☐ UNCLASSIFIED ☐ INTERNAL USE ONLY ☐ CONFIDENTIAL ☐ SECRET

ROUTING AND RECORD SHEET

SUBJECT: (Optional)

FROM: [redacted] 4G21 Hqs.

EXTENSION [redacted]

NO.

DATE

STAT

STAT

TO: (Officer designation, room number, and building)	DATE RECEIVED	DATE FORWARDED	OFFICER'S INITIALS	COMMENTS (Number each comment to show from whom to whom. Draw a line across column after each comment.)
1. Dr. Ken Kress				
2. 255 South Bldg.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				
12.				
13.				
14.				
15.				

FORM 3-62 610 USE PREVIOUS EDITIONS ☐ SECRET ☐ CONFIDENTIAL ☐ INTERNAL USE ONLY ☐ UNCLASSIFIED

Michael N. Kreisler

Are There Faster-than-Light Particles?

A review of the hypotheses about the nature of tachyons and of experimental searches for them

During the last few years there has been an effort to search for tachyons—particles that travel faster than the speed of light. I hope to show here that there is, in fact, some justification for a search for particles that would seem to violate all we have learned about special relativity—and for the very modest investment that has been devoted to the question. The experiments that have been performed to look for these particles will be reviewed, and I will avoid, for the most part, any lengthy discussion of the wealth of recent theoretical papers in which the debate about the existence of these particles still rages.

It has become almost traditional in this subspecialty to begin with a well-known limerick:

A certain young lady named Bright
Could travel much faster than light.
She departed one day
In a relative way
And returned on the previous night.

Now that we have observed tradition, we turn to a more serious consideration of these weird particles.

As is well known, the expression for the energy E of a normal particle of rest mass m_0 which is traveling with a velocity v is given by

$$E = \frac{m_0c^2}{\sqrt{1 - (v/c)^2}}$$

where c is the speed of light. This expression indicates that accelerating a particle to speeds equal to or greater than the speed of light requires an infinite amount of energy and therefore should be impossible. It is this fact that led Einstein to state that "velocities greater than that of light have no possibility of existence" (*1*). In addition, this fact and the apparent problems that faster-than-light particles would create in special relativity—in particular causal paradoxes—have been strong enough theoretical arguments to deter any investigations in the area. We shall return to these paradoxes below.

Although theorists, including Sommerfeld (*2*), had considered such particles as early as 1904 (in pre-special relativity days), it was not until the work of Bilaniuk, Deshpande, and Sudarshan in 1962 and then Feinberg in 1967 that the subject became of interest again. Bilaniuk, Deshpande, and Sudarshan (*3*) countered the first objection regarding infinite energy input by noting that we are all quite happy with the existence and creation of photons and neutrinos, both of which *always* travel at the speed of light. Their proposal was to postulate the existence or creation of particles with velocities *always* greater than c, thereby circumventing the infinite energy requirement.

The possibility of these new particles is rather appealing because their existence would indicate an interesting symmetry—namely, there would be three allowed types of particles, classified by their velocities:

1. Normal particles, which travel
2. Particles such as photons and massless particles which only exist if $|v| = c$ always
3. Particles with $|v| > c$ always

Feinberg (*4*) introduced the name *tachyons*, from the Greek word meaning swift, for the third type of particles. This name has become quite fashionable, and, as an interesting aside, its quick acceptance has led to other proposals for new names for normal particles—*bradyons*, from the Greek for slow, and *tardyons*, a name with an obvious derivation. While perhaps amusing, these names are not very useful and we will avoid them.

Countering the objections of causal paradoxes is not as simple as merely postulating new particles. In order to discuss the problem, we must first examine the paradoxes implied by the existence of tachyons. In standard fashion, as shown in Figure 1, we consider two coordinate frames S and S' which have a common x axis. The frame S' moves at a constant velocity v ($|v| < c$) in the $+x$ direction relative to S. Now, let us assume that an observer in S sees a tachyon created at point A at time t_A. The tachyon travels with a velocity $+u$ to point B where it is absorbed at time t_B. For this observer, the distance and time separations were both positive:

$$\Delta t = t_B - t_A > 0$$

$$\Delta x = x_B - x_A > 0$$

Using the standard Lorentz transformation, we can calculate what an observer in the S′, or moving, frame sees:

$$\Delta x' = \gamma(\Delta x - v\Delta t) =$$

$$\gamma\left(\Delta x - v\frac{\Delta x}{}\right) = \gamma\Delta x\left(1 - \frac{v}{}\right)$$

Michael N. Kreisler is an Associate Professor of physics at the University of Massachusetts at Amherst. He received his Ph.D. in high-energy physics particle research from Stanford University in 1966 and taught physics at Princeton University before joining the faculty at the University of Massachusetts. His research has concentrated on measurements of high-energy neutron interactions, studies of multipion resonances, and searches for rare decays of elementary particles. This work has been supported in part by the National Science Foundation. Address: Department of Physics and Astronomy, University of Massachusetts, Am-

$$\Delta t' = \gamma\left(\Delta t - \frac{v}{c^2}\Delta x\right) =$$

$$\gamma\left(\Delta t - \frac{v}{c^2}\Delta t \cdot u\right) = \gamma\Delta t\left(1 - \frac{vu}{c^2}\right)$$

$$\text{where } \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

Clearly, the spatial separation Δx or $\Delta x'$ is positive in both frames. However, if the velocity of the tachyon is chosen such that $uv > c^2$, the time separation for the moving observer is *negative*! Apparently a paradox exists, because the observer sees the tachyon absorbed before it was created!

The paradox can be resolved by using the "reinterpretation principle," which is merely the statement that, when going from one inertial frame to another, it is essential that the form of physical laws be invariant. However, there is no requirement that the description or interpretation of a particular phenomenon be the same. So long as there is no violation of a physical law in either frame, observers in different frames *could* interpret a given series of events differently.

In the case described above, the physical process was the passage of a tachyon between points A and B. The paradox is resolved if the observer in the S' frame interprets the process as the *creation of the tachyon at B* and *absorption at A*. The observers then agree on the physical process but disagree about the interpretation of the particular event. Carrying these arguments further, if the tachyons are charged or carry any other quantum numbers, the observer in S' must see an anti-tachyon traveling from B to A (see Fig. 1).

Before considering a more difficult paradox, there are certain characteristics of tachyons that must be mentioned. The calculations that were sketched above indicate that the sign of the fourth component of a tachyon four-vector can be changed by a Lorentz transformation. In other words, those tachyons that are traveling backward in time in a given frame also appear to have negative energies. Another interesting possibility that exists if there are tachyons is the decay of a normal, moving particle into itself plus a tachyon. Such decays without tachyons are forbidden, owing to the requirements of simultaneous energy and momentum conservation. We will use these properties of tachyons in the discussion of the following paradox.

Consider our two observers again, one moving at a velocity v with respect to the other (see Fig. 2). These two observers, A and B, agree on the following course of action: A, the stationary observer, will send a tachyon to B at 12:00 noon his (A's) time *unless* he has received a tachyon from B before noon. B, upon receiving the tachyon from A, will immediately send a tachyon back to A. In the happy event that their relative velocity and the velocity of the tachyons are such that the Lorentz transformation between the frames does not reverse the sign of t or E, everything is fine. That is, A sends his tachyon out at noon and gets a return signal sometime later.

However, if we are not so lucky, the tachyon emitted by B will be traveling *backward in time* as viewed from the stationary frame. It will therefore arrive at A before noon. A will detect it and not send out his tachyon. Why then did B send one back?

This paradox may be resolved (*4*) if we examine A's detector, which, for this purpose, can be an atom or a proton. When the detector absorbs a *positive*-energy tachyon, its energy increases and either the proton moves or the atom goes into an excited state. If the observer wants to be sensitive only to positive-energy tachyons, his detector must consist of stationary protons or atoms in the ground state. Such detectors are not able to absorb negative-energy tachyons, and the paradox would not arise. If he wants to be sensitive to both positive and negative energies, he must choose, for example, a proton with some nonzero kinetic energy. The signal that a negative-energy tachyon had been absorbed would be a sudden loss of energy by the proton (for example, it could suddenly come to rest). However, the observer would *in principle* be unable to distinguish that absorption of a negative-energy tachyon from the spontaneous emission of a positive-energy one. For that reason, he would assume that at 11:00 his detector spontaneously emitted a tachyon and would not attribute it to a signal from B. Therefore, the paradox is explained.

The resolution of such simple examples does not mean that apparently unresolvable paradoxes cannot be invented. In fact, arguments regarding the existence of tachyons have filled many journal pages in recent months. However, as there was no compelling argument against their existence and since a good experimental result is usually worth more than a journal of theoretical speculations, Torsten Alväger and I (*5*) decided to see if the question of tachyons was amenable to experiment. If we were fortunate enough

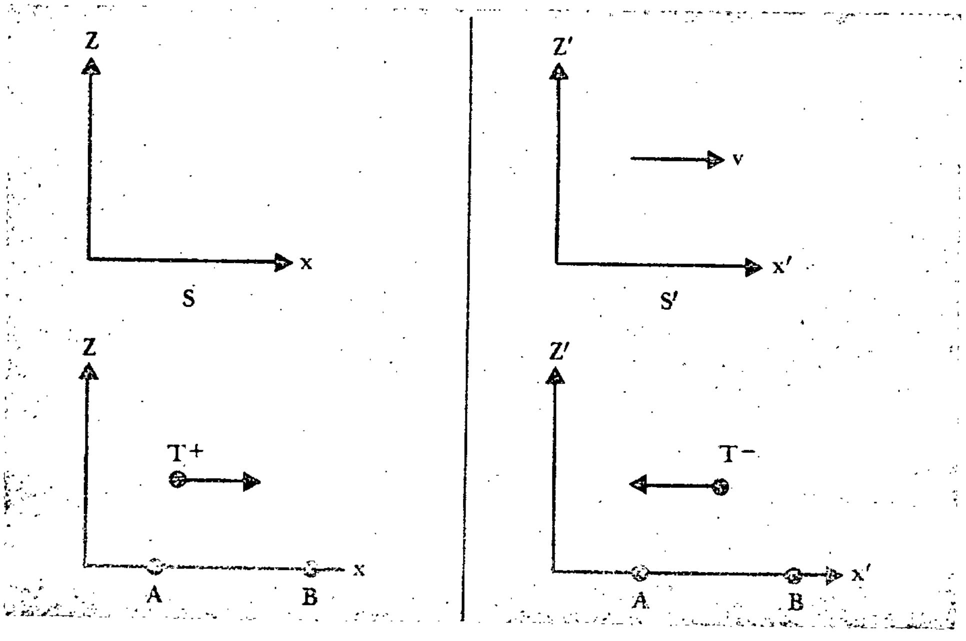


Figure 1. An example of a possible paradox. sorbed at B. In frame S' (*right*), the moving

How do tachyons behave?

Before an experimental search could be conducted, it was first necessary to determine the properties that tachyons should exhibit. In what ways do they differ from normal particles? Do present experimental results put stringent limits on their existence? We present a partial list of the properties of tachyons.

1. The relativistic expressions for the energy and momentum of a particle of rest mass m and traveling at velocity u are

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

$$|\mathbf{p}| = \frac{m|\mathbf{u}|}{\{1 - (u/c)^2\}^{1/2}}$$

If $|\mathbf{u}|$ is greater than c, the "rest mass," m, must be an *imaginary* quantity if the observable quantities E and $|\mathbf{p}|$ are to remain real. Since a tachyon rest mass is unobservable, this choice is allowed. We will use the notation $m = i\mu$, where μ is a real number. Thus for tachyons:

$$E = \frac{\mu c^2}{\left\{\left(\frac{u}{c}\right)^2 - 1\right\}^{1/2}}$$

$$|\mathbf{p}| = \frac{\mu|\mathbf{u}|}{\left\{\left(\frac{u}{c}\right)^2 - 1\right\}^{1/2}}$$

The relation between energy and momentum is then $E^2 = |\mathbf{p}|^2c^2 - \mu^2c^4$ instead of the same expression with a plus sign, which holds for normal particles. If the discussion s restricted to positive-energy tachyons, the bounds on the energy and momentum are

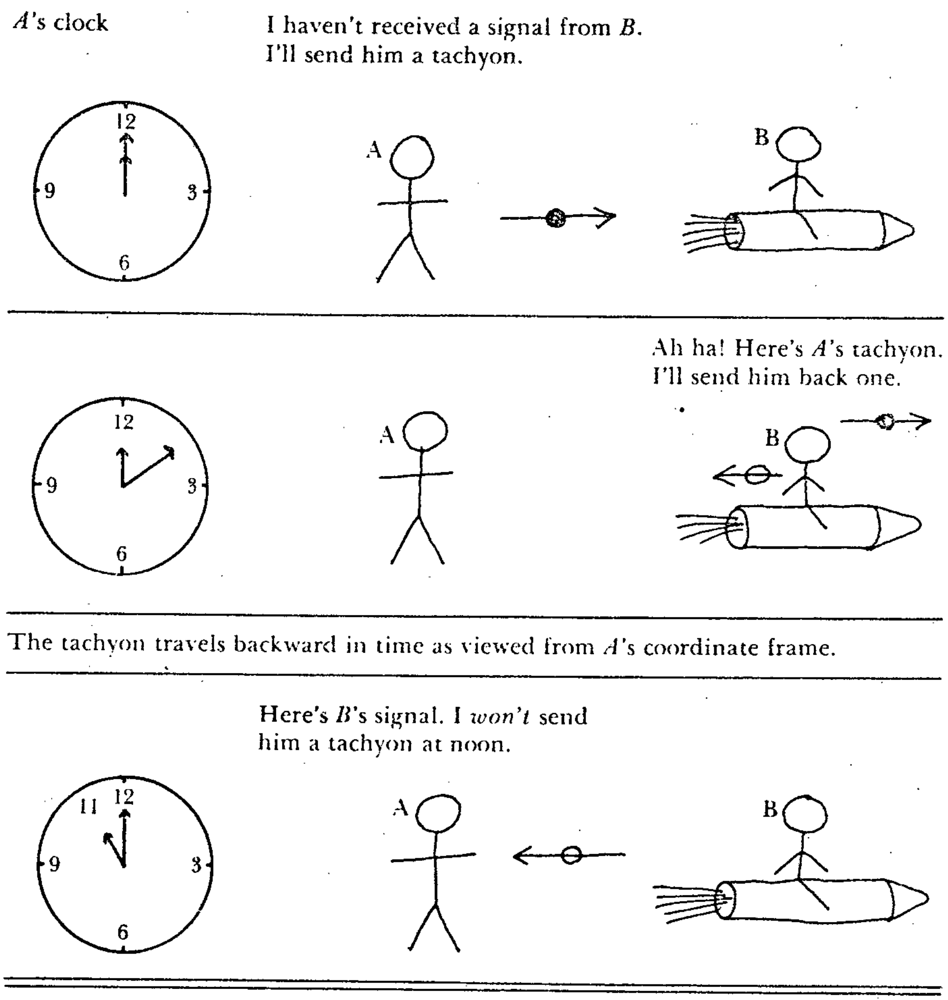
$$0 < E < \infty \text{ and } \mu c < |\mathbf{p}| < \infty$$

These relations indicate several remarkable properties of tachyons: (1) achyons can exist with zero total energy and with finite momentum; 2) infinite velocities are possible; and (3) when a tachyon loses energy, t accelerates!

2. A tachyon appears to be a tachyon n all Lorentz frames. In Figure 3 the algebra of velocity addition is presented. If the velocity is greater han c in one frame, the Lorentz ransformation to any other frame leaves the velocity greater than c.

gure 2. A more puzzling paradox.

A will send *B* a tachyon at 12:00 his (*A*'s) time unless *B* sends him a tachyon signal before noon. *B* will only send *A* a tachyon after he receives one from *A*.



Why did *B* send *A* a tachyon?

total energy, they can in principle be created with zero energy input. One is then led to expect spontaneous tachyon production independent of the value of μ. However, Feinberg (*4*), who has shown that it is possible to include tachyons in the formalism of relativistic quantum mechanics, claims that tachyons most probably obey Fermi-Dirac statistics. In that event, spontaneous production would be severely limited because all the energy states possible to reach via spontaneous creation would be filled, inasmuch as the exclusion principle allows at most a single particle obeying Fermi-Dirac statistics in each available freely specified quantum state.

4. It is kinematically allowed for a tachyon to decay into itself plus a photon. This type of decay is not permitted for normal particles since it is impossible to satisfy both momen-

taneously. For charged tachyons, it is in fact possible to calculate both the energy spectrum of the photons emitted and a total decay rate. This process yields many of the same features as Čerenkov emission, which for normal particles occurs when the velocity of particle propagation in a medium exceeds the velocity of light in that medium. For tachyons, of course, the velocity is always greater than the speed of light—even in a vacuum. Due to the similarity, we will refer to this process of photoemission as Čerenkov emission in a vacuum.

In order to derive an expression for the rate of energy loss by this process, we must impose a cut-off on the radiation energy spectrum—namely, we assume that no photon can carry away from the tachyon enough energy is flat from zero to the energy of the tachyon—that is, all photon energies from zero to the full energy of the tachyon are equally probable. The energy-loss rate per unit path length is

$$\frac{dE}{ds} = -\frac{2\pi^2 Z^2 e^2}{h^2 c^2} E^2$$

for a tachyon of charge Ze and energy E. With this expression it is possible to determine the distance a tachyon would travel before its energy dropped to less than 1 eV. Surprisingly, independent of the initial energy, the distance is very small. Typically, if the initial energy is approximately μc^2, the distance is a fraction of a millimeter!

This result has an important experimental consequence. Because these objects lose all their energy so quickly, it is highly unlikely that they would have been observed in any previous experimental studies. Standard detection devices such as scintillation counters or bubble chambers would not have found tachyons. All such devices require a particle to deposit energy in order to be detected.

5. Tachyons cannot be "stopped" by interactions with matter. But can they be captured by a nucleus or by an electron? If this has an appreciable probability, any experiment looking for such objects would be affected drastically. Feinberg (*4*) claims that it is not at all clear whether such a process could occur. We have attempted to estimate the magnitude of this capture effect using a fairly simple model, in which the tachyons, if captured, enter bound orbits around the capture centers (*5*). Even if all the electrons in lead could serve as capture centers, the mean free path in model, would be on the order of 10^4 meters! We then feel confident that the probability of capture is rather small.

Figure 3. Velocity addition for tachyons. If a tachyon is traveling with a velocity **u** in one Lorentz frame, what is its velocity in another frame moving at a velocity **v** with respect to the first frame?

$$\mathbf{u}' = \frac{\mathbf{u} + \dfrac{(\gamma - 1)|\mathbf{v}||\mathbf{u}|\mathbf{v}}{v^2} - \gamma\mathbf{v}}{\left(1 - \dfrac{|\mathbf{v}|\,|\mathbf{u}|}{c^2}\right)\gamma}$$

$$\gamma = (1 - v^2/c^2)^{-1/2}$$

$$\frac{u'^2}{c^2} = 1 + \left(\frac{u^2}{c^2} - 1\right)\left\{\frac{1 - v^2/c^2}{\left(1 - \dfrac{|\mathbf{u}|\,|\mathbf{v}|}{c^2}\right)^2}\right\}$$

As indicated above, the existence of tachyons cannot be ruled out by their nonappearance in conventional particle detectors. However, it is interesting to see what limits can be set on their production by studying existing experimental data. To do this, we examined photoreactions—those induced by photons—because they are well understood, both theoretically and experimentally. We compared the total cross section for photons interacting with lead with both the sum of experimentally observed partial cross sections and with the theoretical total cross-section predictions. In the low-energy region the total cross section is quite large (at 0.4 MeV, it is ~70 barns), and the agreement between theory and experiment is quite good: ~ ± 2%. This small an uncertainty would still allow a very large cross section for other processes. If it were all due to tachyons, these measurements place an upper limit of only ~ 1 barn on tachyon production. Our conclusion thus was that there was in principle no reason not to have tachyons and there was no overwhelming evidence against their existence.

How to look for tachyons

There are basically two types of experiments that can be performed to hunt for these particles. The first utilizes the tachyon's spacelike four-vector. In other words, in a reaction such as

$$A + B \rightarrow C + X$$

the momenta and energies of A, B, and C are measured. These quantities coupled with energy and momentum conservation determine the square of the mass of the X particle, without any direct observations on X. If X is a tachyon, the square of the mass is *negative*, enabling us to make a unique identification.

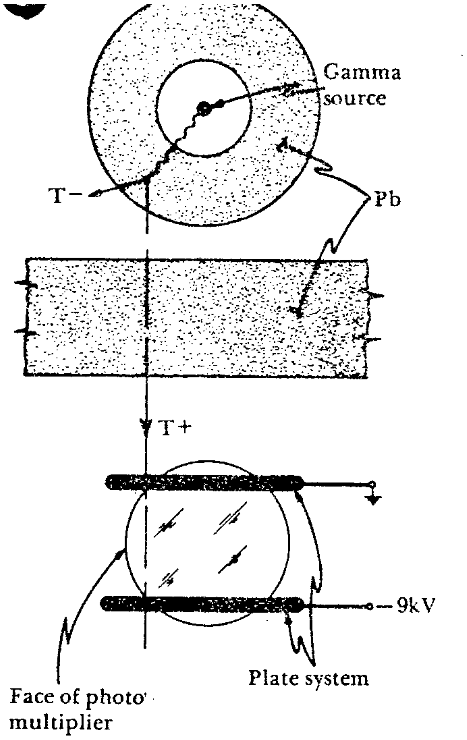


Figure 4. Schematic diagram of a charged tachyon experiment. Tachyons are produced in the lead shield surrounding the radioactive source and travel to the high-voltage plates, where they are detected by the emission of Čerenkov radiation in a vacuum (from *5*).

The second method, suitable particularly for charged tachyons, involves detecting the Čerenkov radiation emitted in a vacuum. Unfortunately, this technique is not easily implemented. In regions close to the production point, there will be large cesses. Far from the production point, in relatively low background areas, the tachyons will, in general, have radiated away almost all their energy, making detection rather difficult.

For reasons of simplicity and cost, T. Alväger and I (*5*) chose to utilize the second technique. In order to overcome the problems just mentioned, we made the additional assumption that charged tachyons interact with electrostatic fields. In particular, we assumed that tachyons could gain energy in the same manner as normal particles. Therefore, it would be possible to increase a tachyon's energy to any desired value at any point along its path. The rate of change of energy along its path is then

$$\frac{dE}{ds} = -\frac{2\pi^2 Z^2 e^2}{h^2 c^2} E^2 + Ze\,|\boldsymbol{\varepsilon}|$$

where $\boldsymbol{\varepsilon}$ is the electric field and we have assumed $E \ll \mu c^2$. The first term in this expression is the rate at which energy is radiated away in the form of Čerenkov light, while the second is the gain of energy in the field. Clearly, the tachyon will reach a stationary energy state when it is emitting energy at the same rate it is gaining. For energy levels in the few

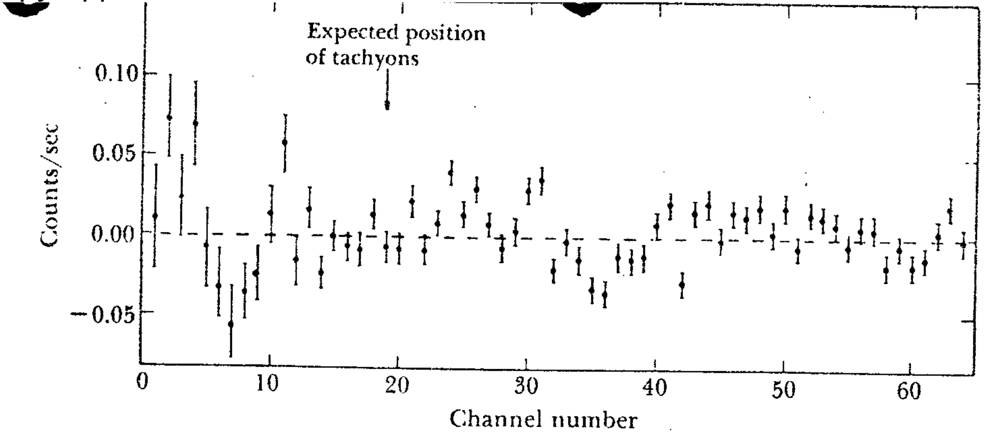


Figure 5. The observed pulse-height spectrum, showing the expected position for a tachyon peak (from *5*).

fields required are only several hundred volts/cm and the levels are reached very quickly—typically in a small fraction of a millimeter. With stationary energy states of a few electron volts, the Čerenkov radiation will be partially in the visible range. The detection problem is then trivial, because standard photomultiplier tubes can be used.

A schematic drawing of experimental apparatus using this technique is shown in Figure 4. A cesium 134 source (emits photons of 797 and 605 keV) was used to produce the tachyons in a lead shield surrounding the source. If tachyons were produced, they would travel through some additional lead shielding and then pass between two parallel plates situated in vacuum and held at 9 kV voltage difference. The phototube looked at the region between the plates. The Čerenkov radiation is expected to be emitted at ∼90° with respect to the direction of motion so that the phototube is located at the optimum angle. The electric field was chosen to place the radiation in the sensitive region of the phototube. The detection technique was rather simple; the pulse height was recorded for all events with measurable pulses. The majority of the events were triggers due either to dark current in the photomultiplier or to light from small corona points on the plates. Data were taken under various conditions—with and without the source and with and without the high voltage.

The number of photons in the sensitive region of the spectrum which will reach the phototube per tachyon can be calculated. Since, on the average, all the tachyons pass through the same field, the existence of tachyons should yield a peak in the pulse height spectrum. Figure 5 shows the pulse height spectrum with the no-source data subtracted and with the position for a tachyon peak indicated. Clearly, there is no evidence for abundant tachyon production. Assuming that a peak with a height of at least 0.1 counts/sec was the minimum "tachyon signal" detectable in this apparatus, we found that the photoproduction cross section for tachyons in lead by 800 keV photons was less than 3×10^{-30} cm². This limit (shown in Table 1) is valid for charges on the tachyons between

charge on the tachyon is too large, the stationary levels yield light which falls below the sensitive region of the phototube; if the charge is too small, it takes a long time to reach a stationary level, thereby greatly reducing our detection efficiency. It is interesting to note that the limit is valid for all masses μ, since tachyons can exist with zero total energy whenever $|\mathbf{p}|c = \mu c^2$.

Although this experiment laid to rest any qualms about the existence of huge fluxes of these particles, the prospect of looking for them was quite appealing. In efforts to improve on the first experiment, we were joined by M. Davis (*8*, *9*). The ground rules for the second-generation experiment were straightforward; it had to be inexpensive and not require a long operating time. The major problem limiting the first experiment was the relatively large counting rate due to corona discharge and to dark current in the phototube. A simple way to avoid these problems would be to use two detectors and place their signals in coincidence. This would also avoid the necessity of pulse-height analysis. A schematic drawing of the experimental setup is shown in Figure 6. The idea is the same as in the first experiment—namely, tachyons are produced in lead by ∼1.2 MeV photons from a Co^{60} source and then travel through two identical detectors consisting of parallel plates in a vacuum.

In order to reduce corona discharges, the plates were covered with opaque construction paper (see Fig. 7). This innovation, which proved very successful, involved an additional cost of 6¢—clearly within the budgetary

two detectors were counted for 10^4 seconds each, with and without the source. In each state, we observed 7 counts, a number consistent with the expected accidental rate. This yielded a counting rate for tachyons of less than

$$4.8 \times 10^{-4} \text{ counts/sec}$$

implying that the photoproduction cross section is less than

$$1.67 \times 10^{-33} \text{ cm}^2 \text{ at } 1.2 \text{ MeV}$$

What does this limit mean? To a physicist, it is instructive to note that this upper limit is more than 10^8 times smaller than electron-positron pair production at the same energy. In terms of a mean free path for photons, a photon could travel through 11,000 miles of lead before it had any noticeable probability of producing a tachyon.

Although these experiments were the first to address this problem, recently there have been others, employing different techniques, that should be discussed. Two bubble chamber experiments (*10*, *11*) have attempted to look for tachyons using the missing mass technique. For normal particles, the square of the missing mass is *always* greater than zero. For single tachyons, the mass squared is always negative, and when a pair of tachyons is created, the pair may have either a positive or negative mass squared. Therefore, if one examines an interaction and calculates the mass squared of missing particles, only tachyons or tachyon pairs would appear to have negative values. Great care must be taken, of course, to ensure that such values are not introduced artificially by measurement errors

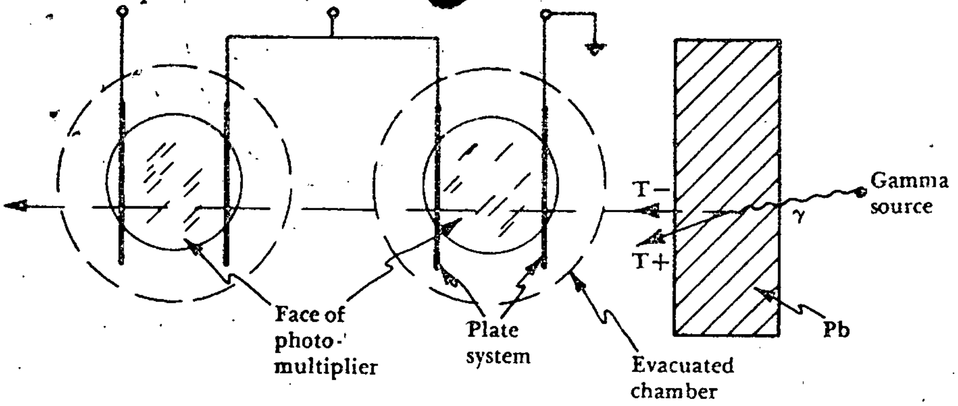


Figure 6. A second-generation detector. Two identical devices are placed in coincidence (from *8*).

The first of the two experiments, by Baltay and his colleagues (*10*), merely looked for negative invariant masses for unseen or neutral particles. The experimenters examined reactions in which either K^- mesons or antiprotons were stopped in a bubble chamber. In particular, they searched for candidates for the following reactions:

$$K^- + p \rightarrow \Lambda^\circ + T^\circ;$$

$$K^-p \rightarrow \Lambda^\circ + T^\circ + \overline{T}^\circ$$

$$+ p \rightarrow \pi^+\pi^- T^\circ;$$

$$\bar{p}\, p \rightarrow \pi^+\pi^- T^\circ + \overline{T}^\circ$$

where T° and $\overline{T}^\circ$ are unseen neutral particles, hopefully tachyons. This particular set of reactions is advantageous as it is *not* necessary to make any assumptions about the interaction of tachyons with matter. The only assumption is that negative values of the square of the mass are not suppressed with respect to positive ones in the case of tachyon pairs. The measurement is quite simple: the momenta of all the visible particles are measured, and the mass squared of any missing particles is calculated. The mass squared is then plotted, and all very low-mass or negative-value events are examined carefully. The data for one reaction is shown in Figure 8. There are some "tachyon candidates" in the data sample; however, in all cases, a careful examination of each questionable event showed that the apparent negative values were incorrect and had been caused either by measurement errors or by additional effects that had not been included in the reconstruction process (for example, scattering of one of the particles after the interaction of interest). The results of the re-analysis of the "borderline" events is also shown in Figure 8. The lack of tachyon candidates indicates that the probability of producing tachyons in these reactions is ~2,000 times less likely than producing π° mesons. experimental results are given in Table 1.)

The other major bubble chamber experiment, by Danburg and his colleagues (*11*), required the assumption that charged tachyons would leave tracks in a bubble chamber similar to those of normal particles. This relies on the assumptions that Čerenkov radiation does not occur and that ionization energy loss does. The experiment consisted of a search for events in which charged pairs of tachyons are produced. Since each member of the tachyon pair can be examined, this technique should detect tachyons (subject to the correctness of the major assumption) independent of the sign of the mass squared of the tachyon pair. As in the previous experiment, no candidates survived careful re-examination, yielding an upper limit on the production cross section (see Table 1).

Other techniques

A slightly different approach has been used by Murthy (*12*), at the Tata Institute. He argues that tachyon production might occur in high-energy cosmic-ray interactions—extensive air showers. Once a primary particle interacts in the atmosphere and a shower develops, the major components of the shower—electrons and photons—travel at $v \cong c$, thereby defining the shower front. Heavier particles tend to travel more slowly and therefore arrive later than the shower front. Some early quark searches used that fact to look for heavy quarks. Tachyons, on the other hand, would arrive *before* the showers. For example, if a tachyon were produced at 2 km above the surface, it would arrive ~2 μsec before the shower front; the full range of the time difference is 0 to 20 μsec.

The experiment consisted of triggering on a *potential* tachyon signal and waiting for ~20 μsec for the arrival of an extensive air shower. The potential tachyon signal could be created by charged tachyons radiating Čerenkov light in a vacuum or by either neutral or charged tachyons interacting with liquid scintillator. The total rate for the arrival of showers following such potential tachyon signals is completely accounted for by accidental coincidences. In addition,

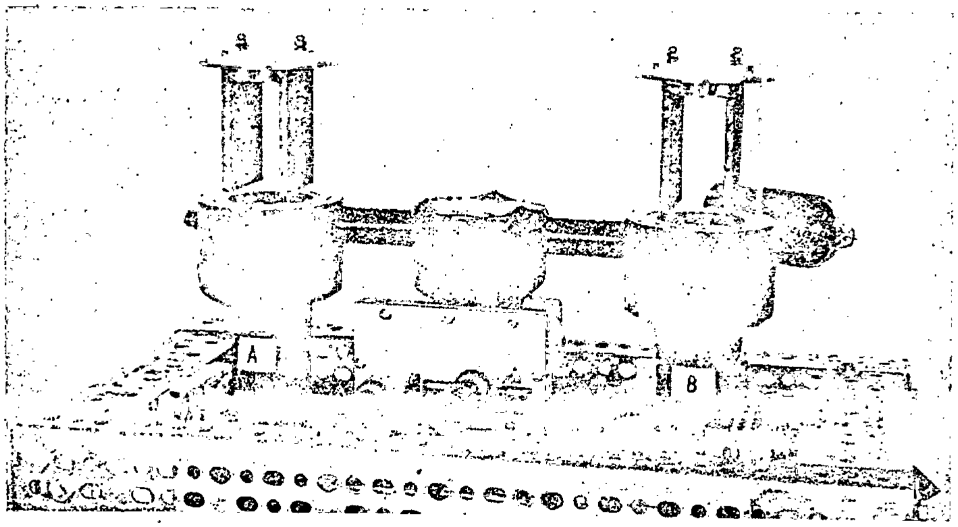


Figure 7. The improved detector. Note the corona (from *9*). (Copyright, 1969, The

random coincidences. Since there is no evidence for tachyon production, the limit on tachyon production in extensive air showers relative to electron production is $\sim 10^{-4}$ to 10^{-5}.

A fairly interesting search for tachyon-like objects has recently been completed by Bartlett and Lahana (*7*). In order to justify their search, they note that ordinary particles are either neutral or electrically charged and that those that move at $v = c$ are neutral. Therefore, there is a certain symmetry if tachyons are either neutral or magnetically charged. The experiment, then, is a search for magnetic monopoles that are traveling faster than c. Although this appears to be a rather uneconomical approach—namely, to hope not only that there are tachyons but that they are monopoles as well—there are some theoretical arguments (*13*) that charged tachyons would, in fact, exhibit all of the properties of magnetic monopoles.

The experiment is analogous to the earlier searches with the appropriate interchanging of $\boldsymbol{\varepsilon}$ and $\mathbf{H}$ fields. The two phototubes detect the Čerenkov light from radiation in the magnetic field and are sensitive to objects with magnetic monopoles between 1/10 and 4 times the size of a Dirac monopole. Working with a 20,000 curie Co^{60} source, the researchers found no candidates. This yields extremely good limits on the production cross sections, which were typically less than 10^{-36} cm^2.

An experiment (*14*) has been conducted at Brookhaven National Laboratory to search for the emission of negative-energy tachyons by protons. In the reaction proton → proton + tachyon, the emission of a negative-energy tachyon appears the same as the absorption of a positive-energy one. A proton at rest would therefore suddenly move if the reaction has occurred. This process can be searched for by examining a bubble chamber with no incident particles; any protons that were suddenly "inspired" to move would leave tracks. The experiment yielded many such tracks—all of which could be explained by gamma emission from radioactive materials near the bubble chamber. Taking one event as an upper limit, the researchers found greater than 10^{21} years. Similar lifetimes can also be obtained from a consideration (*14*) of experiments on baryon conservation and measurements of the heat flux from the earth.

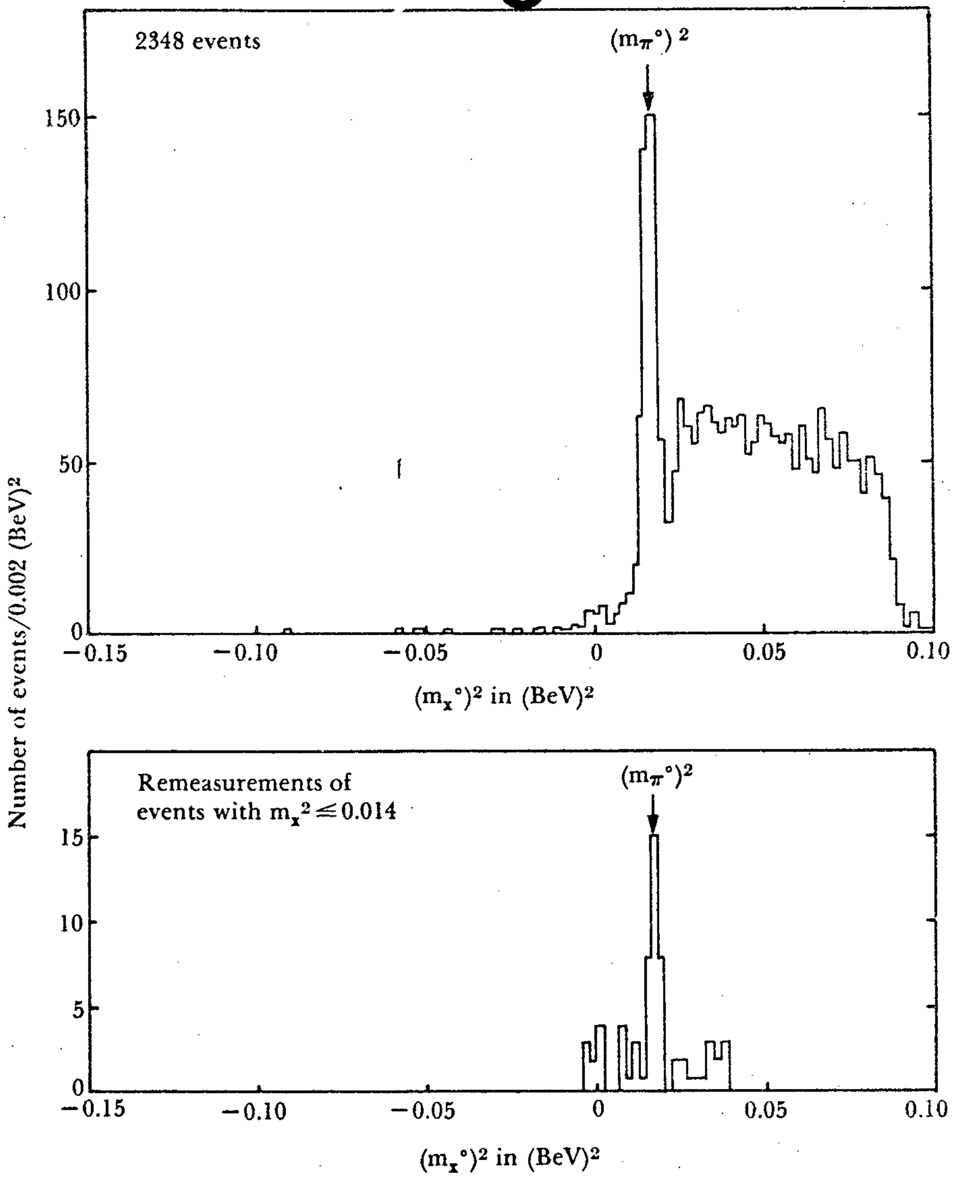


Figure 8. Results of a search for neutral tachyons and tachyon pairs. The upper graph indicates some tachyon "candidates" which do not stand up to a refined analysis, as shown in the lower graph (from *10*).

Philosophical considerations

All of these experiments have one major limitation: since they produce upper limits on the production and/or existence of tachyons, they never seem to satisfy the skeptic. The skeptics—or true believers—give arguments which ask: "But suppose the cross section is *really* only a factor of ten below the current limit?" Usually there is no satisfactory answer to such questions, although the skeptics should be encouraged to perform the experiments themselves. However, there does exist a method which, in principle, argument is presented as a philosophical end to this discussion of tachyons.

L. Parker (13) suggests that there are two types of coordinate systems: (1) the normal, or subluminal, frames in which ordinary particles behave properly and tachyons travel with $|v| > c$; and (2) superluminal ("faster-than-light") frames—relative to which tachyons behave as normal particles. In a world with only one spatial dimension, it can be shown that (1) in the superluminal frame, tachyons have *real* masses, and in such frames it is possible to construct a quantum field theory completely similar to that for subluminal particles in subluminal systems; (2) the mathematical transformations involved in going between the frames are entirely symmetric. Therefore, in a superluminal frame,

Table 1. Summary of searches for tachyons.

Type of search	*Comments*	*Typical results*	*References*
Čerenkov radiation—photomultiplier	$.1e < Z < 2e$	Photoproduction cross section $< 3 \times 10^{-30}$ cm²; 300 KeV photons on lead	(*5*)
Čerenkov radiation—photomultipliers	$.5e < Z < 1.9e$	Photoproduction cross section $< 1.7 \times 10^{-33}$ cm²; 1.2 MeV photons on lead	(*8*)
Missing mass squared—bubble chamber K⁻ and p̄ stopping	neutral	typical result: $\frac{\text{Probability for the reaction: } K^- + p \rightarrow \Lambda^\circ + \text{tachyon}}{\text{Probability for the reaction: } K^- + p \rightarrow \Lambda^\circ + \pi^\circ} < 2 \times 10^{-3}$	(*10*)
Missing mass squared—bubble chamber K⁻ interactions at 2 GeV/c	Assume charged tachyons leave tracks in bubble chamber	Production cross section for charged tachyon pairs $< 2 \times 10^{-31}$ cm²	(*11*)
Cosmic ray—extensive air showers	Tachyons arrive before shower front	$\frac{\text{Occurrence of tachyons in cosmic ray showers}}{\text{Occurrence of electrons in cosmic ray showers}} < 10^{-4}$	(*12*)
Tachyon-like magnetic monopoles	Interchange **ε** and **H**	Photoproduction cross section on lead $< 6 \times 10^{-37}$ cm² on H_2O $< 2 \times 10^{-36}$ cm²	(*7*)
Bubble chamber—emission of negative energy tachyons	Examine bubble chamber with no incident particles	Lifetime for decay $p \rightarrow p +$ negative energy tachyon is greater than 2×10^{21} years.	(*14*)

ordinary particles appear to be tachyons.

These statements and others can be summarized by introducing the extended principle of relativity—namely, all the laws of physics have the same form relative to each of the frames. Therefore, the laws governing tachyons and subluminal particles should be interchanged under the transformation, but the total structure of the laws should have the same form. Clearly, since photons have the same properties in both coordinate systems, the laws describing them should be form-invariant under the transformation. This then leads to the following observation.

Consider photon-photon ($\gamma\gamma$) scattering. This process will appear the same in both coordinate frames. In each frame the process will depend on the contributions from intermediate virtual particle-antiparticle pairs. If the probability of $\gamma\gamma$ scattering in the subluminal system, calculated without considering tachyons, is P, then the probability of $\gamma\gamma$ scattering in the superluminal system, calculated without considering non-tachyons, is also no interference between the two frames, the total probability for $\gamma\gamma$ scattering, including both effects, is $2P$. The situation is a clear one in *principle*. If there are tachyons, the $\gamma\gamma$-scattering cross section should be twice as large as predicted without tachyons.

Ignoring the question of our ability to calculate the cross section to a factor of two, or the question of whether quantum electrodynamics would be thrown out before tachyons were acknowledged, the feasibility of such an experiment is in doubt. Unfortunately, the predicted cross sections (*15*) are very low. In the visible region, the cross section is $\sim 10^{-65}$ cm², implying that experiments are impossible. There is some possibility that at the energies becoming available with high-energy accelerators the experiment could be performed. However, it is doubtful if such experiments will be useful in tachyon searches because the calculation of the expected rates increases in difficulty with increasing energy. Clearly, the limits on the existence of tachyons have been pushed quite low. This author, at least, would be very sur-

References

1. A. Einstein. 1905. *Annalen der Physik* 17: sec 10.
2. A. Sommerfeld. 1904. *Konink. Acad. Wetensch. Amsterdam Proc.* 7:346.
3. O. M. Bilaniuk, V. K. Deshpande, and E. C. G. Sudarshan. 1962. *Am. J. Phys.* 30:718.
4. G. Feinberg. 1967. *Phys. Rev.* 159:1089.
5. T. Alväger and M. N. Kreisler. 1968. *Phys. Rev.* 171:1357.
6. This choice is by no means the only one. An excellent summary of the present theoretical arguments regarding Čerenkov radiation by tachyons can be found in (*7*).
7. D. F. Bartlett and M. D. Lahana. 1972. *Phys. Rev. D* 6:1817.
8. M. B. Davis, M. N. Kreisler, and T. Alväger. 1969. *Phys. Rev.* 183:1132.
9. M. N. Kreisler. 1969. *The Physics Teacher* 7:391.
10. C. Baltay, G. Feinberg, N. Yeh, and R. Linsker. 1970. *Phys. Rev. D* 1:759.
11. J. S. Danburg, G. R. Kalbfleisch, S. R. Borenstein, R. C. Strand, V. VanderBurg, J. W. Chapman, and J. Lys. 1971. *Phys. Rev. D* 4:53.
12. P. V. Ramana Murthy. 1971. *Lett. Nuovo Cimento* 1:908.
13. L. Parker. 1969. *Phys. Rev.* 188:2287.
14. J. S. Danburg and G. R. Kalbfleish. 1972. *Phys. Rev. D* 5:1575.