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Limits on the Rate of Emission of Negative-Energy Tachyons*

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Since the proton is unstable against the tachyonic decay $p\to p+t^0$, in which the tachyon, t^0, has negative energy, we have investigated the limits that can be imposed on such an apparently energy-nonconserving process, as well as on the related process, $p\to p+t+\bar{t}$. Exceedingly long lifetimes for these decays (as well as the corresponding ones involving electrons) were obtained (a) from a careful examination of 5500 bubble-chamber pictures from a special exposure, (b) from reinterpretation of experiments searching for baryon and electron nonconservation, and (c) from data on the heat flow emanating from the earth. The interaction mediating such processes must be much weaker than the gravitational interaction.

I. INTRODUCTION

The topic of faster-than-light particles (tachyons) has recently received considerable attention from theoretical physicists. The extensive theoretical literature which has been produced since the topic of tachyons was first discussed in the framework of the special theory of relativity[1] can be roughly classified into three groups: papers on field theories of tachyons,[2-9] those dealing with various physical properties of tachyons,[10-32] and papers concerned with causality effects associated with tachyons.[33-43] In addition, published data are available on four (negative) experimental tachyon searches made under different assumptions.[44-47] The first of these sought to detect the Čerenkov radiation of tachyons produced by γ rays,[44] two others searched for evidence of tachyon production in a bubble chamber,[45,47] and one was a search for tachyons produced in cosmic-ray interactions.[46] Tachyons obey the relations

$$E=\frac{\mu}{(v^2-1)^{1/2}},\qquad |\vec{p}|=\frac{\mu v}{(v^2-1)^{1/2}},$$

and thus

$$E^2-\vec{p}^{\,2}=-\mu^2<0,\qquad v=|\vec{p}|/E>1$$

(we will use the convention $c\equiv1$, $\hbar\equiv1$ throughout this paper).

As an introduction to the tachyon search which we report, we discuss briefly the type of transitions which can involve tachyons. Consider the transition

$$\text{system }1\to\text{system }2+\text{system }3. \tag{1.1}$$

Take the invariant squared masses of these systems of one or more particles as m_1^2, m_2^2, and m_3^2, respectively. Let systems 1 and 2 be composed of ordinary particles, so that $m_1^2\geq0$ and $m_2^2\geq0$, and consider the process (1.1) in the rest frame of system 1. If $m_3^2<0$, then in this frame $E_2>(m_1^2+m_2^2)/(2m_1)$. As an example, consider the process

$$\text{proton}\to\text{system }2+\text{tachyonic system}. \tag{1.2}$$

Let the proton rest mass be m, and the invariant mass squared of the tachyonic system be $-\mu^2$. If we consider only processes which conserve baryon number, m_2 must be greater than or equal to m, since the proton is the least massive baryon. System 2 could be p, $\Delta^+(1236)$, $p+\gamma$, $p+\pi^0$, etc. In all these cases

$$E_2=\frac{m_2^2+m^2+\mu^2}{2m}>m,$$

so the tachyonic system carries *negative* energy as process (1.2) is written. If the tachyonic system were considered as *incoming* in (1.2), then it would have positive energy.

In the present search we restrict ourselves to the two simplest possibilities, which are the "elastic" tachyonic decays

$$p\to p+t^0 \tag{1.3}$$

and

$$p\to p+t+\bar{t}. \tag{1.4}$$

Call the invariant mass squared of the tachyon in (1.3) $-\mu^2$, and also let $-\mu^2$ be the invariant mass squared of the two-tachyon system in (1.4). We will refer to μ as the "liberty mass"[47] of the tachyon, since it is the tachyon momentum in the Lorentz frame in which $|\vec{p}|=\mu$, $E=0$, $v=\infty$, i.e., where the tachyon is "at liberty." For a proton initially at rest, its final-state energy is

$$E=m+\mu^2/2m. \tag{1.5}$$

Thus reactions (1.3) and (1.4) are characterized by a proton at rest which spontaneously acquires energy. In reaction (1.3) no other charged particles are made, whereas the tachyons in (1.4) could be charged. However, it is not known whether charged tachyons could be detected.[22,23,26,28-30,32]

In both processes just mentioned, if the tachyons are in the final state, then the tachyon in (1.3) would have negative energy equal to $-\mu^2/2m$, and at least one of the tachyons in (1.4) would have negative energy. Because of this fact that the tachyons involved have negative energy, an unheard-of property, these tachyonic decays might seem objectionable. One answer to this objection[1,2] is the "reinterpretation principle," which allows the interpretation of negative-energy tachyons as positive-energy tachyons traveling backward in time. From this point of view, the negative-energy tachyons in (1.3) and (1.4) can be considered as incoming particles. In the searches we describe, we cannot distinguish between absorption of positive-energy tachyons present in the environment and emission of negative-energy tachyons. The net result of processes (1.3) and (1.4) in either interpretation is that a particle gains energy. Such processes, when interpreted as tachyon emission, might seem objectionable because they would constitute an infinite source of energy. However, if the rates for these processes were small enough, the total energy increase might not be readily noticeable. As unusual as these effects (and their explanations) may be, they are possible, and can be tested experimentally. For this reason we have made an investigation of reactions (1.3) and (1.4) and the corresponding reactions involving bound nucleons and atomically bound electrons.

We note that these processes have been discussed by Baltay *et al.*[45] under the different viewpoint that reactions (1.3) and (1.4) can only occur in Lorentz frames in which the tachyon energy would appear to be positive. This requires that the proton initially be moving with momentum $p > \frac{1}{2}\mu$.

Before discussing the search performed here, we briefly mention available data which already place restrictions on the above-mentioned "elastic" tachyonic decays of nucleons and electrons. Assuming that the negative-energy tachyons from these decays do not undergo further interactions, the net result of these processes is that a nucleon (or electron) spontaneously gains energy. If the energy gain is sufficiently large, it can be detected. A number of experiments (to be discussed below) have been performed to test the conservation of baryon number and the conservation of electrons. The negative results of these experiments can be reinterpreted to place limits on the rate of spontaneous energy gain of nucleons and electrons, since a sufficiently large energy gain would produce a detectable effect in these experiments. This will be elaborated in detail in Sec. III. Another source of information on the spontaneous energy increase of nucleons and electrons is the measurements of the heat flow emanating from the earth. Any energy acquired by the nucleons and electrons comprising the earth would be converted to heat, and the earth's heat flux thus places limits on elastic tachyonic decay. We will discuss this in Sec. IV. The results of the next three sections will be summarized in Sec. V.

In general, the experiments on baryon conservation only detect particles with kinetic energies down to about 10 MeV; energy gains below this value would go undetected. We have therefore undertaken an examination of free protons in a hydrogen bubble chamber, where we can reliably identify moving protons with kinetic energies down to about 5 MeV.

II. THE PRESENT SEARCH

For process (1.3) we search for single recoil-proton tracks in the bubble chamber; for this process all the proton recoil energies would be the same (assuming that only tachyons of a single liberty mass are emitted), so this signal, if statistically significant, would be readily distinguished from the continuous spread in proton energies arising from the scattering of ordinary neutral particles. The protons recoiling from process (1.4) could have any energy whatsoever and would thus be difficult to distinguish from scattering of ordinary neutral particles. However, an absence of recoil protons implies a null result for both processes.

For this investigation a special exposure of the Brookhaven 30-in. hydrogen bubble chamber was made. The exposure consisted of one roll of film, comprising about 5500 frames, in each of three camera views. The film was taken at a time when the Alternating Gradient Synchrotron was not in operation; there was no magnetic field in the bubble chamber in order to be able to distinguish low-energy electron tracks. As a control on the sensitivity of the bubble chamber during this non-beam exposure, a radioactive source was held next to the chamber for 10 consecutive frames at intervals of 1000 frames. This check was actually not needed, however, since there were background tracks in almost every frame.

The sensitive time of the bubble chamber was estimated from the shape of the pressure pulse applied to the chamber to be about 5 msec per frame, for a total exposure time of about 27 sec. The total volume of the bubble chamber is about 100 liters, but only about half this volume was scanned, since the Scotchlite backing on one half of the chamber showed slight imperfections which made the identification of very short tracks difficult. Using a liquid-hydrogen density of 0.06 g/cm^3 for an estimated 50 liters of hydrogen means that about 2×10^{27} protons were in the volume scanned.

The film was carefully scanned by the authors; the object of the scan was to identify recoil protons, with or without other associated tracks, down to the minimum distinguishable length of about 1 mm on the scan table, corresponding to about 4 MeV of kinetic energy. Because of the more sensitive experiments on baryon number conservation to be discussed in Sec. III, we did not expect to see any protons from tachyonic decay having energies greater than ≈ 10 MeV (corresponding to about 6 mm on the scan table).

There were three sources of background in the bubble chamber.

The first background source was cosmic-ray tracks which passed through the scanned volume about once every eight frames. These tracks were readily distinguished because they were minimum-ionizing and straight. A small fraction of these were checked for their direction of passage through the chamber by looking at their δ-ray directions. No track was found passing upward through the chamber. A few cosmic-ray tracks were seen to interact in the chamber.

Another, more troublesome, source of background was the presence of minor bubbling in the pictures, especially near some metal plates which were mounted in the chamber for a different experiment. Small elongated bubbles were very similar in appearance to that expected for proton tracks 1 mm or shorter on the scan table. Some 15 heavy tracks were found, all 1 mm or shorter on the scan table, which, although not located in areas of prominent boiling, were nevertheless indistinguishable from elongated single bubbles. Using as a basis of judgment the great number of electron tracks found in the pictures (see below), we are confident, however, that we could distinguish a proton track 1.5 mm or longer on the scan table. This lower cutoff was imposed for positive identification of proton tracks, corresponding to about 4.5 MeV of kinetic energy.

The major sources of background in the chamber were short (about 1–30 mm) recoil-electron tracks, of which there were almost two per frame. These electron tracks were readily identifiable by their low bubble density and their large multiple scattering. From the results of other experiments on electron conservation, we did not expect any visible electron recoils from elastic tachyonic decay, but we nevertheless investigated the source of these tracks. To do this, the projected scan-table length of all visible electron tracks was measured in 10% of all frames.

A histogram of these lengths is shown in Fig. 1. We note that not all the tracks 2 mm long or shorter on the scan table were measured, since these tracks mostly consisted of two bubbles and were difficult to distinguish from short segments of nearly extinct tracks. The curve shown on the histogram is a Monte Carlo prediction of the projected scan-table track-length spectrum to be expected from an isotropic flux of 1.46-MeV γ rays giving rise to Compton-scattered electrons. The Monte Carlo calculation uses the Klein-Nishina formula for the energy spectrum of the Compton electrons and takes into account the spread in magnification due to the fact that tracks can appear at different depths in the bubble chamber. From measurements of background γ radiation at the BNL site,[48] the 1.46-MeV γ ray from the decay of K^{40} is the most important contributor to the γ-ray background, and it is also the most energetic contributor of significant intensity. The fact that the end point of the experimental projected track-length distribution in Fig. 1 lies near the value expected for Compton scattering of 1.46-MeV γ rays makes plausible the conclusion that the events under the curve of Fig. 1 are due to γ rays from K^{40}. (The curve is normalized to the area of the experimental distribution between 18 and 35 mm.) In addition to the 1.46-MeV γ ray just discussed,

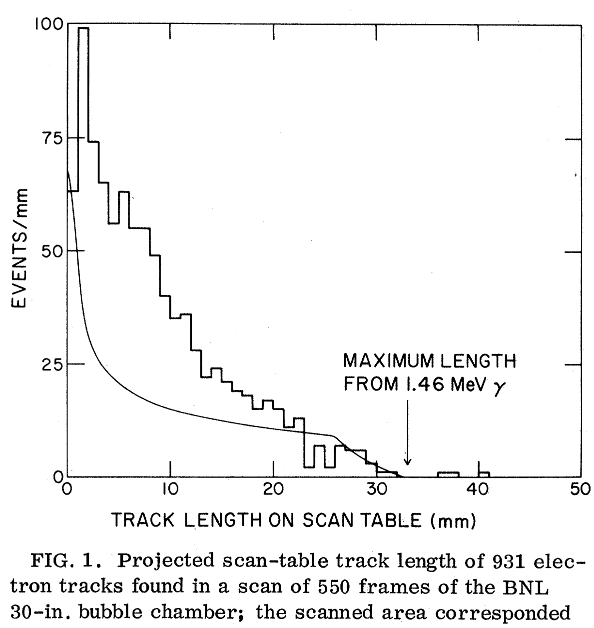

FIG. 1. Projected scan-table track length of 931 electron tracks found in a scan of 550 frames of the BNL 30-in. bubble chamber; the scanned area corresponded to about half of the chamber volume. The curve is a Monte Carlo prediction for the distribution of scan-table track lengths of Compton-scattered electrons from an isotropic flux of 1.46-MeV γ rays. The curve is normalized to the area of the histogram between 18 and 35 mm.

the background measurements[48] mentioned above showed significant contributions from a number of γ rays of energies between about 0.5 and 1.0 MeV. These energies are characteristic of uranium and thorium and their decay products, and also of annihilation of positrons produced by cosmic-ray interactions. The excess of events above the curve of Fig. 1 is consistent with the contributions of Compton-scattered electrons from γ rays in the energy range of $\approx$0.5–1.0 MeV. For this reason we attribute all the low-energy electron tracks found in the chamber to Compton scattering of background γ radiation. (We note that pair production in hydrogen is negligible for the γ-ray energies discussed here; we also note that we have no reason to suspect that the materials of the bubble-chamber apparatus or of the metal plates in the chamber were contaminated with any radioactivity beyond the background sources mentioned above.)

Only one recoil-proton track longer than 1.5 mm was found – its scan-table length was 10 mm, corresponding to a kinetic energy of about 13 MeV. This event can be attributed to the recoil from a scatter of a neutral ordinary particle from a cosmic-ray interaction.

We place an upper limit of one event from processes (1.3) and (1.4), for proton recoil kinetic energies between 5 MeV and 1 GeV. The upper energy limit is noted because protons more energetic that 1 GeV would, in our scan, be indistinguishable (except for average direction) from cosmic-ray tracks. This upper energy limit is of no consequence, however, since the experiments on baryon conservation discussed below yield much longer lifetimes than our search for energies above 1 GeV. In fact, the lifetime limit implied by the present search is only important for proton recoil energies between about 5 and 10 MeV. From an upper limit of one event in 2×10^{27} protons viewed for 27 sec, the lifetime of free protons for elastic tachyonic decay via reaction (1.3) or (1.4) is greater than about 2×10^{21} yr.

III. EXPERIMENTS ON CONSERVATION OF BARYONS AND ELECTRONS

A number of experiments have been performed to search for processes which do not conserve baryons and electrons. These experiments search for the charged decay products of nucleons or for other effects caused by the decay of nucleons or electrons. All such searches reported thus far have yielded null results, implying very long lifetimes for the assumed decays. We will reinterpret the minimum lifetimes from these experiments as lower limits for the lifetime of nucleons and electrons with respect to processes (1.3) and (1.4). We list these experiments and state briefly the lower and upper recoil-kinetic-energy limits that would be detected in reactions (1.3) and (1.4), and the lifetime obtained; in doing this we distinguish between the lifetimes of free protons, bound nucleons, and atomically bound electrons. In this connection we note that processes like $n\to n+t^0$, $n\to p+t^-$, $p\to n+t^+$, etc., are also detectable for both free and bound nucleons, since, e.g., a moving neutron can transfer energy to a proton, which is then detected.

1. *The experiment of Reines, Cowan, and Goldhaber (1954).*[49] These authors search for charged particles from nucleon decay in a liquid scintillator 100 ft underground; the minimum energy deposited in their detector is given as $\approx$15 MeV, and we estimate that particles with energies greater than $\approx$1 GeV would be indistinguishable from cosmic rays. These authors obtain lifetimes of $\tau \gtrsim 10^{21}$ yr for unbound protons and $\tau \gtrsim 10^{22}$ yr for bound nucleons. Since there are about one half as many electrons as bound nucleons in the material of the detector used in this experiment, a minimum lifetime for electron tachyonic decay of about half the value for bound nucleons is obtained.

2. *The experiment of Goldhaber (quoted in Ref. 49).* Goldhaber has searched for nucleon decay by assuming that the decay of a nucleon in Th^{232} would cause the remaining nucleus to fission. He obtains a lower lifetime limit for bound nucleons of 10^{20} yr. We assume that a bound nucleon gaining sufficient energy in process (1.3) or (1.4) to escape from the nucleus would produce the same effect sought by Goldhaber; this energy we estimate very roughly to be 7 MeV.

3. *The experiment of Flerov et al. (1958).*[50] These authors have repeated the above-listed experiment of Goldhaber with greater sensitivity and obtain a minimum lifetime of 2×10^{23} yr.

4. *The experiment of Reines, Cowan, and Kruse (1958).*[51] These authors investigate the decay of protons bound in deuterium; they search for the charged products of proton decay, followed by the γ ray from the capture in cadmium of the remaining neutron from the deuteron. The minimum charged-particle energy they detect is 5 MeV, to which we add the known deuteron binding energy of 2.2 MeV to obtain 7 MeV as the minimum proton energy gained in reaction (1.3) or (1.4) to be detectable in this experiment. The bound-proton lifetime quoted by these authors is $\tau \gtrsim 4\times10^{23}$ yr.

5. *The experiment of Backenstoss et al. (1960).*[52] This experiment detects upward-moving charged particles assumed to come from nucleon decay 800 m underground. The authors state that they

can detect muons and pions with $\gamma = E/m \gtrsim 1.7$, which yields a minimum kinetic energy of ≈ 0.6 GeV for protons; they quote a minimum detectable electron energy of 20 MeV. This experiment yields an unbound-proton lifetime of $\gtrsim 3\times 10^{24}$ yr, and a lifetime for bound nucleons of $\gtrsim 2\times 10^{26}$ yr, from which we deduce an electron lifetime for processes (1.3) and (1.4) of $\gtrsim 10^{26}$ yr.

6. *The experiment of Giamati and Reines (1962).*[53] These authors sought to detect the charged products of nucleon decay in a large liquid scintillator detector 585 m underground, surrounded by a water Čerenkov anticoincidence detector. A steel shield was placed between the scintillator and the anticoincidence detector to prevent events originating in the scintillator from penetrating to the anticoincidence detector. The authors quote a minimum detectable energy of about 8 MeV. We will use this number for unbound protons and electrons, but round it upward to 10 MeV to account for the binding energy of bound nucleons. We estimate very roughly that particles gaining more energy than about 1 GeV would penetrate the steel shield separating the scintillator from the anticoincidence detector; thus we take 1 GeV as an upper limit for detectable energy gains in this experiment. The unbound-proton lifetime in this experiment is $\gtrsim 1.5\times 10^{26}$ yr, that for bound nucleons is $\gtrsim 10^{27}$ yr, and we take one half of the latter value for electron tachyonic decay.

7. *The experiment of Kropp and Reines (1965).*[54] This is essentially the experiment of Giamati and Reines[53] just listed, repeated with greater sensitivity. The authors give 9–10 MeV as the minimum detectable energy, and we simply take 10 MeV as the minimum recoil kinetic energy for free protons, bound nucleons, and electrons. A value of $\approx 10^{28}$ yr is quoted as the minimum nucleon lifetime (most of the nucleons observed in this experiment are bound). Since the lifetime for bound nucleons from this experiment is ten times as large as that from the essentially identical experiment of Giamati and Reines, we take 10 times the free-proton lifetime from the latter experiment, or $\approx 1.5\times 10^{27}$ yr, as the result for the minimum lifetime for free protons.

8. *The experiment of Gurr et al. (1967).*[55] Here charged particles assumed to come from nucleon decay are detected in a liquid scintillator array 3200 m underground. The minimum detectable energy is 20 MeV; we will take this value for free protons, bound nucleons, and electrons. The lifetime limits quoted are $\gtrsim 10^{28}$ yr for free protons and $\gtrsim 10^{29}$ yr for bound nucleons.

9. *The experiment of der Mateosian and Goldhaber (1959).*[56] This experiment was designed to look for charge-nonconserving electron decays, and thus can be reinterpreted to yield information only about electron tachyonic decay. The authors look for effects in an NaI crystal following the decay of K-shell electrons in iodine. We estimate that an elastic tachyonic decay of such an electron resulting in an energy gain greater than the binding energy of ≈ 30 keV would also produce a signal in this experiment. These authors obtain an electron lifetime of $\gtrsim 10^{18}$ yr.

10. *The experiment of Moe and Reines (1965).*[57] This is the same experiment as that of der Mateosian and Goldhaber, with greater sensitivity. The electron lifetime obtained here is $\gtrsim 2\times 10^{21}$ yr.

IV. HEAT FLOW FROM THE EARTH

The outward flux of heat at the earth's surface is known to within about 10%[58]; its value is about 3×10^{13} W, or $\approx 2\times 10^{26}$ MeV/sec. The total number of nucleons in the earth is about 4×10^{51}, almost all of which are bound nucleons, and there are about half this many electrons. The exact concentrations of radioactive substances inside the earth (primarily potassium, uranium, and thorium) are not known, but the heat flow from the earth is in rough agreement with that obtained from making reasonable assumptions about the amounts of the three elements named.[59] To obtain lower limits for the bound nucleon and electron lifetimes with respect to the elastic tachyonic decay reactions (1.3) and (1.4), we proceed in the following conservative fashion: We attribute *all* of the heat produced in the earth's interior to the tachyonic processes under investigation, and we use for the heat produced *twice* the heat flux measured at the earth's surface, to account for the fact that some of the heat produced inside the earth may not yet have arrived at the surface.[59] With this procedure the heat flow from the earth yields for the lifetime of a bound nucleon with respect to elastic tachyonic decay

$$\tau \gtrsim 3\times 10^{17}\ \Delta E \text{ yr}, \tag{4.1}$$

where ΔE is the energy gain of a nucleon in MeV. If, following the same procedure, twice the earth's heat flux is attributed to the elastic tachyonic decay of the electrons inside the earth, then for electrons

$$\tau \gtrsim 1.5\times 10^{17}\ \Delta E \text{ yr}, \tag{4.2}$$

where again ΔE is in MeV.

The above results on the earth's heat flow are entirely valid if the heat flow is interpreted as arising from the absorption of positive-energy tachyons. However, if negative-energy tachyons are being emitted, then we are assuming that these tachyons do not interact often with other (moving)

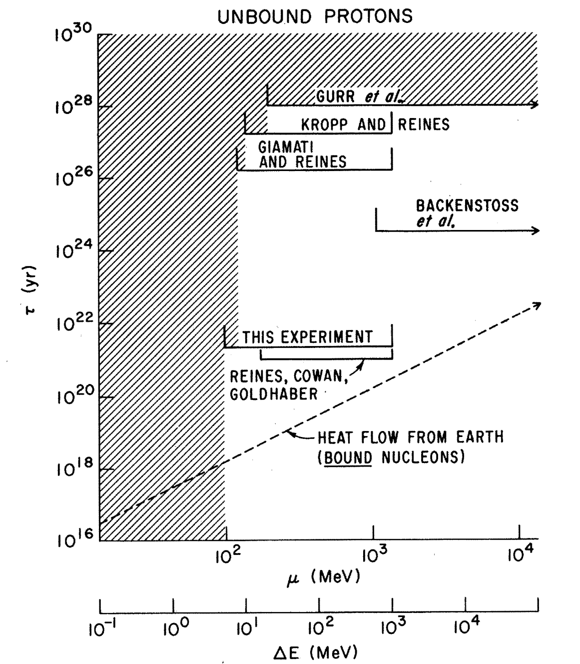

FIG. 2. Lifetime τ for elastic tachyonic decay of free protons vs energy gain ΔE in the proton rest frame. The horizontal lines are lower limits for the lifetime over the specified energy range; the diagonal dashed line is the lower limit of *bound-nucleon* lifetime implied by the heat flow emanating from the earth. Also given on the abscissa is the scale for the tachyon liberty mass in decays involving a single tachyon. The hatched area is the allowed range of lifetimes.

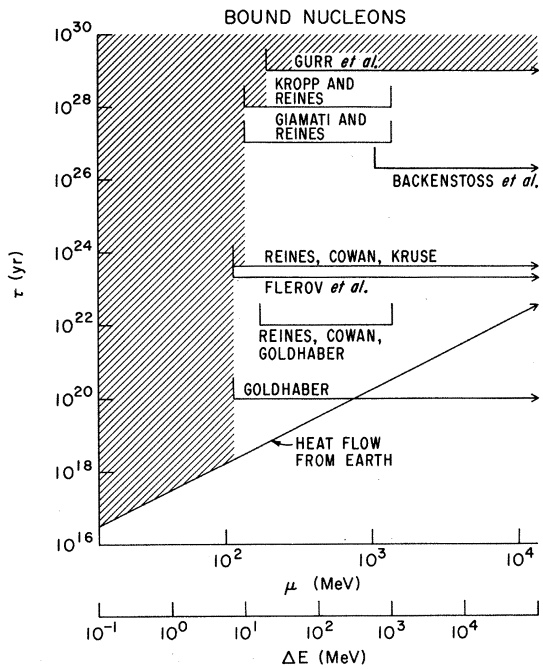

FIG. 3. Lifetime τ for the elastic tachyonic decay of bound nucleons vs energy gain ΔE in the nucleon rest frame. The horizontal lines are lower limits for the lifetime over the specified energy range; the diagonal line is the lower limit of lifetime implied by the heat flow emanating from the earth. Also given on the abscissa is the scale for the tachyon liberty mass in decays involving a single tachyon. The hatched area is the allowed range of lifetimes.

particles inside the earth in such a way as to *remove* energy from them. If this occurs, the net heat production could be much smaller than the energy gained in the original tachyon emission processes.

V. SUMMARY OF RESULTS AND CONCLUSION

The lifetime limits derived in the previous three sections are summarized in Figs. 2, 3, and 4, which show the minimum lifetime *versus* energy gain for free protons, bound nucleons, and electrons, respectively. In each figure the hatched area represents the possible lifetimes for processes (1.3) and (1.4). The abscissa is given both in terms of energy gain ΔE (=kinetic energy) and tachyon liberty mass μ for process (1.3) [μ also is the tachyon-pair invariant mass divided by i in process (1.4)]. The energy gain is given in terms of μ by the second term in Eq. (1.5). The limits of Secs. II and III are given by the horizontal lines in these figures, and those of Eqs. (4.1) and (4.2) are the diagonal lines.

We note that in the case of tachyonic decay of bound nucleons, for energy gains smaller than ~1 MeV, a single nucleon would not be able to escape from a nucleus. Thus if the decay (1.3) involves only tachyons having a specific liberty mass, the entire nucleus must recoil against the tachyon, and the energy gain of the nucleus, which is given by the second term of Eq. (1.5), would be smaller than for a single nucleon. For this reason an extrapolation of the diagonal line to smaller energy values than are given in Fig. 3 must be done with caution. The same remark holds for extrapolating the diagonal line for atomically bound electrons in Fig. 4 to values much smaller than the lower kinetic-energy limit of 10 keV shown in the figure.

To translate the very long lifetimes obtained into coupling constants, we write down a very simple rate calculation for the two-body proton decay (1.3):

$$\Gamma = \frac{1}{\tau} \approx \frac{1}{m}\left(\frac{p}{m}\right)|M|^2 .$$

Here m is the proton mass; (p/m) is the two-body-decay phase space, where p is the proton recoil momentum; and M is the decay matrix element, which we write as

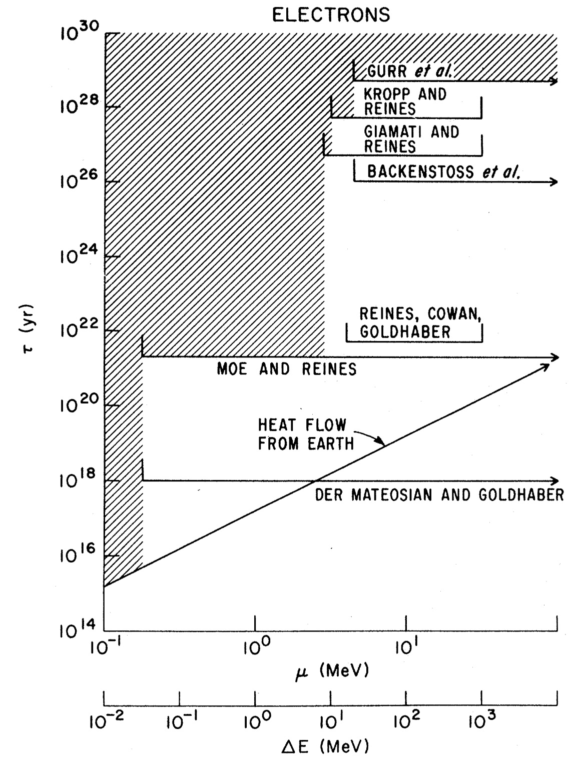

FIG. 4. Lifetime τ for the elastic tachyonic decay of atomically bound electrons vs energy gain ΔE in the electron rest frame. The horizontal lines are lower limits for the lifetime over the specified energy range; the diagonal line is the lower limit of lifetime implied by the heat flow emanating from the earth. Also given on the abscissa is the scale for the tachyon liberty mass in decays involving a single tachyon. The hatched area is the allowed range of lifetimes.

$$M \equiv \epsilon m,$$

where ϵ is a dimensionless coupling constant. From the search reported here, for a recoil kinetic energy of 5 MeV ($p \approx 100$ MeV/c), $\tau \gtrsim 6\times 10^{28}$ sec, so

$$\epsilon^2 \lesssim 10^{-52}$$

from the present search. For bound nucleons (electrons) recoiling with kinetic energies around 1 MeV (0.01 MeV), the lifetime limits imposed by the heat flow from the earth require coupling-constant values which are only a few orders of magnitude larger than that from the present search. A much smaller value can be obtained from the result of Gurr *et al.*[55] for bound nucleons and a recoil energy of, say, 100 MeV ($p \approx 450$ MeV/c). From these authors' lifetime of $\tau \gtrsim 3\times 10^{36}$ sec one obtains

$$\epsilon^2 \lesssim 10^{-60}.$$

Similar small numbers, modified somewhat by phase-space factors, would also result for the three-body decay (1.4). These numbers are exceedingly small; they can be contrasted with the gravitational coupling constant which is, in dimensionless form,

$$Gm^2 \approx 5\times 10^{-39},$$

where m is the mass of the proton.

We conclude that for recoil energies greater than about 1 MeV the interaction which would mediate the tachyonic processes $p \to p + t^0$ and $p \to p + t + \bar{t}$ involving negative-energy tachyons, or the corresponding ones for electron decay, must be very much weaker than the weakest established interaction, that of gravity.

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