PHYSICAL REVIEW VOLUME 171, NUMBER 5 25 JULY 1968

Quest for Faster-Than-Light Particles*

TORSTEN ALVÄGER† AND MICHAEL N. KREISLER
Palmer Physical Laboratory and Princeton-Pennsylvania Accelerator, Princeton University, Princeton, New Jersey 08540

(Received 27 February 1968)

An experimental search for the existence of particles that propagate with velocities that are always greater than the velocity of light in a vacuum has been performed. Subject to some assumptions regarding the behavior of such particles, it is found that the photoproduction cross section for such particles in lead is less than 3×10^{-30} cm^2. This upper limit does not depend strongly on the "rest mass" of the particles and is approximately the same for faster-than-light particles of any "rest mass." This search was sensitive to particles having charges between 0.1 and 2 electron charges.

I. INTRODUCTION

PARTICLES propagating with velocities that are always greater than the velocity of light in vacuum have never been observed. The reason may be that no careful search for such particles has ever been performed in light of arguments that such particles would violate the special theory of relativity and the causality principle. These arguments are usually sufficient to quench any attempts to conduct an experimental search for these particles. The validity of these arguments has recently been questioned, however. Bilaniuk, Deshpande, and Sudarshan[1] and Feinberg[2] have shown that causal anomalies and other pecularities of faster-than-light particles may sometimes be avoided by a reinterpretation of the usual description of events as observed from two different reference systems as long as the velocity of these particles is *always* greater than that of light in a vacuum.

To take a simple example, consider two inertial systems s and s'. Let the x and the x' axis of these two frames coincide, and let s' move with a velocity $v<c$, the velocity of light in vacuum, in the direction of the positive x axis. Assume that it is possible to create particles which propagate with a velocity $u>c$. Let such a particle be emitted from a source A and absorbed at a detector B on the x axis in such a way that the time and distance separations for these two events is $\Delta t>0$ and $\Delta x>0$. For the corresponding time separation in the other frame s', the Lorentz transformation shows that

$$\Delta t'=\gamma(\Delta t-v\Delta x/c^2)=\gamma\Delta t(1-vu/c^2)\,,\quad \gamma=(1-v^2/c^2)^{-1/2}.$$

Thus, by choosing $uv>c^2$, the time difference in the frame s' is $\Delta t'<0$. This seems to indicate that the observer in s' should see the particle being detected before it was emitted—a violation of the causality principle. However, when going from one inertial system to another, it is important that the form of physical laws is invariant but not necessarily the interpretation of the particular phenomena observed. In order that the cause should precede the effect in this example, the observer in s' *could* thus interpret the particle path, not as starting at A and ending at B, but the reverse. That is, he would see an oppositely charged particle going from B to A. If faster-than-light particles exist in nature, this interpretation is certainly what the observer in s' would make.

Bilaniuk *et al.*[1] discussed the possible existence of faster-than-light particles mainly in the framework of the classical theory of special relativity. Feinberg[2] has shown that the formalism of relativistic quantum theory may include such particles. Although the conclusions of these authors have been criticized,[3] it seems meaningful at present to conduct an experimental search for such particles to see if the question of their existence can be resolved experimentally. If we assume that these particles interact with ordinary particles and fields, we can look for these particles by attempting to observe the Čerenkov light which they emit in a vacuum. This paper describes such an effort. The paper is divided into two main sections—a discussion of faster-than-light particles in general and a discussion of the experimental search.

II. SOME PROPERTIES OF FASTER-THAN-LIGHT PARTICLES

We summarize here some of the more remarkable, predicted properties of faster-than-light particles (sometimes called tachyons[2]) that may be of importance in a search for such particles. Only charged particles are discussed. This is not to say that neutral tachyons may not exist, but that the present experiment would not be able to detect neutral tachyons.

(1) The relativistic expressions for the energy and momentum of a particle of rest mass m and velocity u

$$E=\frac{mc^2}{(1-u^2/c^2)^{1/2}}\,,\quad |p|=\frac{mu}{(1-u^2/c^2)^{1/2}} \tag{1}$$

indicate that the mass m of a particle travelling with a velocity $u>c$ must be an imaginary quantity in order to allow the *measurable quantities* E and $|p|$ to remain real. That the mass is an imaginary quantity does not

---

* Supported in part by the U. S. Atomic Energy Commission.

† Present address: Physics Department, Indiana State University, Terre Haute, Ind.

[1] O. M. P. Bilaniuk, V. K. Deshpande, and E. C. G. Sudarshan, Am. J. Phys. **30**, 718 (1962).

[2] G. Feinberg, Phys. Rev. **159**, 1089 (1967).

[3] R. G. Newton, Phys. Rev. **162**, 1274 (1967).

deny the existence of tachyons, since they cannot be brought to rest, and their "rest mass" is therefore not directly measurable. If we set the "rest mass" $m=i\mu$ (μ real) in relation (1), the energy and momentum of a tachyon will be

$$E=\frac{\mu c^2}{(u^2/c^2-1)^{1/2}},\quad |p|=\frac{\mu u}{(u^2/c^2-1)^{1/2}}.\quad (u>c) \tag{2}$$

Relation (2) shows that the energy and momentum limits for a tachyon are

$$0<E<\infty,\quad \mu c<|p|<\infty.$$

Thus at infinite velocity a tachyon carries no energy and has a finite momentum μc.

It is interesting to note that as a tachyon loses energy, it accelerates.

(2) It is believed that faster-than-light particles are most probably created in pairs.[2] In order to produce tachyons, it is not necessary for the available energy in a reaction to exceed twice the "rest-mass" energy, as is the case for ordinary particles. In fact, since tachyons can exist with zero energy, independent of "rest mass," they may be created with zero energy input. Tachyons may therefore be created spontaneously, but this process is probably limited because the particles are supposed to obey Fermi statistics.[2] Those energy states which are possible to reach by spontaneous creation are most probably already filled.

(3) Charged tachyons can emit Čerenkov radiation in vacuum without violating energy and momentum conservation laws.[4] The energy loss per unit path length due to Čerenkov radiation is[4]

$$\frac{dE}{ds}=-\frac{4\pi^2Z^2e^2}{c^2}\int\left(1-\frac{c^2}{v^2n^2}\right)\nu d\nu, \tag{3}$$

where Ze is the charge of the moving particle (e is the electron charge), n is the index of refraction, and ν is the frequency of the emitted radiation. The integration is to be carried out over all frequencies for which $v^2n^2/c^2>1$. For tachyons in vacuum, $n=1$ and the possible frequency range is 0–E/h. Equation (3) may therefore be written

$$\frac{dE}{ds}=-\frac{Z^2e^2\mu^2}{2\hbar^2}\frac{E^2}{p^2}. \tag{4}$$

The distance traveled by a tachyon as a function of energy is found from Eq. (4):

$$S=\frac{2\hbar^2c^2}{Z^2e^2\mu^2c^4}\left[E_i-E_f+\mu^2c^4\left(\frac{1}{E_f}-\frac{1}{E_i}\right)\right], \tag{5}$$

where E_i and E_f are the initial and final energies, respectively.

This distance is in general uncomfortably small. For instance, for $E_i\approx\mu c^2$ and $E_i\gg E_f$, S is

$$S\approx\frac{2\hbar^2c^2}{Z^2e^2E_f}\approx 5\times10^{-3}\text{ cm}$$

for $Z=1$ and $E_f\approx1$ eV. The short distance that the tachyons travel until almost all energy is lost makes it difficult to detect them directly unless the "rest mass" μ or the charge Ze is very small.

(4) Since the velocity of the tachyons is always larger than the velocity of light, they cannot be "thermalized" and stopped. However, it seems plausible that a charged tachyon may be captured by a nucleus or by an electron. Although it is not clear on theoretical grounds whether capture is possible at all,[8] we present here a simple model of such capture in order to estimate its effect on the experiment. Classically, the condition for capture of a tachyon of charge Ze, momentum p, and velocity u in an orbit of radius R around a charge ze may be written

$$Zze^2=Rup.$$

The geometrical cross section is then given by

$$\sigma\approx2\pi R^2=2\pi Z^2z^2e^4E^2/(E^2+\mu^2c^4)^2.$$

To get an idea of the order of magnitude of the capture cross section, consider capture of positive tachyons by electrons and assume that $E=0.5$ MeV, $\mu c^2=10$ MeV, and that no Čerenkov radiation is emitted. Under these conditions the capture cross section is $\sigma\approx3\times10^{-30}$ cm^2 for $Z=1$. The mean free path in lead would therefore be about 10^4 m, allowing all electrons available to serve as capture centers. Taking into account the fact that the tachyons emit Čerenkov radiation, the mean free path will be considerably larger. It seems, therefore, that only when μ is very small does the possibility for capture in matter create a detection problem.

(5) It is of interest to consider what limits can be set on the production cross section of tachyons when one examines how well theory can explain experimentally observed total cross sections without any tachyon production.

The most suitable case for this purpose is certainly photoreactions, since such processes are best understood theoretically. Numerous measurements exist for the total cross section for absorption and scattering of photons. For instance, for photon reactions in lead for photon energies 0.4 and 17.6 MeV, the total cross section is 73 and 20 b, respectively. It is found that experimental and theoretical values agree within an accuracy of 2%.[5] This kind of measurement therefore allows tachyon production cross sections in lead of not more than about 1.5 and 0.4 b for photon energies of 0.4 and 17.6 MeV, respectively.

---

[4] This was first realized by A. Sommerfeld, Koninkl. Ned. Akad. Wetenshap. Proc. 8, 346 (1904); also I. Frank and I. Tamm, Compt. Rend. Acad. Sci. URSS 14, 109 (1937).

[5] S. A. Colgate, Phys. Rev. 87, 592 (1952).

III. MEASUREMENT AND RESULTS

As indicated by relation (5), charged tachyons lose most of their energy in a fraction of a centimeter from the point of production. It is therefore practically impossible to utilize standard detection techniques to observe them directly. However, there are two possible approaches that could detect tachyons:

(1) One could employ some kind of missing-mass spectrometer. In that case, no direct observation of the tachyons is necessary. The tachyons should appear as particles with (missing mass)$^2 < 0$.

(2) One could try to detect the Čerenkov radiation emitted by the tachyons in a vacuum. A straightforward application of this method is not very feasible, however. If the Čerenkov detector is looking directly at the target where the tachyons are created and where the Čerenkov radiation is expected to be the most intense, there will be difficulties with photo background from uninteresting processes. On the other hand, if the Čerenkov detector is looking at the tachyons after the particles have entered a low background area, the energy of the tachyons will be low ($\ll 1$ eV). The frequency of the Čerenkov radiation will then be mainly in the microwave region with subsequent difficulties for observation, mainly due to low detection efficiencies.

In the present work, a modification of the second method has been used, mainly because of its simplicity. The principle is the following. It was assumed that charged tachyons can gain energy in an electromagnetic field in a way similar to ordinary particles. In that case, it would be possible to increase the energy of the tachyons to a value suitable for detection at any point along their path. Consider, for instance, a tachyon in an electrostatic field. The particle will gain energy from the field but lose energy through Čerenkov radiation according to Eq. (4). The net energy gain per unit path length is therefore

$$\frac{dE}{ds}=-\frac{Z^2e^2}{2\hbar^2c^2}E^2+Ze\,\mathrm{grad}V\,, \tag{6}$$

where V represents the electric potential and it is assumed that $E \ll \mu c^2$. For a stationary state, i.e., $dE/ds=0$, the energy is

$$E^2=[2\hbar^2c^2/(Ze)]\;\mathrm{grad}V\,. \tag{7}$$

For $E=1$ eV and $Z=1$, $\mathrm{grad}V=205$ V/cm. From Eq. (6) it can be shown that tachyons reach 95% of the energy of the stationary state within 10^{-2} cm path length. Energies of a few eV are therefore quite reasonable to obtain for tachyons having one electron charge. At these energies a large portion of the Čerenkov radiation is in the visible and can therefore be detected by a photomultiplier.

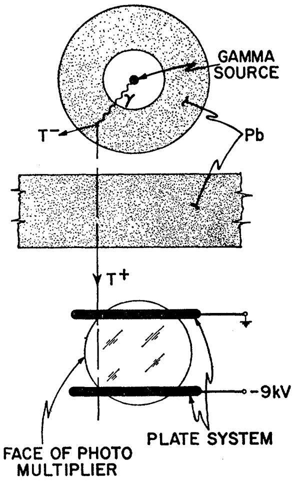

FIG. 1. Schematic representation of detector system. $T^{\pm}$ represents tachyons which would be created in the lead surrounding the γ source. The two plates are located in a vacuum of approximately 10^{-6} Torr.

An experimental setup utilizing this method is shown in Fig. 1. Gamma rays from a 5-mCi cesium-134 source [main γ components[6]: 797 keV (32%) and 605 keV (44%)] are assumed to create tachyon pairs in the cylindrical lead shield surrounding the source. The complete lead shielding was sufficient to prevent any appreciable γ radiation from reaching the detector directly. The detector consists of two parallel plates between which an electrostatic field is maintained and a DuMont 6292 photomultiplier which looks at the region between the plates. The plates are in a vacuum of approximately 10^{-6} Torr. Since the emission angle of the Čerenkov light for tachyons of low energy is close to 90° with respect to the direction of motion, the photomultiplier tube was located perpendicular to the direction of the electric field.

The photomultiplier has a maximum sensitivity for photons with energies from 2.5 to 3.5 eV. The magnitude of $\mathrm{grad}V$ was chosen to be 3 kV/cm. This corresponds to a tachyon energy of 3.8 eV according to Eq. (7) if $Z=1$. Since the total path length in the field was 3 cm (the distance between the two plates), the total energy radiated in the field per tachyon will be 9 kV, which is equally distributed over the energy range 0–3.8 eV. The average number of photons emitted per tachyon in the sensitive region of the photomultiplier is therefore 1000. With the geometry used, the photomultiplier could see 12% of these photons. Thus approximately 120 photons entered the photomultiplier per tachyon. The output of the photomultiplier was analyzed by a pulse-height analyzer. It is expected that tachyons would produce a peak in the pulse-height spectrum, since all tachyons pass through the same field and therefore emit the same number of photons on the average.

The detector was calibrated in the following manner. A NaI(Tl) crystal was placed on the photomultiplier and a radioactive source was used to send a known number of photons into the photomultiplier. From data on the number of photons emitted per keV transferred

---

[6] For example, J. B. Birks, *The Theory and Practice of Scintillation Counters* (Pergamon Press, Inc., New York, 1964).

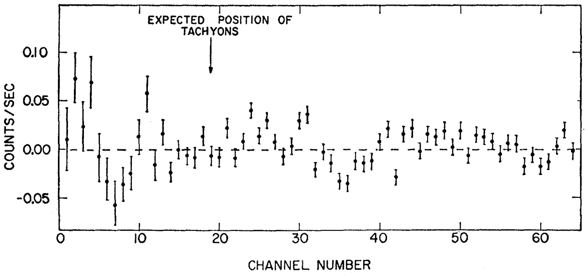

FIG. 2. Experimental results using the tachyon detector system. The position of the peak in the pulse-height spectrum that would be due to tachyons is indicated. The counting rate represents the difference between the rates with and without the γ source present.

to the NaI(Tl) crystal for x-ray energies (20 photons/keV),[7] the position of the peak due to tachyons could be estimated. The width of the peak is more difficult to estimate. However, it seems plausible to assume that this width will not be larger than the corresponding width for photons of x-ray energies having the same pulse height as the suspected tachyon peak.

A measurement made with this detector is shown in Fig. 2. The points represent the difference in the counting rates with and without the γ source present.

The expected counting rate R from tachyons is

$$R=\sigma N\phi_\gamma\Omega\,, \qquad (8)$$

where σ is the production cross section for tachyons in lead, N is the number of target-lead atoms, ϕ_γ is the γ flux of 0.8-MeV γ's at the lead target, and Ω is the portion of the production solid angle subtended by the detector.

Assuming that the target consisted only of the cylindrical lead shield around the source, $N=1.4\times10^{25}$. The mean γ flux $\phi_\gamma=5\times10^5/\mathrm{cm}^2$ sec. The value of Ω depends somewhat upon the "rest mass" μ. For $\mu c^2\ll E_\gamma$, tachyons will be produced mainly in the forward direction; for $\mu c^2\approx E_\gamma$, an isotopic production distribution can be expected; in the case $\mu c^2\gg E_\gamma$, tachyons will emerge perpendicular to the direction of the γ rays, all in the laboratory system. The difference in Ω is not very large, however. A Monte Carlo calculation indicates that for $\mu c^2=0.1$, 1, and 10^3 MeV, Ω is 2, 1, and 0.5%, respectively.

Since there is no pronounced peak in the spectrum presented in Fig. 2, there is no obvious evidence for the existence of charged tachyons. The spectrum does oscillate about zero, however. Examination of the shape of the spectrum indicates that we would be sensitive to tachyons only if the counting rate in the peak was greater than 0.1 counts/sec (90% confidence level). The full width at half-maximum was assumed to be half of the expected peak position. We can therefore put an upper limit on the photoproduction cross section in lead of tachyons having any "rest mass." From Eq. (8), with $\Omega=0.5\%$, we find

$$\sigma\leqslant 3\times10^{-30}\ \mathrm{cm}^2.$$

As seen from the solid-angle estimate given above, this limit is slightly better for low-mass tachyons.

The discussion of the experiment to this point has been limited to tachyons having one electron charge. The measurement is, however, sensitive for a somewhat wider range of charges. From Eq. (6) and with the experimental parameters used, it can be shown that the distance travelled by a tachyon in the electric field until 95% of the stationary energy state is reached is

$$S=2\times10^{-3}\times Z^{-3/2}\ \mathrm{cm}.$$

If $S\lesssim0.1$ cm, full sensitivity in the detection of the particles will be obtained. This shows that tachyons of minimum charge $0.1e$ could be seen. For a tachyon with charge larger than about $2e$, the stationary energies fall below the sensitive region of the photomultiplier. The measurable region is therefore 2 to $0.1e$.

IV. CONCLUSION

This search for faster-than-light particles has placed an upper limit on the photoproduction in lead of such particles of less than 3 μb for photon energies of 0.8 MeV. This limit holds for particles having charges in the range of 0.1 to 2 electron charges. The limit is approximately four orders of magnitude lower than the electron-positron pair-production cross section at energies of a few MeV.

The validity of this limit depends quite strongly on the following assumptions: (1) that tachyons would gain energy in an electrostatic field in the same manner as ordinary particles; (2) that the emission of Čerenkov light in a vacuum is not suppressed by any selection rules (if the number of photons emitted per unit path length was different by more than a factor of 2 from our calculated value, the limit of this experiment would not hold for the same range of charge on the tachyon); and (3) that tachyons do not have a large probability of being captured in matter.

Although there is some reason to believe that these assumptions are correct,[8] the failure of any one of them would tend to change the results of this experiment quite drastically.

In addition to the above, there are two theoretical hypotheses[8] that could affect the results presented here. The first is that it is energetically possible for a tachyon to decay into three tachyons. If this process has a very high probability, tachyons might tend to lose energy by this means rather than by Čerenkov radiation. The lack of any observable Čerenkov radiation, then, does not yield as low an upper limit on tachyon production. The second is that it is possible that all energy levels

---

[7] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C. 20025), NRC 61-2-(106).

[8] G. Feinberg (private communication).

for tachyons up to some energy are already filled. If this energy is above the energy of the photons used in this experiment, no tachyons would have been produced. The limit that is presented assumes that these two effects are not important.

The limit that is presented does not consider the process of a photon decaying into a photon plus tachyons.[2] If such a process has a high probability of occurring, the limit set by this experiment would be lower than the quoted result.

It is important to note that faster-than-light particles of any "rest mass" could have been created in the experiment.[9] It is possible that the production cross section is pathologically small below energies corresponding to the "rest mass" μ of the tachyons. This possibility, although not based on any theoretical arguments, lends some support to efforts to extend the measurements to higher photon energies. Also, there is some interest in placing a limit on the existence of completely neutral faster-than-light particles. Experiments along both of these lines are now being planned, as well as plans to extend the sensitivity of the present experiment. It is felt that it is possible to increase the sensitivity of the present experiment by several orders of magnitude with only minor changes in the detector system.

ACKNOWLEDGMENTS

We would like to thank Professor G. Feinberg of Columbia University for his continued support and encouragement. The Radiation Measurements Group at the Princeton Pennsylvania Accelerator is to be thanked for their help with various radioactive sources.

---

[9] It should be noted that very low mass tachyons might not have been seen in this experiment. This case has been considered in another experiment [T. Alväger, P. Erman, and A. Kerek (unpublished)] which also gave a negative result.

PHYSICAL REVIEW VOLUME 171, NUMBER 5 25 JULY 1968

Gravitationally Induced Electric Field near a Conductor, and Its Relation to the Surface-Stress Concept

CONYERS HERRING
Bell Telephone Laboratories, Murray Hill, New Jersey 07971

(Received 13 March 1968)

The contact potential difference between points just outside different parts of the surface of a conducting body is altered when the body is acted on by a gravitational field, because of the effect of gravity on the work function of the surface. A reciprocity relation due to Schiff and Barnhill relates this effect of gravity to the shift in mass moment of the conductor produced by shifting the position of a test charge near it, and shows how the effect can be expressed as the sum of a purely electronic term and a nuclear term due to distortion of the crystal lattice. It is shown here how the nuclear term, which describes the effect on the work function of the distortion of the body by its own weight, can also be described, via the reciprocity relation, in terms of the local alteration of the surface stress of the body by the electric field due to the test charge. The contribution of the nuclear term to the electric field in a vertical metal tube is expected to be of the order of 10^{-9} to 10^{-8} V/cm, much larger than the Schiff-Barnhill electronic contribution of -5.6×10^{-13} V/cm.

1. THE PROBLEM

CONFLICTING views have recently been expressed[1,2] regarding the theoretical effect of gravity on the electrostatic potential just outside the surface of a conductor. This question arises in connection with any experiment aimed at measuring the force of gravity on charged elementary particles: To avoid having gravity swamped by stray electrostatic fields, one must introduce metallic shields; one must then worry about the electrostatic fields inside these shields. These fields can conceivably arise from random causes such as fluctuations in surface contamination or crystal grain texture, from space charge in the evacuated region, and from a systematic effect of gravity in modifying the charge distribution that would exist in the bulk and surface of the metal in the absence of gravity. The present paper, like those cited,[1,2] will discuss only this gravitational effect; it will show how to reconcile the large field estimated by Dessler *et al.*[2] with the reciprocity-theorem approach of Schiff and Barnhill,[1] which led them to predict a much smaller field.

The most obvious way to attack the problem in question is to view it as one of computing (or at least estimating) the effect of stress on the work function. When the different parts of a conducting body are in equilibrium with one another in a gravitational field, the electrochemical potential $\bar{\mu}$ of the electrons must be the same in all these different parts. In a gravitational field the role played by the electrostatic potential

---

[1] L. I. Schiff and M. V. Barnhill, Phys. Rev. **151**, 1067 (1966).

[2] A. J. Dessler, F. C. Michel, H. E. Rorschach, and G. T. Trammel, Phys. Rev. **168**, 737 (1968).