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SEARCH FOR TACHYON MONOPOLES IN COSMIC RAYS*

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ABSTRACT

We have searched for a particle which combines the properties of a tachyon with those of a magnetic monopole. The tachyon monopole is assumed to exist in cosmic rays striking the earth and to be influenced by the extensive magnetic fringing field of Fermilab's 15-ft. bubble chamber. By hypothesizing that the tachyon monopole will either emit Cherenkov radiation in air or ionize Lexan plastic we set an upper limit of 5×10^{-12} $cm^{-2}sec^{-1}$ on their flux.

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INTRODUCTION

Despite extensive effort, neither tachyons nor magnetic monopoles have been found.[1] Perhaps this failure is because these particles have generally been sought separately.

This paper describes a search for a particle which combines the properties of a magnetic monopole with those of a particle which travels faster than light. Some time ago a search for such a tachyon monopole (TM) was made near a radioactive source.[2] The present search was motivated by the observation that if free tachyon monopoles exist at all they might be found in high-energy cosmic rays of unspecified origin. In contrast, the prospects for finding a tachyon monopole among the particles manufactured by accelerators may not be so sanguine since nothing in current high energy theory or experiment even hints at the presence of tachyon monopoles.

When interest in tachyons was revived a decade ago,[3] physicists were content to predict how faster-than-light particles would interact with apparatus here on earth.[4] In this context, Huygen's wavelet theory makes it appear reasonable that an electrically (or magnetically) charged tachyon would emit Cherenkov radiation even in vacuo. Experimentalists sought in vain for such radiation.[5]

Recently, however, several physicists have formulated extended theories of relativity. In these theories there is assumed to be a universe S' of objects which have velocities less than that of light relative to each other but which have velocities greater than the speed of light relative to our system S. The objects in S' are assumed to obey the normal laws of physics when viewed by an observer in S' In particular, a light wave emitted in S' propagates isotropically according to the equations

$$ds'^2 = dt'^2 - dx'^2 - dy'^2 - dz'^2 \tag{1a}$$

$$= 0 \tag{1b}$$

where we define $c = \hbar = 1$.

Suppose that, when viewed from our frame, S' is moving with a velocity $v > 1$ along the x axis. How does the world line ds' (Eq. 1a) of a particle's motion in S' appear in our frame? It is clear that we cannot simply write $ds'^2 = ds^2 = dt^2 - dx^2 - dy^2 - dz^2$ because then a particle which is at rest in S' ($ds'^2 > 0$) would in our frame have $dx^2 < dt^2$ and thus appear to be moving slower than light, contrary to hypothesis. At the very least the signs of the terms in dx^2 and dt^2 must be interchanged. On this there is general agreement, as there is on the specific transformations:

$$t = \delta(t' + vx'),$$

$$x = \delta(vt' + x') \tag{2}$$

where $\delta = (v^2 - 1)^{-\frac{1}{2}}$.

Theorists disagree however, on the transformations for y and z. If one wishes to have a spherical light wave from a tachyonic source appear spherical to an observer on earth, he must change the signs of y^2 and z^2 to match the change in x^2 and t^2. This procedure yields

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2. \tag{3}$$

Such a transformation has been promoted by Ricami and Mignani in a number of articles.[6] Although preserving the invariance of the speed of light, this transformation has the unfortunate consequence that the coordinates normal to the velocity of the tachyon source become imaginary upon transformation:

$$y = iy'; \; z = iz'. \tag{4}$$

Quaternions and exotic numeration schemes have been proposed to give reality to these imaginary coordinates.[7] The theory, however, has as yet been unable to give experimentalists a definitive test.

Alternatively, one can preserve the invariance of the transverse coordinates,

$$y = y'; \; z = z' \tag{5}$$

at the expense of losing the invariance of the speed of light:

$$ds^2 = -dt^2 + dx^2 - dy^2 - dz^2. \qquad (6)$$

Thus a spherical wave in S' becomes distorted when viewed from S. Such an approach introduces a preferred direction into space. The direction may either be absolute as in the tachyon corridor of Antippa and Everitt[8], or it may be the direction of motion of the tachyonic source as in the theories of Gonzales - Gascon[9] and of Lemke[10]. The latter theory is particularly rich in experimental consequences.

Finally some theorists have questioned whether conventional Lorentz transformations can be meaningfully extended to superluminal objects.[11,12,13] Basano[11] and Barrowes[12] are particularly concerned that it may not be possible to preserve causality in such a transformation. Perhaps the only way we can be assured that cause will always preceed effect for macroscopic processes is to adopt either a preferred inertial frame[12,13] or a preferred direction in space.[8]

TECHNIQUE

Granted that the theory for tachyons is unsettled, we have tried to design an experiment which makes minimum demands of the theory. Our primary assumption is that a superluminal magnetic monopole will be as effective as a sublimal one in extracting energy from a magnetic field. Thus we assume that any monopole of strength Zg which travels a distance ds in a magnetic field H will gain energy in the amount

$$dE = ZgH\, ds, \qquad (7)$$

Where $g = 1/(2e)$ is the Dirac monopole, and $Z = 1,2,3...$

Our experiment can detect this energy in either of two ways. Initially we assumed that the older theories of tachyons to be correct and consequently that a tachyon emits Cherenkov radiation even in vacuo. Specificially, we assumed that in a favorable longitudinal magnetic field a tachyon monopole will reach a constant velocity v at which the rate it gains energy from the field (Eq. 7) is just balanced by its energy loss to Cherenkov radiation.

$$dE = -Z^2g^2(1 - 1/v^2)\int_0^{\epsilon_o} \epsilon d\epsilon\; ds. = -\frac{Z^2g^2\mu^2\epsilon_o^2\, ds}{2p^2} \qquad (8)$$

Here ϵ is the energy of the photon radiated by a tachyon monopole of momentum p and mass parameter μ bearing Z Dirac monopoles g.[14]

Unfortunately, there is no generally acceptable, Lorentz invariant proceedure for choosing the upper limit ϵ_o. We follow the tradition of past experimentalists who assume that a tachyon of energy E can only emit photons of lesser energy. Thus $\epsilon_o = E$.

Upon equating Eqs. (7) and (8) and using the tachyonic relationship $E^2 = p^2 - \mu^2$, we find that a tachyon emits photons up to an energy

$$\epsilon_o = E = \frac{Zg}{2H} \cdot \left(1 - \frac{2H}{Zg\mu^2}\right)^{-\frac{1}{2}} \tag{9}$$

If $\mu^2 < 2H/Zg$, E becomes imaginary and our assumption of constant velocity is clearly untenable. However, we shall be primarily interested in the case $\mu^2 >> 2H/Zg$. Under these conditions,

$$v^2 = p^2/E^2 \approx \mu^2/\epsilon_o^{\,2} \approx \mu^2/(Zg/2H) >> 1. \tag{10}$$

Thus the Chrenkov radiation is perpendicular to the direction of motion of the TM, and the high frequency limit on the emitted photons is

$$\epsilon_o = (2H/Zg)^{\frac{1}{2}} \tag{11}$$

The magnetic fields required to allow Cherenkov radiation in the visible spectrum are reasonable. A 1 000 Oe field will maintain a singly charged TM at an energy of 5 eV. During passage through this field the tachyon will copiously emit visible photons which we try to detect.

As the experiment progressed we became aware of the newer theories of tachyons which use an extended Lorenz transformation. It is easily seen that these theories do not permit a tachyon to emit Cherenkov radiation in vacuo.

Let us assume the tachyon to be moving uniformly with a velocity less than light relative to a superluminal frame S'. Since the normal laws of physics are assumed to be valid in S', the tachyon cannot be radiating any energy there. But the superluminal transformation to our frame S cannot make something out of nothing so the tachyon cannot be radiating in our frame either.

To retain a sensitivity to these theories, we added a detector which is sensitive to ionization loss. We assume that a tachyon will still gain energy during passage through a magnetic field (Eq. 7). If this energy is not lost in Cherenkov radiation, it should remain with the tachyon as increased kinetic energy. Then, upon passing through matter, the tachyon will be able to release this energy in ionizing atoms.

As a specific model for this ionization process we use the extended relativistic theory of Lemke.[15] So far as we can see this theory has not been shown to be fully compatible with causality, but we will use it for purposes of illustration.

Consider an electrically charged tachyon moving with constant velocity v along the x-axis. In Lemke's model, the electric and magnetic fields seen by an observer at $(0,b,0)$ are

$$\vec{E} = (v^2 -1)\ q\ \vec{r}/R^3,\ \vec{H} = \vec{v} \times \vec{E}, \tag{12}$$

where $R = ((vt)^2 + (v^2 - 1)\ b^2)^{\frac{1}{2}}$ and $r = vt\ \hat{x} + b\ \hat{y}$. (Note that, except for signs, these fields have the same algebraic form as those for a subluminal charge).

If we now consider the case of a moving magnetically charged tachyon gZ, the simple substitution $\vec{E}\to\vec{H}$, $\vec{H}\to-\vec{E}$ in Eq. 12 yields

$$\vec{H} = (v^2 -1)\ Zg\ \vec{r}/R^3,\ \vec{E} = -\vec{v} \times \vec{H}. \tag{13}$$

with r and R defined as before. In particular, the electric field at the point (0,b,0) and at time t=0 is seen to be

$$\vec{E} = -v(v^2 -1)\ gZb/R^3\ \hat{z}.$$

We can then use Bohr's impulse approximation to find the energy lost by ionization to electrons in matter. The momentum transferred to a free electron is

$$|\Delta p| = \left|\int F\ dt\right| = \left|e\int E_z dt\right| = 2Zge/b.$$

and the energy lost in such collisions is

$$- dE/dx = 2\pi n\int(\Delta p^2/2m)\ b\ db = 4\pi n\ Z^2 g^2 e^2 m^{-1} \mathrm{Log}\ \frac{b_{max}}{b_{min}}, \tag{14}$$

where m is the mass of the electron and n is the density of electrons in matter.

As in the usual case of a subluminal electric charge, the maximum impact parameter, b_{max}, is set by the adiabatic approximation; namely, that the collision time must be short compared to the period τ of an electron in its orbit. Thus,

$$b_{max} = v\tau/(v^2 - 1)^{\frac{1}{2}} = 2\pi v/\ (v^2 - 1)^{\frac{1}{2}}\ \bar{I}\ , \qquad (15)$$

where $\bar{I} = 2\ /$ is the mean ionization potential.

For small velocities, $v \approx 1$, b_{min} is determined by the usual quantum mechanical limit that the DeBroglie wavelength of the atomic electron when seen from the rest frame of the tachyon monopole must be less than the impact parameter b; thus,

$$b^{qm}_{min} = 1/p = (v^2 - 1)^{\frac{1}{2}}/mv. \qquad (16)$$

For larger velocities a more stringent limit on b_{min} is set by the classical consideration that the momentum transferred to the electron as given by Eq. 7 cannot exceed the momentum transferred in a head-on collision. This latter momentum is $mv_{recoil}(1 - v^2_{recoil})^{-\frac{1}{2}}$, where the recoil velocity of the electron is given by the velocity addition formula, $v_{recoil} = (v + v)\ /\ (1 + v^2)$. (Note that v_{recoil} is always less than 1). Equating these two momenta, we find

$$b^{clss}_{min} = (v^2 - 1)/2mv. \qquad (17)$$

For velocities $v < \sqrt{5}$, the quantum mechanical limit on b_{min} dominates and we have

$$-dE/dx = (4nZ^2g^2e^2)m^{-1}\ \ \mathrm{Log}\ (v^2/(v^2 - 1)(2\pi m/\bar{I})) \qquad (18a)$$

For $v > \sqrt{5}$, the classical limit on b_{min} is the more stringent one and

$$-dE/dx = 4nZ^2g^2e^2m^{-1}\ \mathrm{Log}(2v^2/(v^2-1)^{3/2})(2\pi m/\bar{I}) \quad (18b)$$

In the next section we discuss how the complementary techniques of detection by ionization loss and Cherenkov radiation are used to effect the search.

MEASUREMENTS

To achieve maximal sensitivity to TM's in cosmic rays it was desirable to use as extensive a magnetic field as possible. Such a field is located above Fermilab's 15-foot Bubble Chamber which (for our purposes) is only coincidentally located at a particle accelerator.

As installed at Fermilab in October 1974, the apparatus includes a room-sized box (4.3 x 4.3 x 2.4 m high). The top of the box is 8.8 m above the center of the bubble chamber magnet and is attached directly to the roof of the building. The fringing magnetic field varies between 600 Oe and 2000 Oe over the volume of this box. (see Fig. 1).

The Cherenkov radiation emitted by TM's traversing this box is detected by eight 2-in. RCA 8850 photomultiplier tubes (PMT's) mounted near the top and bottom corners of the box. To maintain reasonable angular acceptance of the PMT's to incident light, we installed Winston cones[16] to reflect deviant rays into the PMT. Finally an elaborate nest of three outer steel cylinders and two inner ones of special alloy was necessary to shield the PMT's from the extensive fringing magnetic field. (see Fig. 2) In a separate test, this arrangement reduced an ambient 3 000 Oe field to 0.5 Oe at the site of the PMT.

Preliminary Run

A tachyon bearing the Dirac magnetic charge and traveling vertically should emit copious visible Cherenkov radiation (if our assumptions discussed earlier are correct). In fact, each photomultiplier tube should be illuminated by a burst of 100,000 photons producing a cathode current of 20,000 photoelectrons. (See Eq.8). Despite this large predicted signal, the threshold for each phototube was set at one photoelectron. By thus "keeping our eyes open", we should be sensitive to tachyons whose radiation is much weaker than postulated. (Such a weak signal could arise if the tachyon is very light, (mass parameter $\mu \leq 1$ eV). In this case, it will have a velocity only a little greater than c and will radiate weakly in the forward direction. Alternatively, if quarks (e = 1/3) exist [17] and the Schwinger quantization condition ($ge_{min} = 1,2...$) holds, [18] the minimum permitted charge for the magnetic monopole may be as large as six Dirac poles. In this case the tachyon would radiate in the red, a color to which our PMT's are relatively insensitive).

The Cherenkov radiation from a very fast tachyon will proceed in a plane perpendicular to the tachyon's direction of motion. Thus a vertically directed tachyon will illuminate all eight phototubes. If the motion is a little slanted, however, only the top or bottom phototube on a given corner can be illuminated. Therefore our electronic trigger requirement is a simultaneous signal in at least one of the pair of phototubes at the top and bottom of each of the four corners. This restrictive four-fold coincidence is used to trigger an oscilloscope on which the last dynode pulses from all eight phototubes are separately displayed and photographed. The PMT's were adjusted to be sensitive to single photoelectrons. A pulsed, light emitting diode (LED) located in the middle of the box was periodically operated to check the sensitivity of the 4-fold coincidence system. The gain of the PMT's was found to be independent of the magnetic field.

The inside of the box is painted black to avoid light bouncing from wall to PMT, but may be covered with white cloth, thus permitting partial sensitivity to a slow tachyon which radiates in the forward direction. In this case the light is bounced from the floor and walls of the box into the PMT's. (This condition is labeled "white box" in Figure 3).

Because of the expected low signal, it was important to investigate various sources of background coincidences. While the 4-fold coincidence requirement effectively removed trigger signals due to random, dark current noise in the PMT's, we did register 4-fold coincidences even with optical shutters covering all eight PMT's. These are almost certainly due to large Extensive Air Showers(EAS) passing directly through the PMT's. To determine this type of background all data were taken with shutters alternately open and closed.

Unfortunately, extensive air showers can also produce scintillation light in the air-filling of our detector. One minimum ionizing, singly charged particle loses ½ MeV in passing vertically through our detector box. Air is weakly scintillating: A ½ MeV energy loss produces about 20 visible photons.[19] Since each PMT subtends an angle of only 0.6 millisterradians at the center of the box, the scintillation light from a single particle would be most unlikely to satisfy our coincidence requirement. Indeed a shower density of approximately 300 electrons/m^2 would be needed to give sufficient scintillation light in the air of the box to trigger our PMT's. Such dense showers have been shown to occur at a detectable rate of about one per hour.[20]

In order to provide some discrimination between a true 4-fold coincidence from a single TM and a coincidence caused by light generated by several simultaneous shower particles, runs were made with the box quartered by black curtains into four independent cells, each containing an upper and lower PMT. With the box thus sectioned (curtains closed), light from a single particle could not cause a 4-fold coincidence. With curtains open, the apparatus is sensitive to single particles as well as to diffuse events. The magnetic field was not under our control. Rather the experimenters using the bubble chamber determined when the field would be on or off. Fortunately, comparable exposure times were had with field both on and off for all the conditions we wished to study. In a preliminary run of about 70 days we obtained the event rates indicated in figure 3a.

Examination of Fig. 3a reveals the following: (1) The magnetic field increases the number of EAS passing directly through the PMT's as shown by condition A (shutters closed); (2) With magnetic field off, quartering the box by curtains had no effect on the coincidence rate, but with field on, the black-walled box with open curtains (condition C) had nearly twice the rate of the sectioned box (condition B); (3) The white-walled box (condition D) showed a much larger coincidence rate than the black box even with no magnetic field, while the increase with field on was in about the same ratio as for the black box. The increased count rate in condition C, compared with condition B cannot be attributed solely to TM's since sectioning the box might prevent a weak EAS from triggering the PMT's in all four cells if the curtains were open. In addition, the curtains would stop electrons of a few Mev from circling around the field lines and generating scintillation light in all four cells.

Thus our preliminary run showed the positive correlation of event rate with magnetic field which would be expected if tachyon monopoles constituted part of the signal. However, the augmentation could also be explained by EAS's which are focussed by the fringing magnetic field.

In addition, several events were followed by a second trigger 1-4 microseconds later. Was this couplet an EAS associated with either an advanced or retarded monopole, or was the problem merely instrumental? Unfortunately the single oscilloscope used to record events did not do justice to the second trigger.

Final Run

During the summer of 1975, our apparatus was modified to clarify the role of the EAS in causing coincidences. Two small (45 x 45 cm) plastic scintillator counters to detect

EAS's were installed about 2 m apart on the bottom of the box. We reasoned that an EAS would give at least one minimum ionizing particle in each of these counters giving a coincidence signal whereas a single tachyon monopole, being localized, could not. We also added a second oscilloscope and camera to record the occasional delayed trigger, mentioned above, and, (for half the run) changed the trigger requirement on the corner PMT's to require 3 photoelectrons in each of 3 photomultiplier tubes.

During a run of 50 days we recorded 1000 coincidence triggers in the corner detectors; 90% of these were associated with signals from the EAS's detectors. Those 100 triggers not associated with EAS were weak. Not one involved signals in more than four of the eight photomultiplier tubes which view the box. Further, 85% of these triggers occurred during the Fermilab accelerator's beam spill and the remaining rate was consistent with our expected accidental rate.

The second oscilloscope fired 30 times on a trigger delayed by 0.2 to 5 microseconds. A scan of these pulses has shown all to be instrumental.

Finally to search for tachyons which do not emit Cherenkov radiation but do strongly ionize matter, we covered the floor of our box with 10-mil Lexan sheets. Twenty of these sheets were stapled together in a light-tight packet having a width of 56 cm and a breadth of 86 cm. Twenty-four packets covered the floor of the box, giving an active area of about 11 square meters.[21]

These sheets were in place during half the final run. The top 3 sheets of each stack were then removed and etched for approximately two weeks in a hot (60°C), concentrated (6mols/ℓ) NaOH solution. The duration of the etch was such that the thickness of each sheet was reduced to 3 mils. At such a thickness small holes due to irregularities in the manufacturing process begin to appear randomly in the sheets at a density of roughly $200/m^2$.

A heavily ionizing TM should leave a continuous track in a Lexan packet. This track would be revealed as a spatial coincidence of holes in the etched Lexan sheets. We scanned the top 3 sheets of each packet carefully for such a coincidence lying within the spatial resolution of our system (about 3mm). No coincident holes were found.

In summary we have found no evidence for tachyon monopoles that either emit Cherenkov radiation in air or ionize matter. To interpret this result as a limit on the flux of TM's it is necessary to examine the sensitivity of our detector.

Detector Sensitivity

The detector is sensitive only to a certain range of TM charge and mass. In addition, the extensive fringing magnetic field will only focus tachyon monopoles which are weak enough to follow the curved field lines. In this secion we shall examine the requirements for detection and for focusing. We shall assume either that the TM can emit Cherenkov radiation or that it cannot.

Let us first consider the problem of detecting a TM which can emit Cherenkov radiation. For the TM to achieve a terminal velocity in the 1000 Oe field of the detection box its mass parameter μ must be greater than $(2H/Zg)^{\frac{1}{2}} = 5\ Z^{-\frac{1}{2}}e\ V$ (see Eq. 9).

Let us assume that $\mu >> 5\ Z^{-\frac{1}{2}}$ eV, then by using Eq. 8 and Eq. 10 we can readily estimate the number of photoelectrons produced by the Cherenkov light hitting each PMT:

$$N_{pe} = QE \quad (\Delta\epsilon/\epsilon_o)\ (2ZgH/E_o)\ (\Delta\phi/2\pi)\ \Delta s, \text{if} \quad \epsilon < E_o \qquad (19)$$

In this formula, ϵ is the photon energy, E_o is the steady tachyon energy, QE is the average number of photoelectrons emitted for each incident photon in the detectable energy interval $\Delta\epsilon$, $\Delta\phi$ is the azimuthal angle subtended by the phototube and Δs is the path length available for the TM to radiate light into a PMT. For our PMT's QE = 20% for

2.0 eV $<\epsilon<$ 4.8 eV. Using Eq. 10 and assuming a singly charged tachyon (Dirac) in a field of 1000 Oe, we find that E_o = 4.8 eV and ZgH = 20 MeV/cm. Assuming the Cherenkov light has to travel the full diagonal of the box, $\Delta\phi$ = 0.012 rad and Δs = 6.5 cm. Thus N_{pe} = 12 000; i.e. a TM of the type assumed above should produce enormous signals in the PMT's.

When scanning the photographic film used to record the oscilloscope traces we demand that three out of eight PMT's have a signal in excess of 5 photoelectrons. Since N_{pe} scales as Z^2, the minimum Z to which we are sensitive is $\sqrt{5/12\ 000}$ = 1/50. We find no events.

Alternatively, if Z>6, the tachyon has a steady energy E_o of only 2.0 eV and can no longer radiate in the visible and near ultraviolet wavelengths to which the PMT is sensitive. (See Eq. 10).

Now let us consider a TM which cannot radiate Cherenkov light but can ionize matter and thus leave etchable tracks in our Lexan sheets. Such tracks will be made only if the rate of ionization is high enough.

In a separate calibration using 600 MeV/nucleon ^{56}Fe ions at the Lawrence Berkely Laboratory we determined that detectable holes are left in Lexan sheets when the ionization loss is greater than 7 GeV/cm of Lexan. Thus a TM should be detectable if it deposits at least this energy in the first three sheets of the Lexan stack.[22]

In Fig. 4 we plot the expected dE/dx in Lexan and air for a singly charged TM as a function of its velocity. To determine whether a given TM will be sufficiently heavily ionizing, we make the conservative assumption that the TM has lost all its energy in the roof above the box. The trajectory of the TM in the air-filling of the box is then analyzed. Here the magnetic field pumps energy into the TM; whereas ionization in air depletes it. At the bottom of the box the TM either has or has not sufficient energy to leave an etchable track in the Lexan.

This computer study shows that if a $Z = 1$ TM has $\mu<10^7$ eV, it ionizes air so heavily that it has insufficient energy left to make etchable holes in the first three sheets of Lexan. Alternatively, if the TM has $\mu>10^{11}$ eV the monopole is not slowed enough in passage through the field that it can ionize Lexan. For a $Z = 2$ TM, the corresponding limits are 10^{10} eV and 10^{12} eV.

Now let us consider the conditions for a TM to be focused by the fringing magnetic field. Suppose a TM is moving with a velocity $\dot{v}$ at an angle θ with respect to the magnetic field. Applying the Lorentz force condition we have for the local curvature of the trajectory,

$$k = \frac{d\theta}{ds} = \frac{dp_\perp}{p\ ds} = -\frac{gZH_\perp}{vp} \tag{20}$$

Assume that $v \gg 1$ so that $p \approx \mu$ and further that $\theta \ll 1$ so that $H_\perp = H \sin \theta \approx H\theta$. Then we have

$$k = \frac{d\theta}{ds} = -\frac{gZH\theta}{v\mu} \tag{21}$$

This equation defines a relaxation length $\lambda = v\mu/ZgH$. For focusing to occur, λ must be less than the radius of curvature of the field line.

The field lines outside the bubble chamber building are shown in fig. 5. It is evident that the field lines emanating from the bubble chamber make an S-shaped bend to join with those of the earth's field. This field, 0.6 Oe, continues in an essentially straight direction for many kilometers. Any TM which can be focused at all will be bent by the earth's field so that it is travelling along a field line as it approaches the first bend at an elevation about 80m above the bubble chamber.

This first bend is the critical one. Here H is low (about 1 Oe) and hence λ is likely to be large. At the reverse bend nearer the bubble chamber H is relatively larger (30 Oe) and v is smaller so that any TM which follows the initial bend will follow the second. (This situation contrasts with that in focusing of thermalized bradyonic monopoles where the bend near the magnetic dipole is the critical one).[23]

At the upper bend, $1/k \approx 70m$, and $gH = 2$ MeV/m. For a TM to be focused, it must satisfy $\lambda < 1/k$ or

$$v\mu < 140 \text{ Z MeV}. \qquad (22)$$

Now for a TM which emits Chrenkov radiation we have $v = p/E \approx \mu/E = \mu/(2H/Zg)^{\frac{1}{2}}$. At the upper bend this equation reduces to $v = 7\mu Z^{\frac{1}{2}}$, where μ is in eV. Substituting this value for v in equation (22), we find that a Cherenkov radiating TM will be focused if its mass parameter

$$\mu < 4\ 10^3\ Z^{\frac{1}{4}} \text{ eV}. \qquad (23)$$

A TM which does not emit Cherenkov radiation will generally not be decellerated by the earth's magnetic field. It should approach the upper bend at steady velocity $v \approx 137$. At this velocity the marginally small rate of energy lost to ionization balances the small energy gained from the earth's field. Substituting this value for v in equation (22), we see that a TM which does not emit Cherenkov radiation will be focused only if

$$\mu < Z \text{ MeV}. \qquad (24)$$

We have made a computer simulation of such TM's moving in the fringing magnetic field of the bubble chamber. We find that one having a mass parameter of 1 MeV in fact is not focused; whereas a 100 keV TM is. (See fig. 5).

Unfortunately such a light, non-radiating TM will not leave etchable tracks in Lexan, Leaving this detector sensitive only to TM's which are not focused.

Table I summarizes the limits which this experiment sets of TM's. For nearly all TM's to which we are sensitive the focusing action of the fringing field is not operative and our limit (90% confidence) is that the flux of TM's is less than 5 $10^{-12} cm^{-2} sec^{-1}$.

In experimental arrangement, this experiment most closely resembles that of Carithers, Stefanski and Adair.[23] In that experiment the core of a 30-inch bubble chamber magnet was used to gather bradyonic monopoles which had been thermalized in the earth's atmosphere. The upper limit on such monopoles was found to be $3 \times 10^{-14} cm^{-2} sec^{-1}$. When viewed as a search for TM's, their experiment was sensitive to roughly the same range of TM charge and mass as ours.[22] However the strong focussing action of that experiment would not work for TM's; thus the quoted limit for bradyonic monopoles must be reduced by 1/10,000 for tachyonic monopoles to reflect this absence of focussing. Furthermore only their scintillators and not their spark chambers would have been sensitive to Cherenkov radiating TM's, reducing the bradyonic limit by another factor of 30. So if we interpret their experiment as a search for TM's, the appropriate limits are $10^{-8} cm^{-2} sec^{-1}$ for TM's emitting Cherenkov radiation and 3×10^{-10} for those TM's which do not. Both experiments were sensitive only to north magnetic monopoles, since both experiments were conducted in the earth's northern hemisphere.

In a recent experiment at the Institute for Theoretical and Experimental Physics at Dubna, V. P. Perepelitsa has searched for pairs of tachyon monopoles that might be produced in e^+e^- collisions.[24] He sets a limit of 10^{-6} to 10^{-9} on the branching ratio for the production of lightly charged (g=e) TM's relative to $e^+e^- \rightarrow \gamma\gamma$.

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TABLE

Summary of results

Elapsed Exposure Times (Final Run)	
a. One photoelectron trigger	490 hours
b. three photoelectron trigger	630 hours
c. Lexan in place	550 hours
Effective Area of the Apparatus	
a. measured	11 m^2
b. using fringing magnetic field to gather TM's	1.3×10^4 m^2
90% Confidence Limits on Flux of TM's	
a. assuming Chrenkov radiation	($cm^{-2} sec^{-1}$)
1. $1/70<Z<6$, $\mu>4.8\ Z^{-\frac{1}{2}}$ eV, $0.1<\mu< 4 \times 10^3\ Z^{\frac{1}{4}}$ eV	3×10^{-15}
2. $1/70<Z<6, \mu>4.8\ Z^{-\frac{1}{2}}$ eV	5×10^{-12}
b. detected by ionization in Lexan	
1. $Z = 1$ and 10^7 eV$<\mu<10^{11}$ eV	1×10^{-11}
2. $Z = 2$ and 10^{10} eV$<\mu<10^{12}$eV	1×10^{-11}

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21. In principle we already have a detector of ionization since our detecting box was filled with air which is a weak scintillant. However our detection of TM's having $Z \leq 2$ by the

scintillation light emitted in the air filling was too marginal to be relied on.

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Figure Captions

Fig. 1 Schematic View of Apparatus. Detector suspended from roof above spherical 15-foot bubble chamber. Curtains and EAS counters were used in specific phases of measurement (see text).

Fig. 2. Detail of PMT housing. The outer shields are plain carbon steel. The inner ones are made from a molybdenum-permalloy and a Co-netic material.

Fig. 3. a) Comparison of rates (events/day) in preliminary run under different conditions of box and magnetic field. Solid circles are with field off; open circles are with field on.

b) Two-fold coincident rate (per day) signifying EAS with field off and on.

Fig. 4. Ionization loss of TM in air and Lexan as a function of velocity. Curves were plotted from equations 18 after multiplying by factor $(2/(1 + e^{v/137}))$ to allow for atomic form factor. For Lexan b_{max} was limited to 5000 $h/m_e c$ to compensate for density effect. $\bar{I}_{Lexan} = 70$ eV.

Fig. 5 Magnetic field lines (solid) above apparatus. For simplicity, field of earth is assumed to be vertical rather than having proper dip angle of 20°. Computer

Figure captions cont...

generated trajectories of non-radiating TM's :

μ = 1 MeV (dashed); μ = 100 keV (dot-dashed)

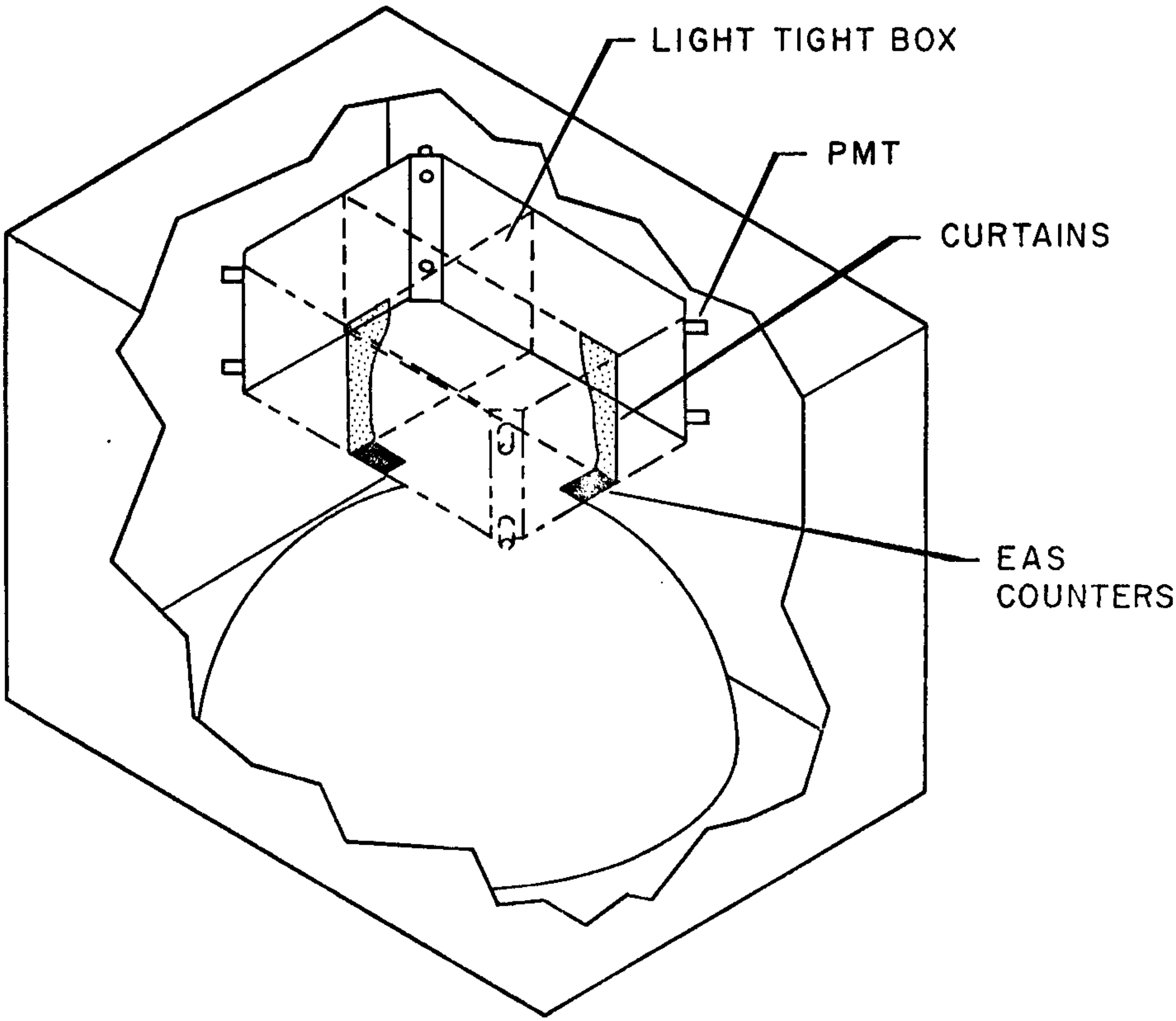


fig 1

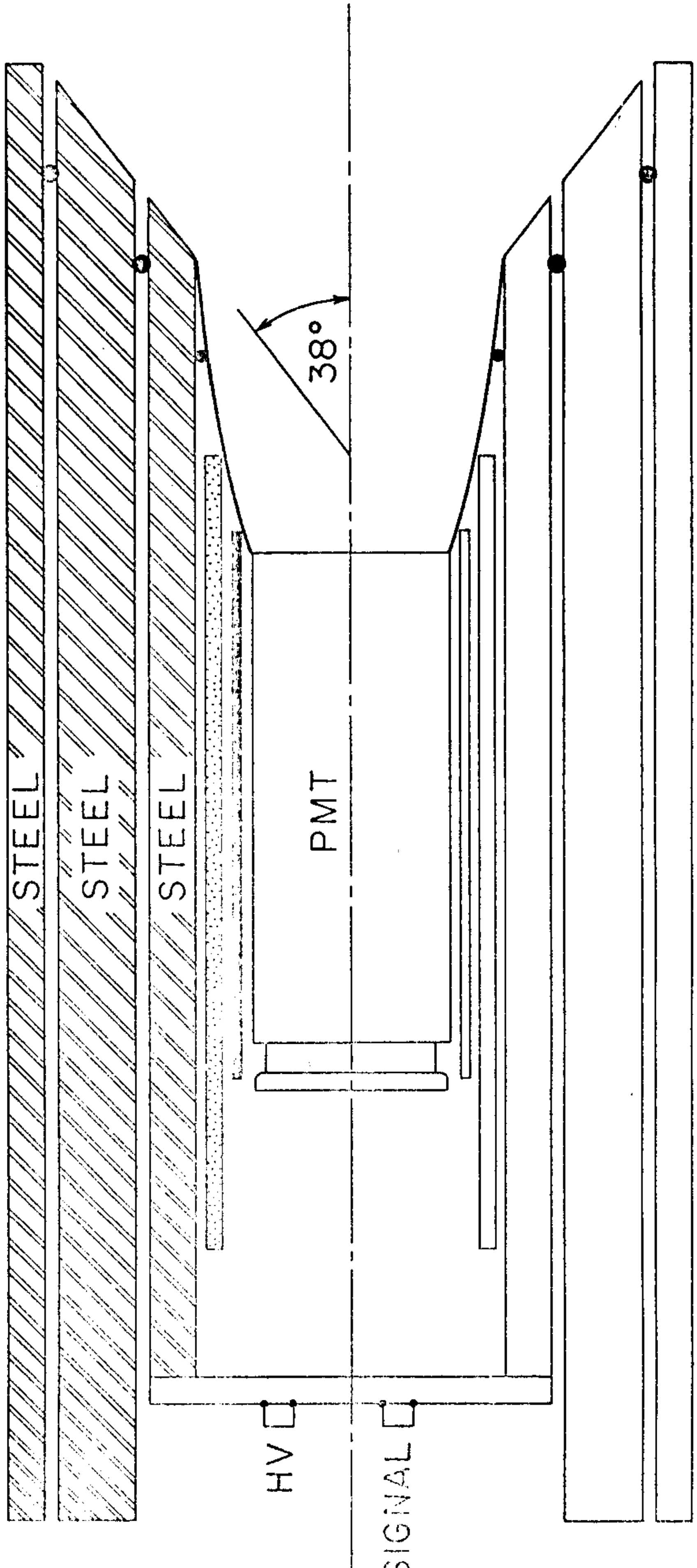
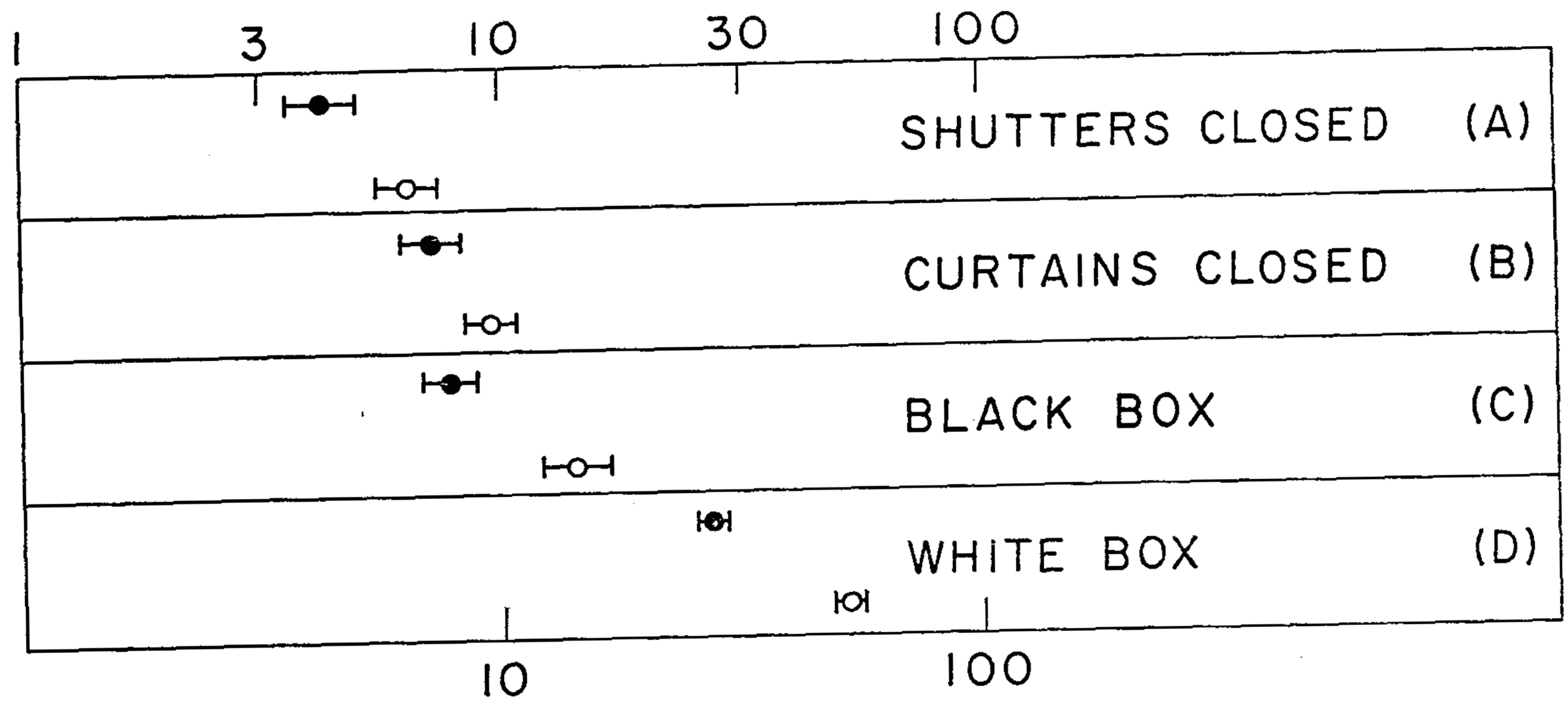


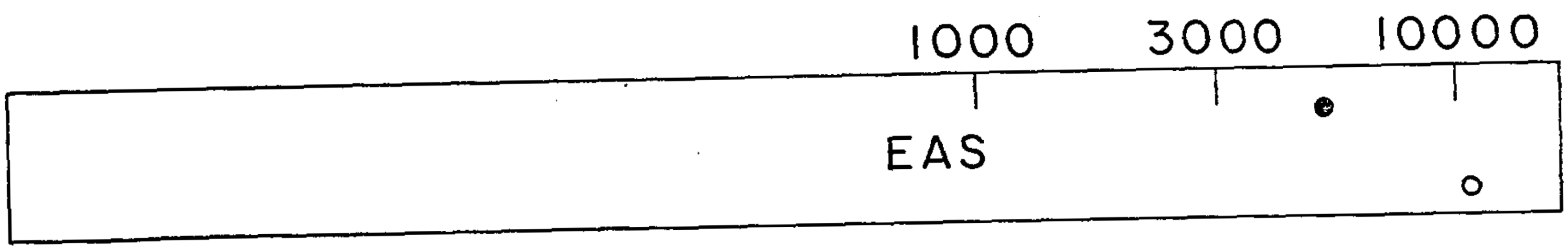
fig 2

Fig 3



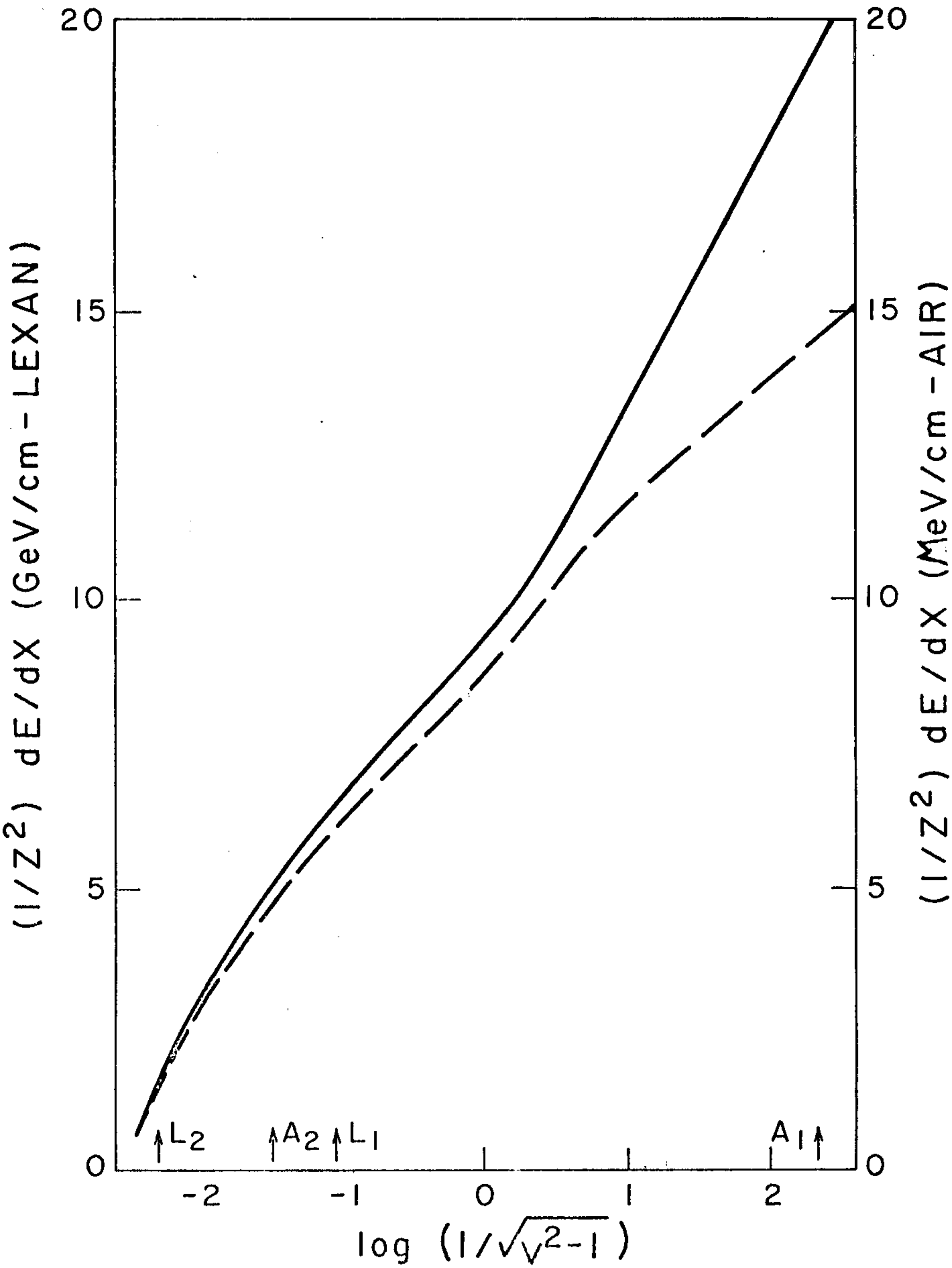
1
3
10
30
100
SHUTTERS CLOSED
(A)
CURTAINS CLOSED
(B)
BLACK BOX
(C)
WHITE BOX
(D)
10
100

(a)



1000
3000
10000
EAS

(b)



20
15
10
5
0
(1/Z^2) dE/dX (GeV/cm - LEXAN)
(1/Z^2) dE/dX (MeV/cm - AIR)
L$_2$
A$_2$
L$_1$
A$_1$
-2
-1
0
1
2
log (1/$\sqrt{\gamma^2-1}$)

Fig 4

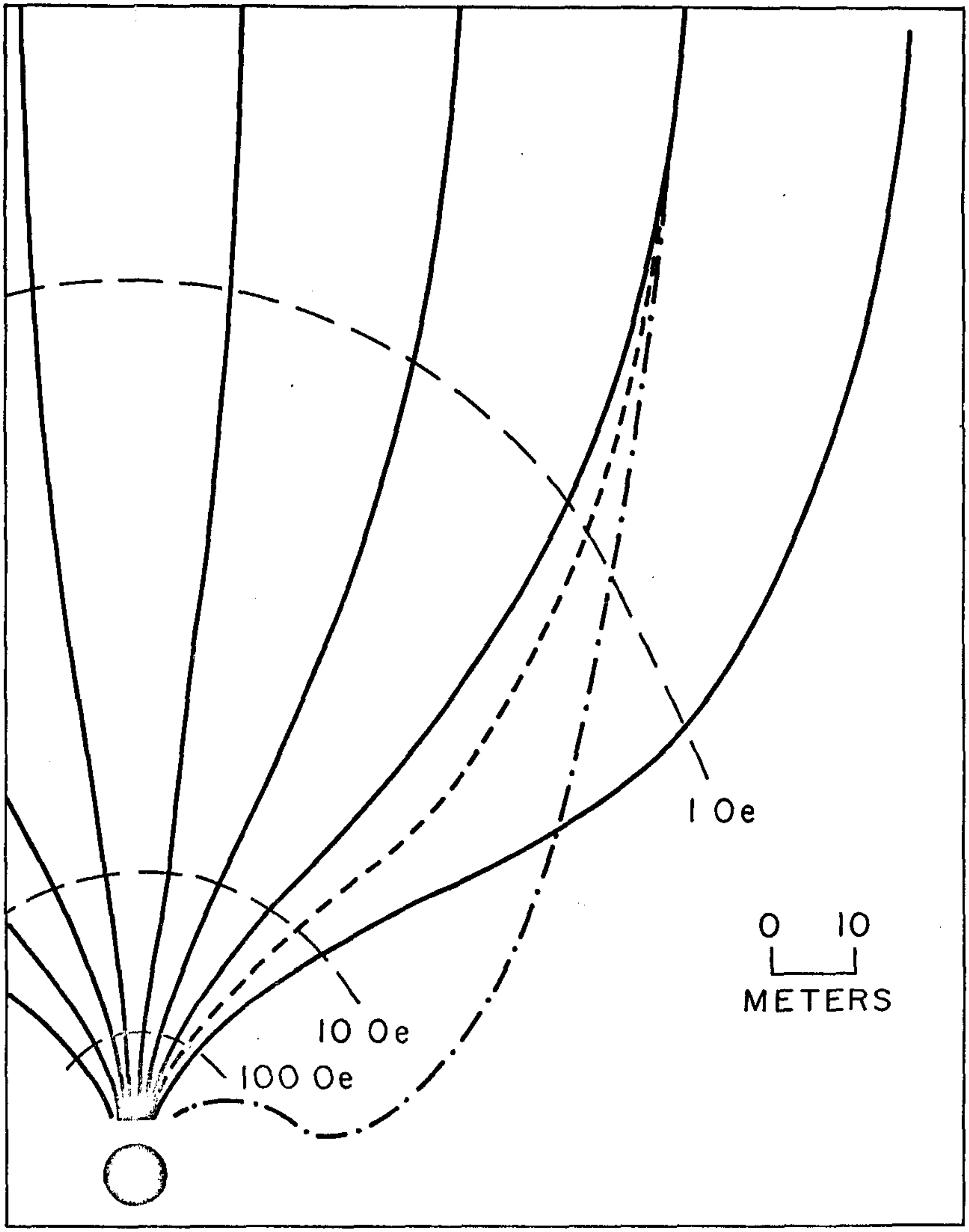


fig 5