Search for Uncharged Faster-than-Light Particles*

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An experiment has been carried out to search for uncharged particles with spacelike four-momentum which presumably travel faster than light. No evidence for such particles has been found. The results can be expressed as upper limits on the production rates for such particles by stopped K^- and $\bar{p}$ compared to production rates of pions in similar reactions: $(K^-+p \to \Lambda^0+t^0)/(K^-+p \to \Lambda^0+\pi^0) \leq 2\times10^{-3}$, $(K^-+p \to \Lambda^0+t^0+\bar{t}^0)/(K^-+p \to \Lambda^0+\pi^0) \leq 2.5\times10^{-3}$, $(\bar{p}+p \to \pi^++\pi^-+t^0)/(\bar{p}+p \to 3\pi) \leq 2\times10^{-3}$, $(\bar{p}+p \to \pi^++\pi^-+t^0+\bar{t}^0)/(\bar{p}+p \to 4\pi) \leq 1\times10^{-3}$. Other sources of information placing limits on the interactions of tachyons are discussed.

I. INTRODUCTION

THE possible existence of particles with spacelike four-momentum, which presumably travel faster than light in vacuum, has been suggested.[1] These particles ("tachyons") are allowed by relativistic quantum mechanics, and the question of their existence is an experimental one. A search for charged particles, which could be detected through their Čerenkov radiation in vacuum, has been carried out, with negative results,[2] and upper limits for the production of charged tachyons by photons have been established. This result suggests that charged tachyons do not exist, but does not rule out the possible existence of neutral tachyons.

We have searched for neutral tachyons in two bubble-chamber experiments. These searches have made use of the defining property of tachyons, their spacelike four-momentum, to recognize the possible production of tachyons, without the need for detection of the tachyons after production. The lack of necessity to detect the tachyons has the advantage of making the experiment insensitive to unsolved problems of the interaction of tachyons with matter or their propagation through space. To see how such an experiment may be done, we consider a reaction

$$A(p_A) \to B(p_B)+x(p_x). \tag{1.1}$$

Here A is some observed set of ordinary particles, with timelike total four-momentum p_A, and B is an observed set of ordinary particles with timelike four-momentum p_B. x is a set of unobserved neutral particles, carrying a "missing" four-momentum $p_x=p_A-p_B$. It is easy to see that if x contains only particles of timelike or null four-momentum, then

$$p_x^2 \equiv E_x^2-\mathbf{p}_x^2 \geqslant 0. \tag{1.2}$$

On the other hand, if x were a single neutral tachyon, then

$$p_x^2=-\mu^2<0, \tag{1.3}$$

where μ is the tachyon mass parameter. If x contains one or more tachyons together with other ordinary particles, or more than one tachyon, then p_x^2 can be positive or negative. However, any events for which $p_x^2<0$ must contain at least one tachyon. Hence a measurement of missing mass squared in any reaction is a sensitive test for the possible production of neutral tachyons in the reaction.

If a single stable tachyon could be produced in reaction (1.1), it would show up as a spike in the plot of missing mass. Because single tachyons are kinematically allowed to decay into several tachyons, this spike might be broadened into a resonance, as for an unstable ordinary particle. However, it is unlikely that single tachyons can be produced in (1.1) at all. In one theory of tachyons,[3] they are spinless fermions, and their single production is forbidden by the conservation of angular momentum and statistics. More generally, it can be shown that boson tachyons must differ from their antiparticle, and so presumably carry a conserved quantum number. Nevertheless, since the theory of tachyons is hardly complete, we can interpret our experimental results in terms of an upper limit for single-tachyon production.

Production of two tachyons, or of tachyon-antitachyon pairs, is a more promising channel. Suppose x consists of two tachyons, each with $p^2=-\mu^2$. Then

$$p_x^2=(p_1+p_2)^2=-2\mu^2+2E_1E_2-2p_1p_2\cos\theta. \tag{1.4}$$

Here $\mu<p_1<\infty$, $\mu<p_2<\infty$ and $E_1=(p_1^2-\mu^2)^{1/2}$, $E_2=(p_2^2-\mu^2)^{1/2}$ are non-negative. By varying $\cos\theta$, p_1,

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[1] G. Feinberg, Phys. Rev. **159**, 1089 (1967); O. M. P. Bilaniuk, V. K. Deshpande, and E. C. G. Sudarshan, Am. J. Phys. **30**, 718 (1962); S. Tanaka, Progr. Theoret. Phys. (Kyoto) **24**, 171 (1960).
[2] T. Alväger and M. N. Kreisler, Phys. Rev. **171**, 1357 (1968).
[3] See G. Feinberg, Phys. Rev. **159**, 1089 (1967).

and p_2, we can, for any value of μ^2, obtain any value for p_x^2 between $\pm\infty$. This circumstance, which is a stumbling block for making a theory of interacting tachyons, is of great value for this experiment. Because of it, we are able to detect pairs of tachyons with arbitrarily great values of μ^2. We show in Sec. III that the phase space for obtaining a value of p_x^2 within the range observable in these experiments remains large over almost the whole mass range $-\infty < -\mu^2 < 0$, so that these experiments can be used to search for an unlimited range of tachyon masses.

In order to see what we have tried to observe, suppose that in reaction (1.1) a system x with spacelike total momentum $p_x^2 = -M^2$ is produced. In our experiments $\mathbf{p}_A = 0$. Hence, $-M^2 = p_x^2 = (p_A - p_B)^2 = (E_A - E_B)^2 - p_B^2$ and

$$-M^2 = E_A^2 + M_B^2 - 2E_A E_B. \qquad (1.5)$$

So

$$E_B = (E_A^2 + M_B^2 + M^2)/2E_A > (E_A^2 + M_B^2)/2E_A,$$

where M_B is the invariant mass of the observed recoiling particle or particles. In the production of a system of ordinary particles,

$$E_B \leqslant (E_A^2 + M_B^2)/2E_A.$$

Therefore, tachyon production is characterized by recoil energies beyond the usual limit. Since in any case production of particles is restricted by the conservation of energy, we have

$$M_B < E_B \leqslant E_A. \qquad (1.6)$$

If the upper inequality is not satisfied, then a neutral particle must have been absorbed in addition to those detected. Since that will depend on the ambient density of such particles in the environment, it is unknown, and we disregard that possibility in the following. Combining (1.5) and (1.6), we see that the quantity M^2 is constrained by

$$-E_A^2 + M_B^2 < -M^2 < (E_A - M_B)^2, \qquad (1.7)$$

where of course only the negative values are of interest.

For single-tachyon production $M^2 = \mu^2$, and (1.7) then gives the range of values that can be explored in any experiment. For pair production we must take M^2 to be the total mass of the pairs, as given by (1.4), and then (1.7) gives the region of the spectrum of this variable accessible in the experiment.

In Sec. II of this paper, we present our results for the two reactions in which we have searched for tachyons, i.e.,

$$(1) \quad k^- p \to \Lambda^0 + x^0$$

and

$$(2) \quad \bar{p} p \to \pi^+ \pi^- + x^0.$$

In Sec. III we discuss the kinematics and phase space relevant to these reactions. Finally, in Sec. IV, we analyze the implications of our results for tachyon couplings to ordinary particles, consider other sources of information about tachyon interactions, and summarize our present knowledge of them.

We are aware that other experiments can be done or other data reanalyzed to search for tachyon production, and probably better limits than the ones obtained in this experiment could be so established, but so far as we know, this has not yet been carried out. We mention several examples in order to indicate what might be done.

A. $\pi \to \mu \nu x^0$

If the x^0 is one tachyon or more, the muon energy can be greater than the usual kinematic limit for pions at rest. From Eq. (1.5), we see that muons may be produced with energies in the region

$$(m_\pi^2 + m_\mu^2)/2m_\pi < E_\mu < m_\pi.$$

This reaction would be of interest because it would test tachyon production in weak decays. Of course, it would be necessary to exclude pion decays in flight.

B. $K^+ \to \pi^+ + x^0$

In this case, the emitted pion energy can range up to m_K, or beyond the usual limit in K^+ decay. This would be interesting as a test of tachyon emission in strangeness-changing reactions.

C. $\pi^- + p \to n + x^0$

This is one example of many possible production processes that could be used to search for tachyons. If x^0 is made up of or contains tachyons, the neutron can have a higher momentum than would be otherwise allowed [see Eq. (1.5)]. A sensitive search could be carried out by using counter techniques to look at a large number of events.

II. DESCRIPTION OF EXPERIMENT

We have carried out the search for neutral tachyons in four final states:

$$\begin{aligned} K^- + p &\to \Lambda^0 + t^0 \\ &\to \Lambda^0 + t^0 + \bar{t}^0, \\ \bar{p} + p &\to \pi^+ + \pi^- + t^0 \\ &\to \pi^+ + \pi^- + t^0 + \bar{t}^0, \end{aligned}$$

where both the K^- and the $\bar{p}$ were captured at rest in hydrogen. The incoming energy and momentum (zero) are precisely known; the energy and momenta of the outgoing regular particles, the Λ^0 or the $\pi^+\pi^-$ pair, are measured. The energy E and momentum p of the remaining neutrals can then be calculated, using energy and momentum conservation. If these neutrals are made up of slower-than-light particles, then $E^2 - p^2 > 0$, where E and p are the total energy and momentum of the neu-

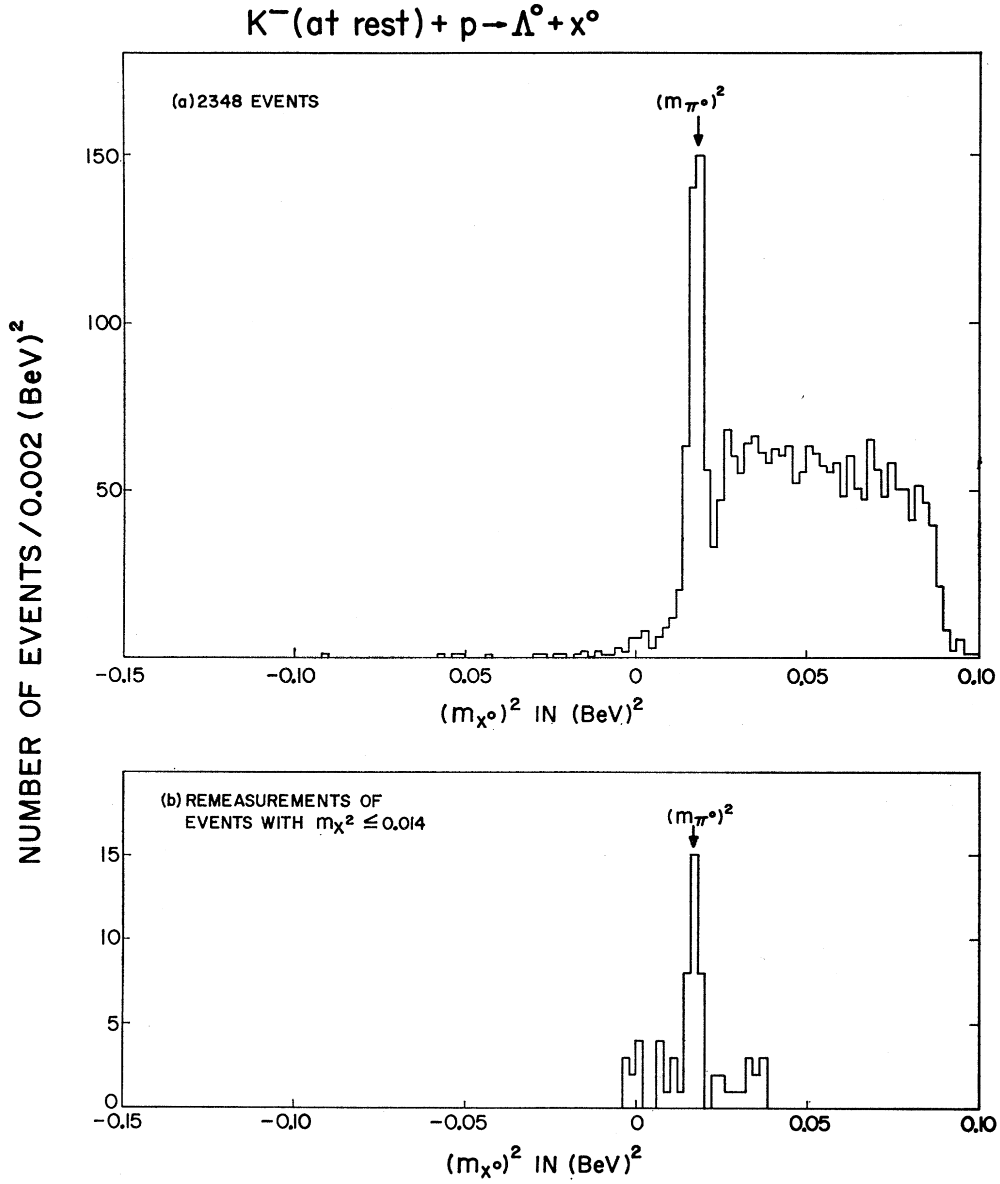

FIG. 1. Distributions in missing mass squared $m_{x^0}{}^2$ in the reaction $K^-+p\rightarrow\Lambda^0+x^0$ for (a) original sample of 2348 events; (b) remeasurements of events which had originally $m_{x^0}{}^2$ below 0.014 BeV^2.

trals. The presence of a tachyon or tachyon pair would be indicated by $E^2-p^2<0$ (i.e., a negative missing mass squared, where $m^2\equiv E^2-p^2$).

This method of searching for tachyons has the advantage that no assumptions have to be made about the behavior of tachyons or their interaction with our apparatus; their detection depends on the momentum measurements of well-known particles like the Λ or the pions.

The main experimental problem is a background of events in which the missing neutral is one or more π^0's, but the measured value of m^2 is negative because of measurement errors, scattering of one of the outgoing tracks, or the finite spread in momentum of the incident particle.

We have selected the reactions initiated by K^- or $\bar{p}$ at rest for two reasons: The energy and momentum of the initial state is very precisely known (except for a small contamination of inflight events); and secondly, the outgoing particles (the $\Lambda^0\rightarrow p+\pi^-$ and the $\pi^\pm$) have relatively low energy and therefore their momenta can be measured more accurately than at higher energies. These two factors lead to a smaller background of events with negative m^2 due to measuring errors.

The K^- and $\bar{p}$ were produced at the Brookhaven alternating-gradient synchrotron (AGS). They were

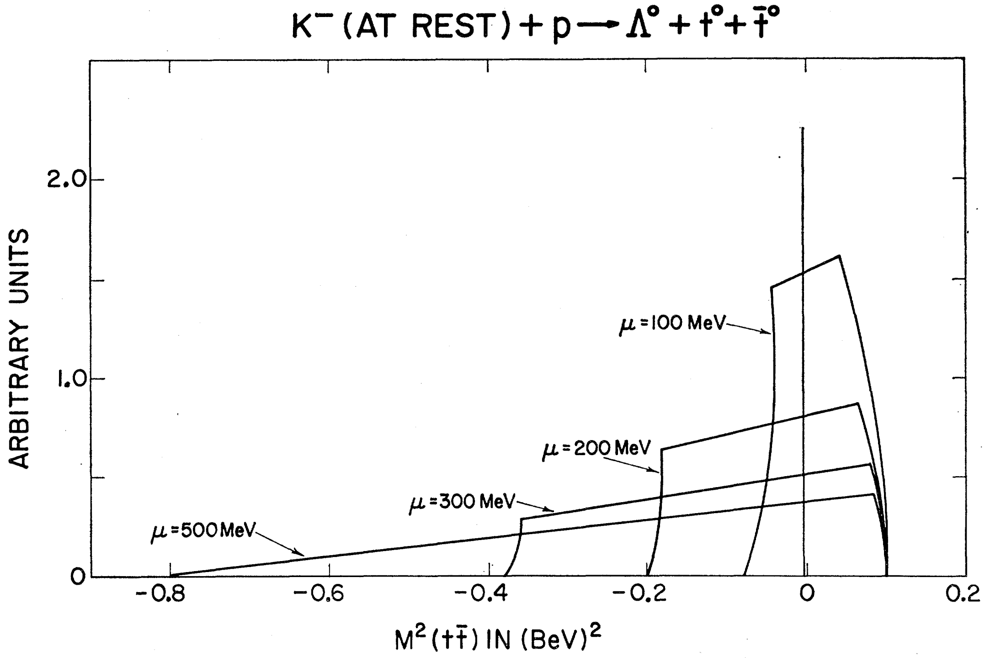

FIG. 2. Typical distributions in the square of the effective mass of the tachyon pair, $M^2(t\bar{t})$, in the reaction $K^-+p \rightarrow \Lambda^0+t+\bar{t}$, for various tachyon rest masses $m_t=i\mu$. (Note that M^2 in the text is defined with a minus sign.)

brought to rest and their interactions with protons were photographed in the 30-in. Columbia-BNL liquid-hydrogen bubble chamber. Approximately 20 000 pictures containing eight K^- stops each and $\sim$10 000 pictures containing on the average of $1\frac{1}{2}$ antiproton stops each were used in the tachyon search; these pictures were parts of large exposures obtained for a variety of other purposes. About 6000 events consisting of a K^- stop and an associated $\Lambda \rightarrow p+\pi^-$ decay and 4800 events consisting of a $\bar{p}$ annihilation into two charged products were used; these events had been previously measured as parts of other experiments.[4,5] The measurements were processed through the TVGP and SQUAW geometrical reconstruction and kinematic fitting programs.

The square of the invariant effective mass of the undetected neutrals in these reactions (called the missing mass squared m^2, for short) was calculated assuming that the incident K^- or $\bar{p}$ were captured at rest. However, of the order of 3–5% of these events were due to interactions of inflight K^- or $\bar{p}$, with typical momenta of around 100–250 MeV/c. These events, when (incorrectly) interpreted as due to at-rest annihilation, had apparent negative m^2 if the visible particles, the Λ^0 or the $\pi^+\pi^-$ pair, were produced in roughly the same direction as the incident K^- or $\bar{p}$. This can be seen by considering for example the reaction $K^-+p \rightarrow \Lambda^0\pi^0$, with an inflight K^-, with the Λ^0 given off in the same direction as the incident K^-. The Λ^0 will then have a larger lab momentum than would be allowed if the K^- had interacted at rest. If the missing mass squared for this event were calculated assuming the K^- to be at rest, a negative m^2 would result. These events constitute a background in the region where the tachyons are expected to be. This situation will not arise if the Λ^0 is given off at a large angle with respect to the K^- direction.

To eliminate this background, all events in which the Λ^0 momentum, or the vector sum of the π^+ and π^- momenta, was within 60° of the incident K^- or $\bar{p}$ direction, respectively, were removed from the sample. Since the Λ^0 and the $\pi^+\pi^-$ pairs from annihilations at rest have to be isotropic, independently of whether the neutral particles produced along with them are pions or tachyons, this cut cannot bias in any way the search for tachyons produced by K^- or $\bar{p}$ at rest.

A. $K^-+p \rightarrow \Lambda^0+$ Neutrals

From a large sample of events consisting of an incident K^- track and an associated $\Lambda \rightarrow p+\pi^-$ decay, a smaller sample was selected which occurred in a small fiducial volume in the chamber, to ensure that all outgoing tracks had sufficient length for accurate measurement. It was further required that the path length of the Λ^0 be longer than 0.2 cm projected on the chamber window, and shorter than 5.0 cm. A threefold overconstrained kinematic fit was performed for these events to make sure that the Λ^0 originated at the K^- stop. Because of the short lifetime of the Σ^0, events which were K^-

[4] C. Boltay, P. Franzini, G. Lütjens, J. C. Severiens, D. Tycko, and D. Zanello, Phys. Rev. **145**, 1103 (1966). Other references to the $\bar{p}$ work are given in this paper.

[5] N. Yeh, C. Baltay, A. Bridgewater, W. A. Cooper, and M. Habibi, Bull. Am. Phys. Soc. **14**, 94 (1969); (to be published).

$+p\rightarrow\Sigma^0+$neutrals, followed by $\Sigma^0\rightarrow\Lambda^0+\gamma$, satisfied this fit and were included in the sample. The final condition, that the angle between the Λ^0 and the K^- direction be larger than 60° in the lab, was imposed.

After these cuts, a sample of 2348 events remained. The distribution in m^2 for these events is shown in Fig. 1(a). A sharp peak at $m_{\pi^0}{}^2$ is due to $K^-+p\rightarrow\Lambda^0+\pi^0$ events; the sharpness of the peak indicates that the resolution in m^2 is $\sim$0.002 BeV^2. The events above the peak are due to the reaction $K^-+p\rightarrow\Sigma^0+\pi^0$. There is an indication of a small cluster around $m^2=0$ which is probably due to the reaction $K^-+p\rightarrow\Lambda^0+\gamma$. There were 23 events with $m^2\leqslant-0.004$. To check whether these were valid events, all 95 events with $m^2\leqslant+0.014$ were reexamined on large-magnification measuring tables. Of these, 29 were found to be not good events; the remainder were remeasured. The distribution in m^2 for these remeasurements is shown in Fig. 1(b). The nine events between $m^2=-0.004$ BeV^2 and $m^2=0.004$ BeV^2 are probably due to $K^-+p\rightarrow\Lambda^0+\gamma$. There are no events below $m^2=-0.004$ BeV^2. The peak at $m_{\pi^0}{}^2$ corresponds to $\sim$500 events of $K^-+p\rightarrow\Lambda^0+\pi^0$, and the remaining 1839 events are due to $K^-+p\rightarrow\Sigma^0+\pi^0$ (the contribution from $K^-+p\rightarrow\Lambda^0\pi^0\pi^0$ is suppressed by phase space and is negligible here).

In the case of single-tachyon production in the reaction $K^-+p\rightarrow\Lambda^0+t^0$ at rest, there is a kinematic limit on the mass of the tachyon given by Eq. (1.7); it cannot be heavier than $m_t=900i$ MeV. (The limiting case occurs when the full energy of the K^-+p system goes to the Λ^0, and the tachyon carries off zero energy.) Single tachyons would be detected in this experiment if they were heavier than $m_t=80i$ MeV (if they were lighter, they could not be separated from $K^-+p\rightarrow\Lambda\gamma$). Between these two limits we can then set the following upper limits on single-tachyon production, interpreting the 0 observed events as an upper limit of 1 event:

$$\begin{aligned}(K^-+p\rightarrow\Lambda^0+t^0)/(K^-+p\rightarrow\Lambda^0+\pi^0)&\lesssim2\times10^{-3},\\(K^-+p\rightarrow\Lambda^0+t^0)/(K^-+p\rightarrow\Sigma^0+\pi^0)&\lesssim5\times10^{-4}.\end{aligned}\tag{2.1}$$

If a pair of tachyons are produced, the square of the effective mass of the pair can be positive or negative. A calculation of the distribution in $M^2(t\bar{t})$ based on a simple phase-space model is described in the next section. Figure 2 shows some typical distributions. The detection efficiency for observing a tachyon pair in this experiment as a function of the tachyon mass $m_t=i\mu$ is taken to be the fraction of the phase-space distribution with $M^2(t\bar{t})\leqslant-0.004$. This efficiency is shown in Fig. 3 as a function of μ. For μ above $\sim$300 MeV, the efficiency levels off at 80%. In this region, the upper limits for tachyon pair production can be given as

$$\begin{aligned}(K^-+p\rightarrow\Lambda^0+t^0+\bar{t}^0)/(K^-+p\rightarrow\Lambda^0+\pi^0)&\\ \leqslant2.5\times10^{-3},&\\(K^-+p\rightarrow\Lambda^0+t^0+\bar{t}^0/)(K^-+p\rightarrow\Sigma^0+\pi^0)&\\ \leqslant7\times10^{-4}.&\end{aligned}\tag{2.2}$$

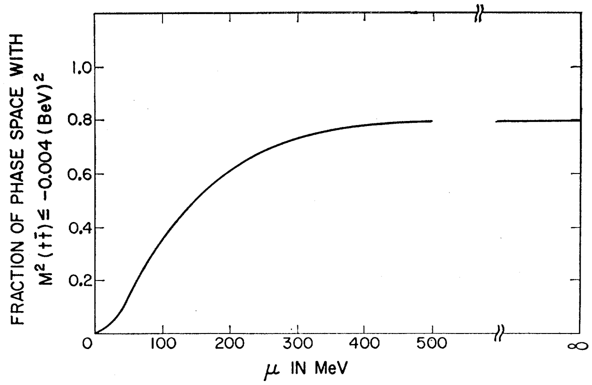

FIG. 3. Detection efficiency for tachyon pairs in the reaction $K^-+p\rightarrow\Lambda+t+\bar{t}$ as a function of the tachyon mass $m_t=i\mu$.

B. $\bar{p}+p\rightarrow\pi^++\pi^-+$Neutrals

A sample of antiproton annihilations into two charged products was selected where the annihilations occurred in a small, clearly visible fiducial volume in the center of the bubble chamber. Thirty-eight events which made a successful four-constraint kinematic fit to the reaction $\bar{p}+p\rightarrow\pi^++\pi^-$ were removed from the sample. In addition, all events for which the angle between the incident $\bar{p}$ direction and the vector sum of the π^+ and the π^- momenta was less than 60° were removed from the sample, to eliminate the background due to inflight annihilations, as discussed above. After these cuts, 2903 events remained. The distribution in m^2, the square of the effective mass of the missing neutrals, is shown in Fig. 4(a). A peak at the π^0 mass squared is due to the reaction $\bar{p}+p\rightarrow\pi^++\pi^-+\pi^0$. There is also a considerable number of events with $m^2\leqslant0$, presumably due to the tail of the π^0 peak. To eliminate the π^0 background in the region $m^2\leqslant0$, all events consistent with $\bar{p}+p\rightarrow\pi^++\pi^-+\pi^0$ were removed from the sample. Events were called consistent with $\bar{p}+p\rightarrow\pi^+\pi^-+\pi^0$ if $|m^2-m_{\pi^0}{}^2|\leqslant3\delta m^2$, where δm^2 is the combined measurement and multiple-scattering error on m^2, computed for each individual event in the kinematical fitting programs. Removing these events also would remove some fraction of any possible true tachyon events if their m^2 was close to zero. Typically, $\delta m^2=0.06$ BeV^2, so approximately one-half of a true signal would be removed at $M^2(t)$ or $M^2(t\bar{t})=-0.16$ BeV^2; the loss would be negligible for $M^2(t\bar{t})\leqslant-0.28$ BeV^2. This loss of efficiency for tachyon events at M^2 near zero has been folded into the detection efficiency curves shown in Fig. 6.

The distribution in missing mass squared for the events remaining after the $\bar{p}+p\rightarrow\pi^++\pi^-+\pi^0$ events were removed is shown in Fig. 4(b). There are eight events with negative m^2. These events were carefully examined on high-magnification measuring tables; five of these eight events were found to be not two-pronged or to have scatters on one of the outgoing tracks which were not noticed on the first measurement of these events. The remaining three seemingly good events

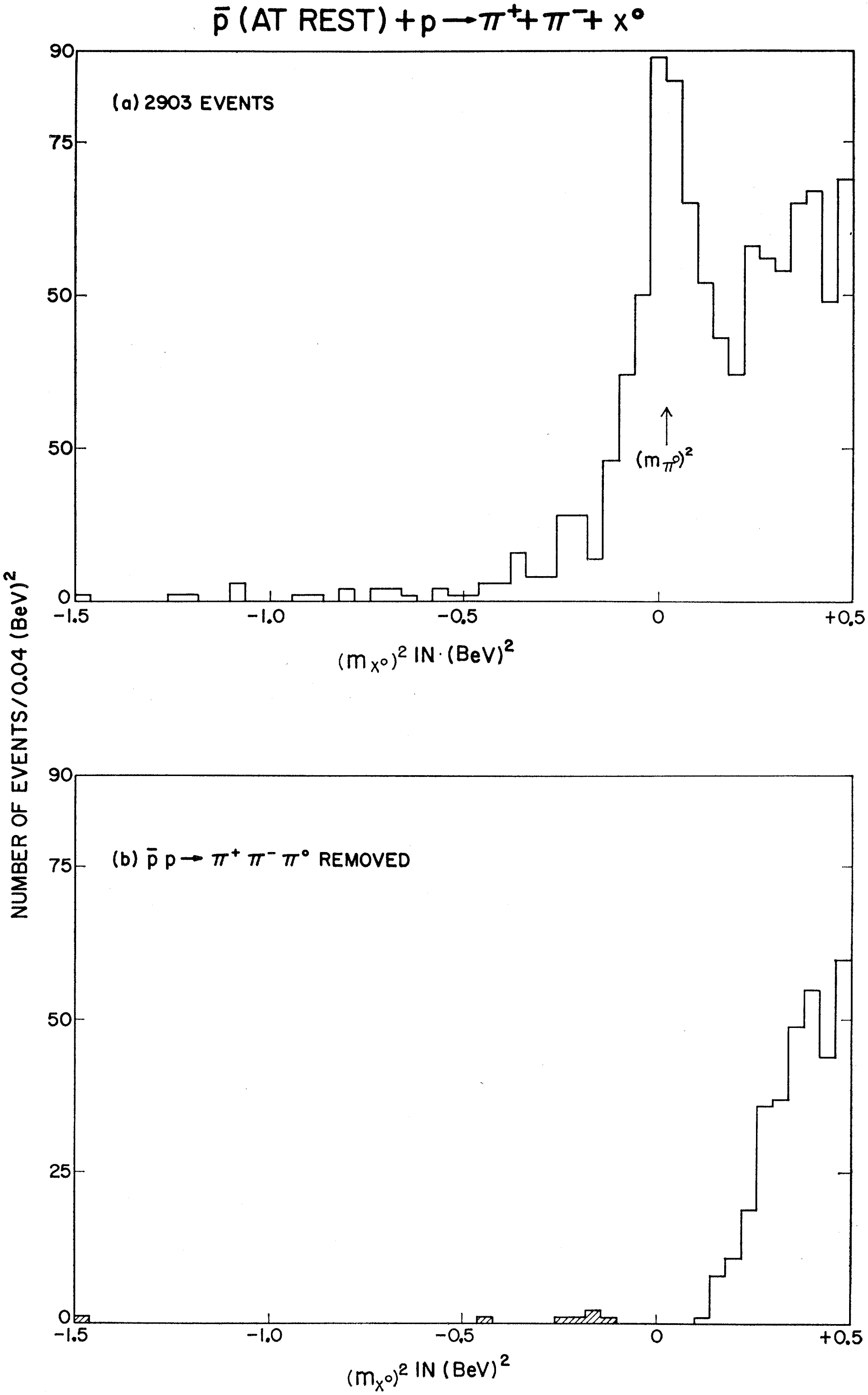

FIG. 4. Distribution in missing mass squared $m_{x^0}{}^2$ in the reaction $\bar{p}+p\rightarrow\pi^++\pi^-+x^0$. (a) Complete sample of 2903 two-pronged events; (b) distribution left after events consistent with $\bar{p}+p\rightarrow\pi^++\pi^-+\pi^0$ were removed. The cross-hatched events were reexamined and found to be mismeasured or not valid two-prong events.

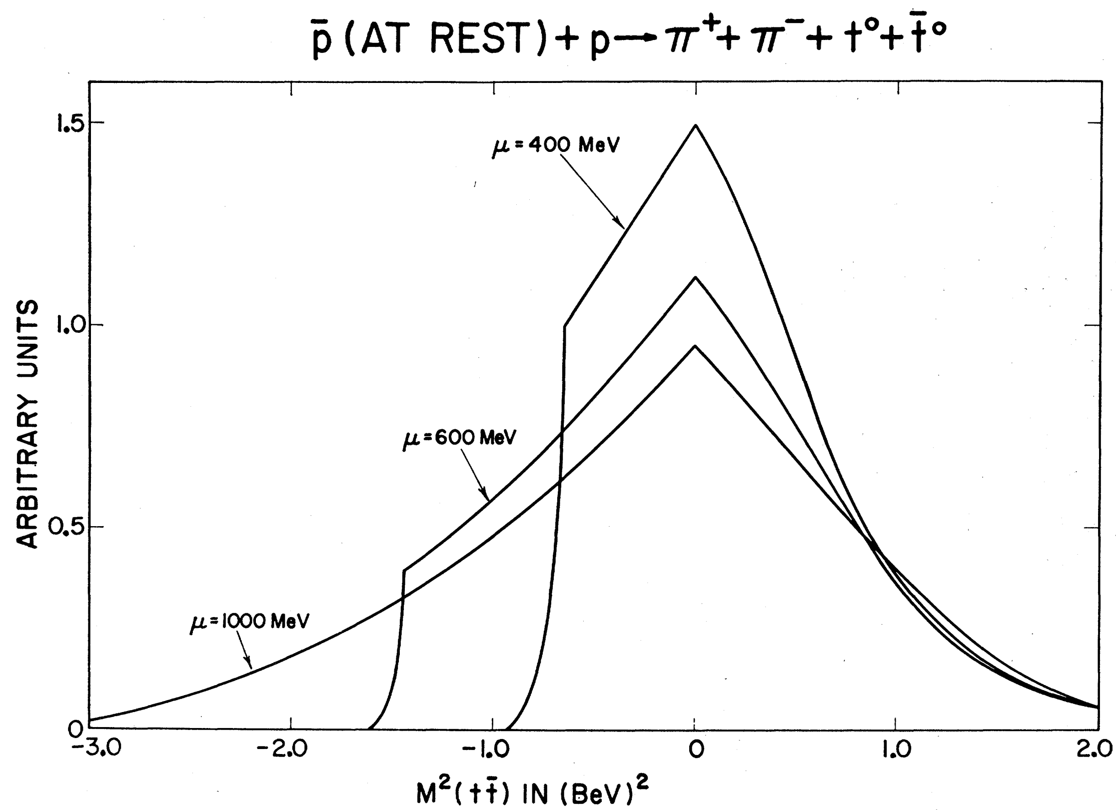

FIG. 5. Typical distributions in the square of the effective mass of the tachyon pair, $M^2(t\bar{t})$, in the reaction $\bar{p}+p \rightarrow \pi^+ + \pi^- + t + \bar{t}$ for various tachyon masses $m_t = i\mu$.

were remeasured. All of these remeasurements yielded positive m^2, consistent with $m_{\pi^0}{}^2$. There are thus no events left with negative missing mass squared.

For single-tachyon production in the reaction $\bar{p}+p \rightarrow \pi^+ + \pi^- + t^0$ at rest, the kinematic upper limit on the tachyon mass is $m_t = 1860i$ MeV. The experimental sensitivity drops off below $m_t = 400i$ MeV. Between these values, the upper limit on the annihilation rate, interpreting the 0 observed events as less than one event, is

$$\text{Rate}(\bar{p}+p \rightarrow \pi^+ + \pi^- + t^0) \leqslant 1/2903 \times 0.426 = 1.5 \times 10^{-4},$$

where 0.426 is the annihilation rate into all two-prongs.[4] (The annihilation rate is defined here as the fraction of all annihilations.)

The phase-space-model calculation is presented in the next section. Figure 5 shows some typical distributions in M^2 for various tachyon masses. As shown in Fig. 6, the detection efficiency approaches 0.46 above $\mu = 400$ MeV. Using this value, we calculate an upper limit on the annihilation rate:

$$\text{Rate}(\bar{p}+p \rightarrow \pi^+ + \pi^- + t^0 + \bar{t}^0) \leqslant 1/2903 \times 1/0.46 \times 0.426 \leqslant 3 \times 10^{-4}.$$

For comparison, the annihilation rates into three and four pions are estimated to be 0.09 and 0.25, respectively.[6] This gives the following upper limits on the ratios:

$$(\bar{p}+p \rightarrow \pi^+ + \pi^- + t^0)/(\bar{p}+p \rightarrow 3\pi) \lesssim 2 \times 10^{-3},$$
$$(\bar{p}+p \rightarrow \pi^+ + \pi^- + t^0 + \bar{t}^0)/(\bar{p}+p \rightarrow 4\pi) \lesssim 1 \times 10^{-3}. \quad (2.3)$$

III. KINEMATICS AND PHASE SPACE FOR PRODUCTION OF TACHYONS

In this section, we consider the kinematics and phase space for the two processes that we have examined in

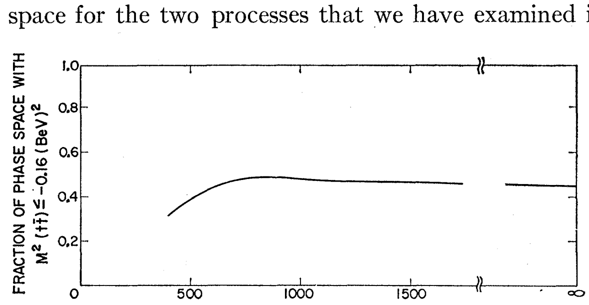

FIG. 6. Detection efficiency for tachyon pairs in the reaction $\bar{p}+p \rightarrow \pi^+ + \pi^- + t + \bar{t}$ as a function of the tachyon mass $m_t = i\mu$.

[6] These numbers contain all pion charge configurations and were obtained by using Table I of Ref. 3, and making some reasonable assumptions about the $2\pi^0$ contents of the channels $\bar{p}+p \rightarrow n + \pi^0$ and $\bar{p}+p \rightarrow \pi^+ + \pi^- + n + \pi^0$, where $n = 2$ or larger.

Sec. II. We do this in some detail because the unfamiliar properties of tachyons lead to a quite distinct behavior of their kinematics and phase space. We do not attempt here to give a detailed treatment of the interactions that may produce tachyons, and hence we use the simplest possible covariant expressions for the relevant matrix elements.

The kinematics of single-tachyon production are elementary, and have been essentially given in Sec. I, Eq. (1.7), when the tachyon is produced with one additional particle. If, instead, it is produced with two ordinary particles, as in the $p\bar{p}$ experiment, the mass M_B of Eqs. (1.5)–(1.7) is a variable quantity, which is defined by $(p_1+p_2)^2$, with p_1 and p_2 the four-momenta of the two particles. Since we are interested in exploring large negative values of missing mass squared, it follows from Eq. (1.7) that we wish to choose $(p_1+p_2)^2$ as small as possible, which for two pions corresponds to $4m_\pi^2$, which we may anyway neglect compared to $E_A{}^2=4m_{\rm prot}{}^2$.

For tachyon pair production, however, the kinematics are more complicated. Suppose that the pair is produced with one additional particle, as in the K^-p reaction. We know that the range in missing mass squared that can be observed is given by Eq. (1.7). We would like to know the values of tachyon mass $i\mu$ for which a pair could have a total mass in this range, given that each tachyon has a non-negative energy. It is shown below that there are two cases to consider:

(a) When $4\mu^2<E_A{}^2-M_B{}^2$, the total mass lies in the range

$$\frac{-\mu^2(E_A{}^2+M_B{}^2)-[E_A{}^2\mu^2(E_A{}^2-M_B{}^2)^2+4E_A{}^2M_B{}^2\mu^4]^{1/2}}{E_A{}^2-M_B{}^2}<-M^2<(E_A-M_B)^2.$$

The lower limit is greater than $-E_A{}^2+M_B{}^2$, for any value of $\mu^2<\frac{1}{4}(E_A{}^2-M_B{}^2)$.

(b) When $4\mu^2>E_A{}^2-M_B{}^2$, the total mass lies in the range

$$-E_A{}^2+M_B{}^2<-M^2<(E_A-M_B)^2.$$

Hence, in either case, and so for all values of μ^2, there are kinematical configurations of the tachyons which give total mass squared in the observable region.

Since for positive or slightly negative values of $-M^2$ the tachyon pair cannot be distinguished from a pair of ordinary particles, we must ask for the probability that the value of $-M^2$ for a given μ^2 lies below some cutoff mass. This has been calculated below using a simple covariant phase-space model. The result is roughly that a substantial portion of the phase space occurs for values of M^2 that the experiment is sensitive to. This implies that an experiment will be sensitive to tachyon pairs with individual masses above some minimum value, depending on the smallest $-M^2$ that can be experimentally distinguished from a positive value. The fraction of all tachyon pair events which lie in that region are given for the parameters of our experiments in Figs. 3 and 6.

We turn to the phase-space calculations.

A. Three-Body Decay

We first consider the decay of a system of energy E_A at rest into one ordinary particle (energy E_1, rest mass M_B) and two tachyons (energies E_2 and E_3, and rest mass$=i\mu$). The transition probability per second is

$$W=\int\frac{|M|^2}{(4\pi)^3E_A}\delta(E_A-E_1-E_2-E_3)\times\frac{p_1{}^2dp_1p_2{}^2dp_2d\eta}{E_1E_2E_3},\quad(3.1)$$

where $\eta\equiv\cos(\mathbf{p}_1,\mathbf{p}_2)$ and the matrix element $|M|^2$ will be chosen to be Lorentz-invariant. Performing the integration over η, we find

$$W=\int\frac{|M|^2}{(4\pi)^3E}dE_1dE_2\,,\quad(3.2)$$

$$\eta=(\alpha-2E_1'E_2)/2p_1p_2\quad(3.3)$$

is the constraint imposed by the δ function in (3.1). Here we have introduced

$$E_1'\equiv E_A-E_1$$

and

$$\alpha\equiv-M^2.$$
$$=E_1'^2-p_1{}^2.\quad(3.4)$$

We note that

$$E_1'=(E_A{}^2-M_B{}^2+\alpha)/2E_A\quad(3.5)$$

and

$$p_1=[(\alpha-M_B{}^2)^2-2E_A{}^2(\alpha+M_B{}^2)+E_A{}^4]^{1/2}/2E_A.\quad(3.6)$$

The requirement that $|\eta|\leqslant1$ implies that

$$\alpha E_2{}^2-\alpha E_1'E_2+(\tfrac{1}{4}\alpha^2-p_1{}^2\mu^2)\leqslant0.\quad(3.7)$$

Because we are dealing with tachyons, α may take on both negative and positive values. The range of values of E_2 allowed by (3.7) depends upon α as follows:

$$\begin{aligned}&\text{If}\quad\alpha<-4\mu^2:\quad E_2\leqslant E_{2-}\quad\text{or}\quad E_2\geqslant E_{2+};\\&\text{if}\quad-4\mu^2<\alpha<0:\quad\text{all } E_2\text{ are allowed};\\&\text{if}\quad0<\alpha:\quad E_{2-}\leqslant E_2\leqslant E_{2+},\end{aligned}\quad(3.8)$$

where

$$E_{2\pm}\equiv\tfrac{1}{2}[E_1'\pm p_1(1+4\mu^2/\alpha)^{1/2}].\quad(3.9)$$

Requiring in addition that $0\leqslant E_2\leqslant E_1'$ gives the following cases $[s\equiv(1+4\mu^2/\alpha)^{1/2}]$:

If $\alpha<-4\mu^2$ and $E_1'<-\alpha s/2\mu$:

no value of E_2 is allowed;

if $\alpha < -4\mu^2$ and $E_1' \geqslant -\alpha s/2\mu$:

$$\text{all } E_2 \text{ satisfying } 0 \leqslant E_2 \leqslant E_{2-} \text{ or } E_{2+} \leqslant E_2 \leqslant E_1' \text{ are allowed;} \quad (3.10)$$

if $-4\mu^2 < \alpha < 0$: $0 \leqslant E_2 \leqslant E_1'$ are allowed;

if $\alpha > 0$ and $E_1' \geqslant \alpha s/2\mu$:

$$0 \leqslant E_2 \leqslant E_1' \text{ are allowed;}$$

if $\alpha > 0$ and $E_1' \leqslant \alpha s/2\mu$:

$$E_{2-} \leqslant E_2 \leqslant E_{2+} \text{ are allowed.}$$

Since $0 \leqslant E_1' \leqslant E$, and since p_1 must be real, we have

$$M_B^2 - E_A^2 \leqslant \alpha \leqslant (E_A - M_B)^2. \quad (3.11)$$

Thus, if $\mu > \mu_0 \equiv \frac{1}{2}(E_A - M_B^2)^{1/2}$, α cannot be $< -4\mu^2$. Incorporating (3.11) into (3.10) and writing the E_1' inequalities as conditions on α, we completely determine the limits of the phase-space integration as follows.

For $\mu < \mu_0$:

case I: $\alpha_- < \alpha < -4\mu^2$: $0 \leqslant E_2 \leqslant E_{2-}$ or $E_{2+} \leqslant E_2 \leqslant E_1'$; (3.12)

case II: $-4\mu^2 < \alpha < \alpha_+$: $0 \leqslant E_2 \leqslant E_1'$;

case III: $\alpha_+ < \alpha < (E_A - M_B)^2$: $E_{2-} \leqslant E_2 \leqslant E_{2+}$.

For $\mu > \mu_0$, case I does not occur, and the lower limit on α in case II should be changed from $-4\mu^2$ to $M_B^2 - E_A^2$. We have used

$$\alpha_\pm \equiv \frac{-\mu^2(E_A^2 + M_B^2) \pm [E_A^2\mu^2(E_A^2 - M_B^2)^2 + 4E_A^2M_B^2\mu^4]^{1/2}}{E_A^2 - \mu^2}.$$

We note that in this calculation we have integrated only over positive tachyon energies.

In Fig. 2 we have plotted $dW/d\alpha$ versus α for the process $K^-p \to \Lambda^0 tt'$, for several values of μ. $|M|^2$ has been taken to be constant (for fixed μ) and each curve has been normalized to the same total area. Several features are noteworthy: (1) The cusps at $\alpha = -4\mu^2$ (when $\mu < \mu_0$) and at $\alpha = \alpha_+$ are mathematically sharp; (2) the linear region (corresponding to case II) depends on μ only through $|M|^2$; and (3) for $\mu \gtrsim 500$ MeV, the entire curve is nearly insensitive to changes in μ, because the case-III region is almost negligible. The fraction of the total area that lies to the left of $\alpha = -(63\text{ MeV})^2$ (i.e., in the region to which this experiment was sensitive) is given in Fig. 3 as a function of μ. The physical significance of the α and E_2 bounds is indicated in Fig. 7, for $\mu < \mu_0$.

B. Four-Body Decay

We now consider the decay of a system of energy E at rest into two massless particles (energies E_1 and E_2) and two tachyons (energies E_3 and E_4, rest mass $= i\mu$). The results of the analysis will be applied to the process $p\bar{p} \to \pi^+\pi^- tt'$, where the pion mass is to be ignored for simplicity. We again integrate only over positive tachyon energies.

The calculation proceeds as in the three-body case; the restrictions imposed upon E_3 by condition $|\cos(\mathbf{p}_1 + \mathbf{p}_2, p_3)| \leqslant 1$ are given by Eq. (3.10), when the replacements $E_1' \to E_2' \equiv E - E_1 - E_2$, $E_2 \to E_3$, $E_{2\pm} \to E_{3\pm}$, and $p_1 \to |\mathbf{p}_1 + \mathbf{p}_2|$ are made, and α is defined as $= E_2'^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2$. We next eliminate the angular variable $\gamma \equiv \cos(\mathbf{p}_1, \mathbf{p}_2)$ in favor of α by noting that

$$\gamma = \frac{2EE_2' - E^2 - \alpha}{2p_1(E - p_1 - E_2')} + 1. \quad (3.13)$$

Then $|\gamma| \leqslant 1$ implies

$$E_2' \leqslant (E^2 + \alpha)/2E \quad \text{and} \quad E_2'(2p_1 - E) \leqslant \tfrac{1}{2}(4p_1E - 4p_1^2 - E^2 - \alpha). \quad (3.14)$$

Requiring, in addition, that $0 \leqslant p_1 \leqslant E$ and $0 \leqslant E_2' \leqslant E - p_1$ gives the over-all constraints on E_2' as a function of α and p_1. (We define $A \equiv [4p_1(p_1 - E) + E^2 + \alpha]/2(E - 2p_1)$ and $s \equiv (1 + 4\mu^2/\alpha)^{1/2}$.)

For $\alpha < 0$:

If $0 \leqslant p_1 \leqslant \frac{1}{2}E$: $A \leqslant E_2' \leqslant (E^2 + \alpha)/2E$;

if $\frac{1}{2}E \leqslant p_1 \leqslant (E^2 - \alpha)/2E$: $0 \leqslant E_2' \leqslant (E^2 + \alpha)/2E$; (3.15a)

if $(E^2 - \alpha)/2E \leqslant p_1 \leqslant \frac{1}{2}[E + \sqrt{(-\alpha)}]$: $0 \leqslant E_2' \leqslant A$;

if $\frac{1}{2}[E + \sqrt{(-\alpha)}] \leqslant p_1$: no E_2' is allowed.

For $\alpha > 0$:

If $0 \leqslant p_1 \leqslant (E^2 - \alpha)/2E$: $A \leqslant E_2' \leqslant (E^2 + \alpha)/2E$; (3.15b)

if $(E^2 - \alpha)/2E < p_1$: no E_2' is allowed.

For $\alpha < -4\pi^2$, we have the additional condition

$$-\alpha s/2\mu \leqslant E_2' \leqslant E - p_1. \quad (3.15c)$$

Combining (3.15a) with (3.15c) and introducing Eq. (3.10) (modified for the four-body case as described above), we obtain the α, p_1, E_2', and E_3 ranges to be used as the limits of the phase-space integrations:

$$-E^2 \leqslant \alpha \leqslant E^2. \quad (3.16)$$

Case I. For $E^2\mu/(\mu - E) \leqslant \alpha \leqslant -4\mu^2$:

If $0 \leqslant p_1 \leqslant \frac{1}{2}E + (\alpha/4\mu)(s+1)$:
use $A \leqslant E_2' \leqslant (E^2 + \alpha)/2E$;

if $\frac{1}{2}E + (\alpha/4\mu)(s+1) \leqslant p_1 \leqslant (E^2 - \alpha)/2E$:
use $-\alpha s/2\mu \leqslant E_2' \leqslant (E^2 + \alpha)/2E$; (3.17)

if $(E^2 - \alpha)/2E \leqslant p_1 \leqslant \frac{1}{2}E + (\alpha/4\mu)(s-1)$:
use $-\alpha s/2\mu \leqslant E_2' \leqslant A$.

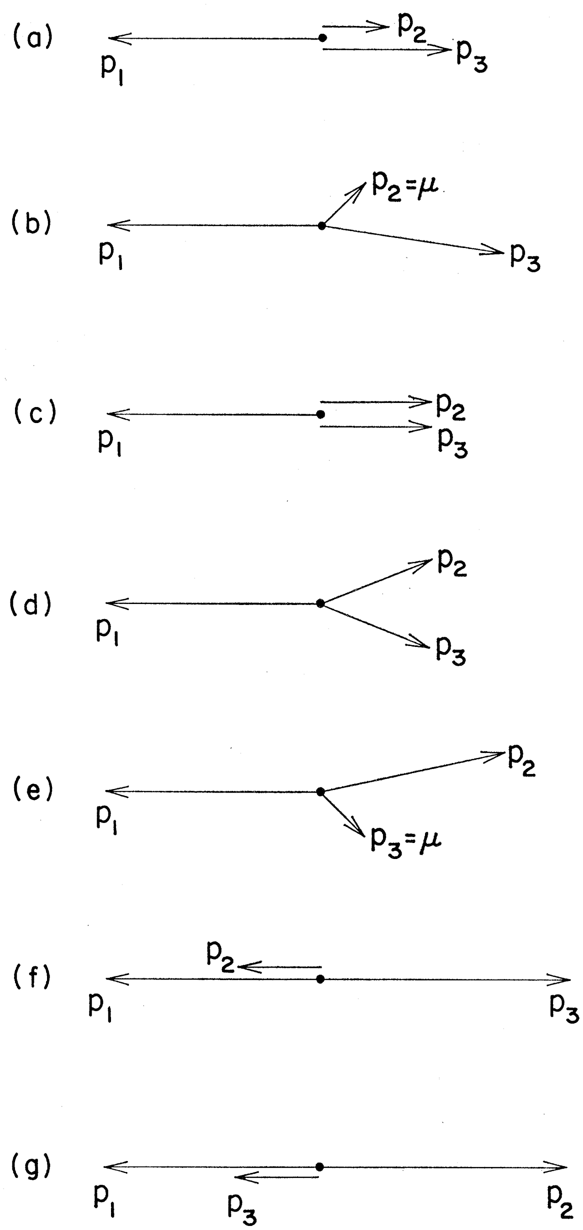

FIG. 7. Momentum configurations for three-body decay. For $\alpha=\alpha_-$, (a) with $p_2=0$ or $p_3=0$ are the only allowed configurations. For $\alpha_-<\alpha<-4\mu^2$, the configuration passes from (b) when $E_2=0$ to (a) (with $\mu<p_2<p_3$) when $E_2=E_{2-}$. At $\alpha=-4\mu^2$, p_2 and p_3 become equal as they approach collinearity (c); we thus pass from (b) through (c) to (e) without a break in the allowed value of p_2, as E_2 is increased from zero to E_A-E_1. For $-4\mu^2<\alpha<\alpha_+$, as E_2 in increased from zero to E_A-E_1, we pass from (b) through (d) to (e). At $\alpha=0$, the angle between p_1 and p_2 in (b), or between p_1 and p_3 in (e), equals $\frac{1}{2}\pi$; it decreases to zero as α is increased to α_+. Finally, when $\alpha>\alpha_+$, the angle between p_1 and p_2 increases from zero to π as E_2 increases from E_{2-} to E_{2+} [(f) $\rightarrow$ (d) $\rightarrow$ (g)].

The allowed E_3 ranges for (3.17) are $0\leqslant E_3\leqslant E_{3-}$ and $E_{3+}\leqslant E_3\leqslant E_2'$, where $E_{3\pm}\equiv\frac{1}{2}[E_2'\pm s(E_2'^2-\alpha)^{1/2}]$. When $E<2\mu$, case I is forbidden by $\alpha\geqslant -E^2$ and therefore does not arise.

Case II. For $-\frac{1}{4}\mu^2\leqslant\alpha\leqslant 0$:

If $0\leqslant p_1\leqslant\frac{1}{2}[E-\surd(-\alpha)]$:

$$\text{use } A\leqslant E_2'\leqslant (E^2+\alpha)/2E;$$

if $\frac{1}{2}[E-\surd(-\alpha)]\leqslant p_1\leqslant (E^2-\alpha)/2E$:

$$\text{use } 0\leqslant E_2'\leqslant (E^2+\alpha)/2E;$$

if $(E^2-\alpha)/2E\leqslant p_1\leqslant\frac{1}{2}[E+\surd(-\alpha)]$:

$$\text{use } 0\leqslant E_2'\leqslant A\,. \qquad (3.18)$$

The allowed E_3 range for (3.18) is $0\leqslant E_3\leqslant E_2'$. When $E<2\mu$, the inequality that defines case II should read $-E^2\leqslant\alpha\leqslant 0$.

Case III. For $0<\alpha\leqslant E^2\mu/(E+\mu)$:

If $0\leqslant p_1<\frac{1}{2}E-(\alpha/4\mu)(s+1)$:
use $A\leqslant E_2'\leqslant (E^2+\alpha)/2E$ with $0\leqslant E_3\leqslant {}_2E'$;

if $\frac{1}{2}E-(\alpha/4\mu)(s+1)\leqslant p_1\leqslant\frac{1}{2}E-(\alpha/4\mu)(s-1)$:
the ranges are $A\leqslant E_2'\leqslant\alpha s/2\mu$
with $E_{3-}\leqslant E_3\leqslant E_{3+}$, (3.19)
and $\alpha s/2\mu\leqslant E_2'\leqslant (E^2+\alpha)/2E$
with $0\leqslant E_3\leqslant E_2'$;

if $\frac{1}{2}E-(\alpha/4\mu)(s-1)\leqslant p_1\leqslant (E^2-\alpha)/2E$:
use $A\leqslant E_2'\leqslant (E^2+\alpha)/2E$ with $0\leqslant E_3\leqslant E_2'$.

Case IV. For $E^2\mu/(E+\mu)\leqslant\alpha\leqslant E^2$:

$0\leqslant p_1\leqslant (E^2-\alpha)/2E$, with $A\leqslant E_2'\leqslant (E^2+\alpha)/2E$
and $E_{3-}\leqslant E_3\leqslant E_{3+}$,
is the only allowed region. (3.20)

Assuming the matrix element $|M|^2$ [in the four-body analog of Eq. (3.1)] to be constant, we may explicitly perform the phase-space integrations over the limits of (3.17)–(3.20). With the definition $C=|M|^2/(4\pi)^5\times 8E$, the results are:

For $E^2\mu/(\mu-E)\leqslant\alpha\leqslant -4\mu^2$:

$$\frac{dW}{d\alpha}=C\left[\left(E+\frac{\alpha}{E}\right)^2-s\left(E^2-\frac{\alpha^2}{E^2}\right)-2\alpha s\ln\left(\frac{\alpha}{E^2}\cdot\frac{s+1}{s-1}\right)\right];$$

for $-4\mu^2\leqslant\alpha\leqslant 0$:

$$\frac{dW}{d\alpha}=C\left(E+\frac{\alpha}{E}\right)^2;$$

for $0<\alpha\leqslant E^2\mu/(E+\mu)$: (3.21)

$$\frac{dW}{d\alpha}=C\left[\left(E+\frac{\alpha}{E}\right)^2-2\alpha s\ln\left(\frac{s+1}{s-1}\right)\right];$$

for $E^2\mu/(E+\mu)\leqslant\alpha\leqslant E^2$:

$$\frac{dW}{d\alpha}=C\left[s\left(E^2-\frac{\alpha^2}{E^2}\right)-2\alpha s\ln\left(\frac{E^2}{\alpha}\right)\right].$$

Inspection of (3.21) shows that the slope of $dW/d\alpha$ (plotted versus α) has discontinuities at the transition points $\alpha=-4\mu^2$ and $\alpha=0$, but not at $\alpha=E^2\mu/(E+\mu)$. The curves for the process $p\bar{p}\to\pi^+\pi^-tt'$, normalized to constant total area, are presented in Fig. 5 for several values of μ.

IV. EXPERIMENTAL LIMITS ON TACHYON INTERACTIONS WITH ORDINARY PARTICLES

Since we have seen no evidence for tachyon production, we must interpret our experiment in terms of upper limits for such production. From Sec. II, Eqs. (2.1)–(2.3), we see that in each case, the upper limit for production of either one or two tachyons is of the order of 10^{-3} of typical strong-interaction processes. The only place where this conclusion might be questioned is for the three-body production

$$K^-p\to\Lambda^0t^0\bar{t}^0,$$

which we have compared with the two-body reaction

$$K^-p\to\Lambda^0\pi^0.$$

It might be thought that we should compare it instead to a three-body reaction like

$$K^-p\to\Lambda^0\pi^+\pi^-.$$

However, the latter is strongly suppressed by phase space, and is only about 1% of the single-pion reaction. On the other hand, the tachyon production reaction is not especially suppressed by phase space, and we therefore believe that it is reasonable to compare it with the single-pion production rather than with the double production.

The production of tachyon pairs in K^- capture at rest could be somewhat suppressed by parity requirements, since the pair must be produced in a p wave. This might give a suppression factor of around $(E_A-m_A)/2m_A\sim\frac{1}{10}$, which would not affect our conclusions substantially. No such effect should occur in $p\bar{p}$ annihilation.

Our conclusion from this experiment is therefore that the production of neutral tachyons in two typical hadron processes is at least three orders of magnitude smaller than the strong interactions. It would therefore seem doubtful that tachyons of any kind can be produced strongly.

We consider next what other information may be available about tachyon production. We calculate all processes by analogy with the production of ordinary particles although we have no detailed theory of interacting tachyons to base the calculations on. For that reason, the estimates below may be considered as somewhat provisional.

If we do not believe that single-tachyon production by ordinary particles is forbidden, we can consider the reaction

$$p\to p+t,$$

which is allowed kinematically whenever the initial proton energy E satisfies

$$E^2>m^2+\tfrac{1}{4}\mu^2. \tag{4.1}$$

If we assume a matrix element for this reaction

$$M=g_{1t}\bar{u}u/(2E_t)^{1/2}, \tag{4.2}$$

we can calculate the rate at which protons will lose energy by emitting tachyons:

$$\frac{dE}{dt}=\frac{1}{4\pi^2}\int|M^2|\,d^3p_t\,\delta(E-E_t-E')E_t \tag{4.3}$$

$$=\frac{g^2}{4\pi}\int\frac{\mu^2+2m^2}{EE'E_t}d\cos\theta\,p_t^2dp_tE_t$$
$$\times\delta(E-E_t-[(p-p_t)^2+m^2]^{1/2}) \tag{4.4}$$

$$=\frac{g_{1t}^2}{4\pi}\int\frac{p_tdp_t}{Ep}(\mu^2+2m^2) \tag{4.5}$$

$$=\frac{g_{1t}^2}{4\pi Ep}\int E_tdE_t(\mu^2+2m^2) \tag{4.6}$$

$$=\frac{g_{1t}^2}{8\pi Ep}(\mu^2+2m^2)\times\left[p\left(\frac{\mu^2}{m^2}+\frac{\mu^4}{4m^2}\right)^{1/2}-\frac{\mu^2}{2m^2}E\right]^2. \tag{4.7}$$

Note that dE/dt is not a scalar quantity, since it depends on E. If we were to integrate over all E_t, both positive and negative, the dE/dt would in fact become a scalar, and would also have opposite sign, corresponding to an energy gain. However, this would correspond to adding tachyon absorption coherently to tachyon emission, which is incorrect, since the absorption rate depends on the tachyons present in the environment. If this is nevertheless done, the result for dE/dt becomes

$$\frac{dE}{dt}=-\frac{g_{1t}^2}{4\pi}(\mu^2+2m^2)\frac{\mu^3}{m^4}(\mu^2+4m^2)^{1/2}. \tag{4.8}$$

Using Eq. (4.7) and assuming $E\gg m$ and $m^2\approx\mu^2$, we get

$$\frac{dE}{dt}\simeq\frac{g_{1t}^2}{8\pi}(\mu^2+2m^2)\left(\frac{\mu^2}{2m^2}\right)^2\left[\left(1+\frac{2m^2}{\mu^2}\right)^{1/2}-1\right]^2 \tag{4.9}$$

$$\simeq(g_{1t}^2/8\pi)m^2. \tag{4.10}$$

It is known that protons of up to 30 GeV travel for times up to 10^{-6} sec in external beams without losing more than, say, 100 MeV. Hence,

$$\frac{g_{1t}^2}{4\pi}m^2<\frac{10^{-1}m}{10^{18}(1/m)}=10^{-19}m^2, \tag{4.11}$$

or

$$g_{1t}^2/4\pi<10^{-19}. \tag{4.12}$$

A similar low limit may be derived for the emission of single tachyons by electrons. Even better limits could be obtained by considering propagation of cosmic rays, but it seems unnecessary. This limit is very small compared to any known coupling (other than gravitational). We can therefore conclude that production of single tachyons is unlikely in laboratory experiments.

Consider next the interaction of charged tachyon pairs with photons. The reaction

$$\gamma \to t+\bar{t}$$

is kinematically allowed for any photon momentum. If we assume the simplest gauge-invariant matrix element

$$M=\frac{e_t}{(8EE_1E_2)^{1/2}}(p_1-p_2)_\mu \mathcal{E}_\mu , \tag{4.13}$$

with e_t the tachyon charge and p_1, p_2 the tachyon four-momenta, we obtain a decay rate

$$R=(e_t^2/4\pi)\mu_t^2/3E. \tag{4.14}$$

It is known that photons of radio frequency (say, $E=10^{-19}$ erg) travel distances of 10^9 light years, or for 10^{16} sec. Hence the decay rate cannot be greater than, say, 10^{-16}/sec. This gives the limit

$$(e_t^2/4\pi)\mu_t^2c^4/\hbar^2<(3E/\hbar)\times 10^{-16},$$

$$(e_t^2/4\pi)\mu_t^2<3\times 10^{-19}\times 10^{-16}\times 10^{-27}\times 10^{-42},$$

or

$$(\alpha_t/\alpha)\mu_t^2/m_e^2<3\times 10^{-104}\times 10^{2}\times 10^{+54}\sim 10^{-48},$$

so

$$(e_t/e)\mu_t/m_e<10^{-24}. \tag{4.15}$$

Therefore, unless their mass is a very small fraction of the electron mass, charged tachyons, if they exist, must have a charge very small compared to the electron's charge.

Finally, we consider other information about the production of neutral tachyon pairs by hadron systems. Again, we may use the fact that protons are known to travel across macroscopic distances without substantial energy loss to obtain a limit for such production processes.

We consider the reaction

$$p\to p+t+\bar{t},$$

which we assume is described by the matrix element (neglecting spin)

$$M=g_{2t}/(16E_pE_p'E_1E_2)^{1/2}. \tag{4.16}$$

This gives a rate of energy loss

$$\frac{dE}{dt}=\frac{g_{2t}^2}{(2\pi)^5E_p}\int\frac{d^3p'd^3p_1d^3p_2}{E_p'E_1E_2}\delta^3(p-p'-p_1-p_2) \times\delta(E_p-E_p'-E_1-E_2)(E_p-E_p'). \tag{4.17}$$

We have calculated this rate of energy loss for the case $E_p\gg m$ and $E_p\gg\mu$, and get

$$\frac{dE}{dt}=\frac{g_{2t}^2}{4\pi}\frac{E^2}{64\pi^2}. \tag{4.18}$$

If we again require $dE/dt<10^{-19}m^2$ for $E^2\sim 10^3m^2$, we obtain

$$g_{2t}^2/4\pi<10^{-19}. \tag{4.19}$$

A similar low limit may be derived for the emission of tachyon pairs by electrons. These limits could also be substantially reduced by consideration of cosmic-ray propagation. Therefore, the coupling constant for tachyon pair production, if nonzero, is also much smaller than any known elementary-particle process. This conclusion could be perhaps avoided only if the interaction has a very different form than any interactions with which we are familiar. However, it seems safe to conclude that tachyons of any kind, if they exist at all, are very weakly interacting with ordinary matter.

In spite of this, we feel it is worthwhile to present the results of our direct search for tachyon emission in hadron processes, since it is imaginable that the usual notions of quantum field theory, according to which a particle which is produced with some coupling in one reaction should be produced with that coupling in other reactions involving the same particle whenever kinematically possible, may be incorrect for tachyons. Therefore, we think it would be worthwhile to analyze other available data for tachyon production along the lines indicated in the Introduction.

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