production of two neutral tachyons would give a broad distribution of the total missing mass squared over both positive and negative values without any sharp peaks. In an early set of measurements (*top*) a number of events were found with a negative missing mass squared, which suggested tachyon production. In a subsequent test (*bottom*), which involved rechecking some of the measurements, the number of events with negative missing mass squared was reduced to essentially zero, indicating that most of the supposed tachyon events were actually errors in the first set of measurements.

Both of the direct experimental searches for tachyons that have been carried out have therefore yielded negative results. Indirect arguments have also tended to restrict still further the possible interactions of tachyons. According to one of these arguments, if charged tachyons exist, the photon would not be a stable object but instead would decay within some time period into a pair of charged tachyons. We know that photons can travel for billions of years across intergalactic space without so decaying. This implies that if charged tachyons exist at all, then either their charge is many orders of magnitude smaller than that of the electron, which means that they interact very weakly with photons, or else their mass squared is very close to zero, which makes them difficult to distinguish from ordinary particles. Similar conclusions can be drawn from indirect arguments about the very small interactions of neutral tachyons.

The possibility that tachyons exist but do not interact at all with ordinary particles need not concern us, because if they do not interact with the objects that compose our measuring instruments, we have no possible way to detect them, and for our purposes it is the same as if they do not exist at all.

If we plausibly interpret the above results to conclude that tachyons cannot be produced at all from ordinary particles, we seem to be left with two possibilities. One remote possibility is that tachyons do interact with ordinary particles and can exchange energy with them but cannot be produced from them. This situation would strongly contradict all our experience with relativistic quantum theories of particles, and so it is improbable but perhaps not impossible. The hypothesis could be tested by searching for tachyons in natural phenomena, such as cosmic rays. A difficulty in carrying out such a search is that tachyons should lose energy rapidly and become hard to detect. The second possibility is that tachyons simply do not exist, and that nature has not filled the niche that is allowed by the theory of relativity. If this is the case, as now seems probable, we may not understand why it should be so until we reach a much deeper understanding of the nature of elementary particles than now exists.