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A search for heavy leptons in cosmic radiation underground

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Abstract. An experiment to search massive long-lived, weakly interacting particles (leptons) in cosmic radiation has been conducted at Kolar Gold Fields at a depth of 7·6 hg cm^{-2} (1 hg cm^{-2}=100 g cm^{-2}) below surface. The apparatus was senstive to sub-relativistic (velocity < 0·75 c) charged leptons of mass greater than that of a proton and life times greater than a microsecond. The method consists of selecting charged particles using a scintillator counter telescope and vetoing relativistic particles (velocity >0·75 c) by using a water Čerenkov detector. The range of the particle is observed in arrays of neon flash tubes interspersed with iron absorbers. During 3000 hours of observation 28 events were recorded satisfying the trigger and event selection criteria. Bulk of these events were interpreted as due to recoil protons (low energy) from the inelastic scattering of high energy muons in the overhead absorber. The remaining events were interpreted as either atmospheric stopping protons or stopping muons that failed to generate a Čerenkov signal. The observed events are thus consistent with the background and no heavy leptons were seen. From our observations an upper limit of 2·12×10^{-7} (with 90% confidence level) is set on the ratio of the flux of heavy leptons to that of all muons at this depth.

Keywords. New particles; heavy leptons; sub-relative particles in cosmic radiation.

1. Introduction

In the world of elementary particles there are many questions unanswered and many puzzles unsolved. The existence of both the electron and the muon, particles so dissimilar in mass and yet alike in all other aspects, is still not understood. One is not sure if the electron and the muon are the only charged leptons in the nature. One of the many speculations is that electron and muon are the first two lowest members of a family of leptons e, μ, E, M, E', M' ... with ν_e, ν_μ, ν_E, ν_M, $\nu_{E'}$, $\nu_{M'}$, ... as the corresponding neutrinos (see Perl 1971 for details). The particles listed above will naturally have their corresponding antiparticles. This speculation is also supported by the theoretical necessity that new leptons with specific properties are required for renormalizability of a large class of gauge theories of weak and electromagnetic interactions. The possible decay modes, then one can think of, among others are:

$$E^- \rightarrow \nu_E + \mu^- + \bar{\nu}_\mu$$
$$\text{or } E^- \rightarrow \nu_E + e^- + \bar{\nu}_e.$$

These postulated heavy leptons presumably participate in weak and electromagnetic interactions. Being massive, the dominant electromagnetic interaction process the particles loose energy by, is the ionization loss since bremsstrahlung and pair production processes decrease in importance as $1/m^2$. Since ionization losses are small in magnitude, heavy leptons can penetrate large amounts of matter provided they are sufficiently long-lived. Let us look into some theoretical estimates on the lifetimes and production cross-sections of heavy leptons.

Assuming that heavy leptons decay with the same coupling constant as in muon decays (conventional weak interaction theory), Thacker and Sakurai (1971) have calculated the total decay widths of heavy leptons as

$$\Gamma^{\text{Total}}_{\text{Leptonic}} = 3{\cdot}47 \times 10^{10}\, M_E^5 \text{ sec}^{-1}$$

where M_E is the heavy lepton mass in GeV. Then a heavy lepton of mass 0·5 GeV will have a lifetime as short as $\sim 10^{-9}$ sec. Heavier leptons have even smaller lifetimes.

Some of the production processes of heavy leptons which can possibly take place in the atmosphere are:

$$\text{(i)}\ \gamma + Z \rightarrow Z + E^+ (M^+) + E^- (M^-) \tag{1}$$

$$\text{(ii)}\ \mu^- + Z \rightarrow \mu^- + Z + E^+ (M^+) + E^- (M^-) \tag{2}$$

$$\text{(iii)}\ \nu_\mu + Z \rightarrow M^+ + Z + \text{anything} \tag{3}$$

$$\text{(iv)}\ \nu_e + Z \rightarrow E^+ + Z + \text{anything} \tag{4}$$

Here Z is the target nucleus. High energy gamma rays from π^- decay or cosmic ray muons or neutrinos can potentially initiate the above processes. Some theoretical estimates have been made on the cross-sections for the above processes. Calculations by Kim and Tsai (1972) show that production cross-section of a 0·5 GeV heavy lepton by a gamma ray of energy 20 GeV is $\sim 1{\cdot}7 \times 10^{-32}$ cm^2/Be nucleus.* Similarly Albright and Jarlskog (1974) have estimated theoretically that at neutrino energy of $E_\nu \sim 100$ GeV, heavy leptons of rest mass ~ 2 GeV are produced with a production cross-section $\sim 7 \times 10^{-37}$ cm^2/proton target.

Admittedly, the theoretically calculated production cross-sections as well as expected lifetimes of heavy leptons, are too small to enable us to detect heavy leptons in the present experiment. But all these calculations are made on the basic assumption that no radically new feature enters in the interaction, which would alter the results by orders of magnitude. The muon-electron problem is so little understood that some new concept may have to be invoked for its solution. It is therefore believed that it is not prudent to rely too much on these model-dependent calculations but use them only as guidelines wherever possible. The experimental searches for new particles should not be inhibited by preconceived ideas that short lifetimes are to be expected for massive weakly interacting particles as expressed also by Barna *et al* (1968). Keeping these ideas in mind, an experiment was conducted to search for long-lived weakly interacting heavy particles in cosmic radiation at a shallow depth of 7·6 hg cm^{-2} below ground level. The cosmic radiation at sea level

*See Smith *et al* (1977) for a more recent calculations on the cross-sections for photoproduction of heavy leptons (of mass 1·8 GeV) by gamma rays of various energies.

consists of hadrons, electrons, muons, neutrinos and heavy leptons, if any. By choosing a site for the experiment with a reasonable amount of matter (see Bhat 1977 for details of the location) overhead, we attenuate hadrons and electrons considerably (760 g cm^{-2} of rock in this case wherein the hadrons are attenuated by a factor of $\sim 10^{-3}$) thereby enriching the beam in muons and heavy leptons. The method consists of selecting charged particles with velocities less than 0·75c and determining their ranges in iron. From a knowledge of the range and of the upper limit of the velocity, a lower limit to the mass of the particle is deduced. Charged particles are selected by a scintillator telescope. That the velocity of the particle is less than 0·75c is assured by a veto signal from a water Čerenkov tank. Range is determined by employing a series of crossed neon flash tube (abbreviated as NFT hereafter) arrays interspersed with iron absorbers. Detection of low energy muons, which are in abundance at this depth, is uninteresting. A minimum range of 160 g cm^{-2} of iron is therefore required so as to prevent muons and indeed all other particles of sub-protonic mass from triggering the apparatus. It is inferred that the leptonic nature of heavy particles require a penetration of 760 g cm^{-2} of rock overhead and a minimum of 160 g cm^{-2} of iron within the range telescope without showing any signs of interaction. If it is assumed that the heavy mass particles which we are looking for are produced in the atmosphere, it is necessary that they should have a lifetime greater than or of the order of a microsecond so as to be detected in the present experiment.

2. Experimental arrangement

2.1. *Apparatus*

The apparatus used in this experiment was basically a velocity discriminated charged particle range spectrometer wherein the subrelativistic particles are detected using a system of scintillation and Čerenkov counters.

The experimental arrangement is shown in figure 1. S_1, S_2 and S_3 are three liquid scintillation (Shellsol-A) detectors each of dimension $50 \times 50 \times 10$ cm cand Č is a Ĉerenkov detector of dimension $60 \times 60 \times 30$ cm placed in between S_2 and S_3. S_1 is viewed by one photomultiplier (6810A) and S_2 and S_3 by two each. S_1, S_2 and S_3 are symmetrically placed one above the other such that S_1S_2=20 cms and S_2S_3=111 cms.

Č is a water Čerenkov detector used for velocity discrimination of charged particles. This contains $\sim$ 108 litre of water with a wavelength shifter, 4 β-methyl umbelliferone (100 mg/litre) dissolved in it in order to render the highly directional Čerenkov radiation isotropic and also to serve as a wavelength shifter (see Ross 1971 for details). Č is viewed from top by 6 photomultipliers (DuMont 6364, photocathode dia 12·5 cm) with their faces partly dipped into water. A, B, C, D and E are five pairs of NFT trays. Two trays of each pair are placed orthogonal to each other and all the pairs are placed symmetrically with respect to the $S_1S_2S_3$ axis. Pairs A and B are of size $60 \times 60 \times 4$ cm containing 4 layers of NFT's (of size 60×1 cm external dia) compactly arranged as shown in figure 1. Pairs C, D and E are trays

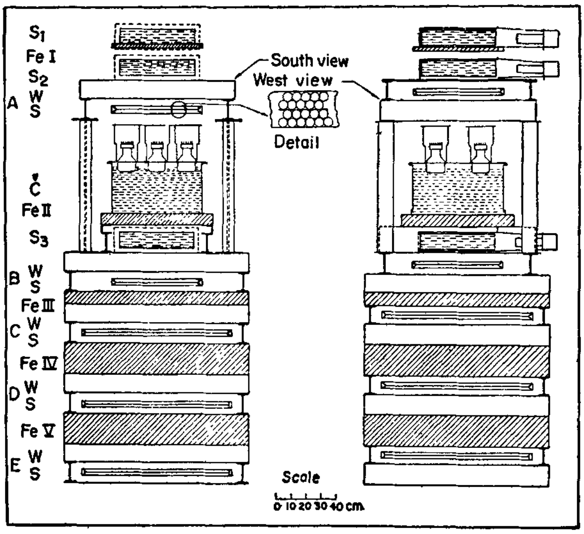

Figure 1. Experimental arrangement to detect heavy leptons in cosmic radiation underground. S_1, S_2 and S_3 are scintillation detectors (each of dimension 50 × 50 × 10 cm), Č a water Čerenkov detector (of dimension 60 × 60 × 30 cm³) A, B (of dimension 60 × 60 × 4 cm) C, D and E (each of dimension 1 m × 1 m× 4 cm) are pairs of NFT detectors interspersed with iron absorbers Fe I, Fe II, Fe III, Fe IV and Fe V of thicknesses 20, 60, 60, 160 and 160 g cm^{-2} respectively. The inset shows in detail the arrangement of NFT's in each 4-layer tray.

of dimension 1 m × 1 m × 4 cm consisting of (i) 4 layers of NFTs (arranged as in A or B) of dimension 1·1 m × 1 cm external dia, in the case of three trays, two of C and one of the pair D and (ii) 2 layers each of NFTs of dimension 1·1 m × 2 cm external dia, in the case of remaining trays in D and E.

Pairs of visual detectors A, B, C, D and E are separated by iron absorbers (as shown in figure 1) Fe I, Fe II, Fe III, Fe IV and Fe V of thickness 20 g cm^{-2}, 60 g cm^{-2}, 60 g cm^{-2}, 160 g cm^{-2} and 160 g cm^{-2} respectively.

2.2. *Electronics employed in the experiment*

A block-diagram of the electronics used in this experiment is shown in figure 2.

The pulses from the pair of photomultipliers viewing S_2 are designated S_2' and S_2''. Similarly those from the photomultipliers viewing S_3 are called S_3' and S_3''. The pulses from the single photomultiplier viewing S_1 are designated as S_1. Each of the pulses S_1, S_2', S_2'', S_3' and S_3'' are amplified (gain ∼25) and fed to pulse height discriminators (rise time and decay time of the output ∼ 10 nsec with FWHM ≈ 50 nsec, the pulse pair resolution ∼ 65 nsec). The outputs S_2' and S_2'' of the discriminators are fed to a coincidence circuit (resolving time ≈ 50 nsec) to generate a two-fold coincidence pulse S_2. Similarly S_3', S_3'' from the discriminators are put in coincidence to generate S_3. S_1, S_2 and S_3 are then fed to a three-fold coincidence circuit (resolving time ≈ 50 nsec) to generate $S_1S_2S_3$.

The pulses from the six photomultipliers (designated as C_i, i=1, 6) viewing the Čerenkov counters are amplified separately through preamplifiers (gain ∼ 10) and then OR-ed. The resulting output is called C. This is then amplified by two ampli-

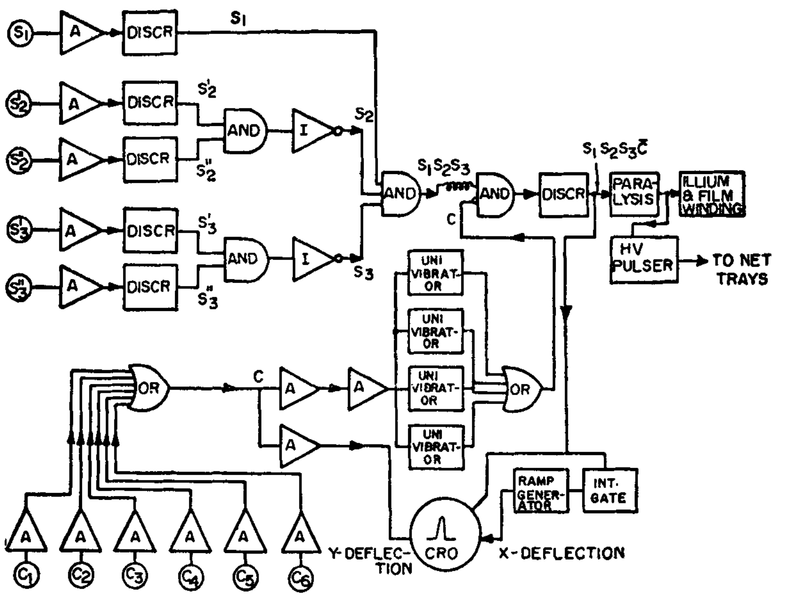

Figure 2. A block diagram of the electronics employed in the experiment to detect heavy leptons.

fiers (each of gain ≈ 25) in cascade and then made to trigger four univibrators simultaneously.

The four univibrator outputs (the FWHM of these four outputs are 185, 275, 390 and 495 nsec) are OR-ed and the output of this OR circuit (C) is put in *anticoincidence* with the $S_1S_2S_3$ pulse.* $S_1S_2S_3$ is suitably delayed such that the anticoincidence pulse C is fully effective. The pulse $S_1S_2S_3\ \bar{C}$ thus obtained constitutes the master pulse.

The master pulse then triggers the high voltage system to apply an electric field across the NFTs and subsequently activates the illumination and film winding circuits. Those of the NFTs through which the charged particles passed through glow with a characteristic orange glow on the application of the electric field. The photographs therefore reveal the trajectories of charged particles in the two orthogonal views. A call-counter keeps a record of the total number of events that have occurred. A paralysis circuit is employed to limit the event repetition rate to $\lesssim$ 3 per min so as to allow the high voltage condensers to charge to the peak voltage.

3. Description of methodology

3.1. *Determination of the working voltages on the various photomultipliers*

In order to ensure cent per cent efficiency of the system to detect charged particles, one has to ensure that all the photomultipliers operate at their respective optimum

*The dead-time of each of these gates (i.e. pulse pair resolution) is $\tau \sim 75$ nsec. The Čerenkov rate is $N_C \sim 2{\cdot}73 \times 10^4$/sec in which case the inefficiency of the veto circuit due to gate dead-time will be $N_C\ \tau \approx 2{\cdot}1 \times 10^{-3}$, which is unacceptably high. On the other hand if we use four gates of unequal widths, as is done here, the inefficiency due to gate dead-times is $(N_C\ \tau)^4 \approx 1{\cdot}7 \times 10^{-11}$, which is within the acceptable limits voltages. The optimum working voltages for the photomultipliers are decided as follows: If we have to determine the working voltage for a photomultiplier, say C_1, then reasonably high and arbitrary voltages are applied on all the other photomultipliers (except C_2 to C_6). Then a plot of the $S_1S_2S_3\, C_1$ (four-fold coincidence) rate as a function of voltage on the photomultiplier C_1 shows a rising portion followed by a plateau. The optimum working voltage for C_1 was fixed at 25 v higher than the voltage at the onset of the plateau. The optimum working voltages for the other photomultipliers also were determined in a similar fashion.

3.2. *Efficiency of the Čerenkov counter*

In view of the rarity of the events one is looking for, it is necessary to ensure that the Čerenkov counter is fully efficient in rejecting particles of velocity greater than 0·75c. An inefficient Čerenkov counter will otherwise, allow some of the much more abundant particles (e.g. muons) to masquerade as heavy particles.

The efficiency of the Čerenkov counter to detect relativistic particles was quantitatively estimated as follows: The photocathode of each of the photomultipliers $C_i(i=1, 6)$, was covered with a perforated aluminium mask. The transmittance of light through this mask was 1/12. The counting rate $S_1S_2S_3\bar{C}_i$ was measured with only one of the six photomultipliers C_i viewing $\check{C}$ at a time (the remaining not powered) and also the $S_1S_2S_3$ coincidence rate. The inefficiency of the Čerenkov detector being viewed by the *i*th photomultiplier (with mask on) is then given by,

$$\eta_i' = S_1S_2S_3\, \bar{C}_i/S_1S_2S_3 = e^{-n'}$$

where n' represents the number of photoelectrons released at the photocathode with mask on. When the mask is removed, the number of photoelectrons is clearly $n=12n'$. One expects the inefficiency of the *i*th photo tube when the mask is removed to be, $\eta_i=e^{-n}=e^{-12n'}=(\eta_i')^{12}$. Then the expected inefficiency η_i is compared with that observed by removing the mask and measuring the ratio $S_1S_2S_3\bar{C}_i/S_1S_2S_3$. The results are summarised in table 1. There is reasonably good agreement between the values in columns 4 and 5 (table 1). Since the inefficiency of the individual photo-

Table 1. Measurement of the inefficiency of the Čerenkov detector

Photo-multiplier number	Rate of C_i per min.	Inefficiency with mask on η'_i	Expected inefficiency $\eta_i=(\eta'_i)^{12}$	Observed inefficiency with mask removed
1	240K	0·75	$3{\cdot}2 \times 10^{-2}$	$(2{\cdot}5 \pm 0{\cdot}36) \times 10^{-2}$
2	82K	0·83	$10{\cdot}7 \times 10^{-2}$	$(6{\cdot}2 \pm 0{\cdot}65) \times 10^{-2}$
3	768K	0·87	$18{\cdot}8 \times 10^{-2}$	$(12{\cdot}6 \pm 1{\cdot}1) \times 10^{-2}$
4	688K	0·85	$14{\cdot}2 \times 10^{-2}$	$(8{\cdot}4 \pm 0{\cdot}9) \times 10^{-2}$
5	148K	0·78	$5{\cdot}0 \times 10^{-2}$	$(6{\cdot}3 \pm 0{\cdot}8) \times 10^{-2}$
6	197K	0·83	$10{\cdot}7 \times 10^{-2}$	$(6{\cdot}0 \pm 0{\cdot}8) \times 10^{-2}$

The average number of photoelectrons, emitted at all the six photocathodes is given by, $e^{-\bar{n}}=6{\cdot}2 \times 10^{-8}$ or $\bar{n}=16{\cdot}6 \pm 0{\cdot}3$

multipliers η_i are independent, the overall inefficiency of the Čerenkov detector with all the six photomultipliers viewing simultaneously is

$$\eta = \prod_{i=1}^{6} \eta_i = (6{\cdot}2 \pm 1{\cdot}8) \times 10^{-8}.$$

This rather high degree of efficiency $(1-\eta)$ of the Čerenkov counter to recognise particles with velocity >0·75c and reject them was necessary since we were looking for an admittedly rare phenomenon. Besides ensuring a high degree of efficiency of the Čerenkov detector as well as the reliability of the veto circuit, we have taken a further precaution in order to rule out any possibility of an event being recorded spuriously. For this purpose the Čerenkov pulses (C_i, $i=1$, 6) are summed and amplified separately independent of the remaining circuitry and displayed on an oscilloscope. This oscilloscope is photographed after every event. For an event to be accepted as due to heavy lepton, we insist that there should be no pulse on the oscilloscope.

3.3. *Sensitivity of the experiment to heavy mass sub-relativistic particles*

Figure 3 shows a plot of the Čerenkov yield (in photons/cm) and the range of muons

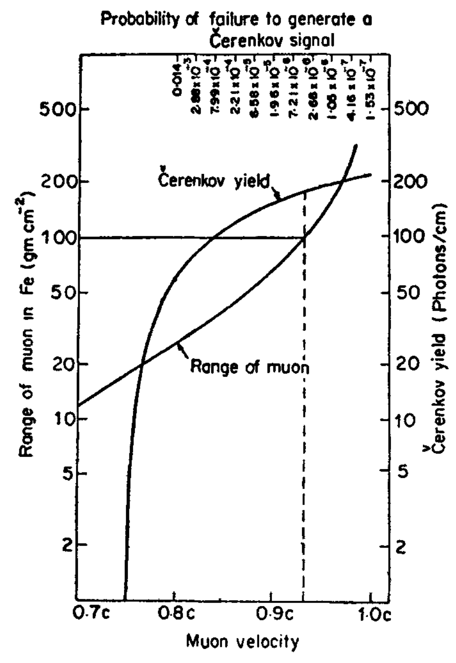

Figure 3. A plot of the range (in units of g cm^{-2} of iron) of a muon and the Čerenkov yield (in units of photons/cm) as a function of its velocity (expressed as a ratio of the velocity of light) at the centre of the Čerenkov detector Č. A muon has to have a range of 99 g cm^{-2} (after the mid-point of Č) to generate a three-fold coincidence $S_1S_2S_3$ in the present experiment. The corresponding velocity value is 0·932 c. A muon of this velocity radiates 175 photons/cm as Čerenkov radiation in water as shown in the figure. Also shown at the top are the calculated (see the text) probabilities of failure to generate a Čerenkov signal at different velocities of the charged particle.

(in g cm^{-2}) as a function of velocity (β). By insisting that a particle must penetrate a total of 160 g cm^{-2} of Fe equivalent (or 99 g cm^{-2} after the mid point in Č) we ensure that $\beta_r > 0{\cdot}932$ and, therefore that Čerenkov emission by a muon is $\geqslant 175$ photons/cm of water as shown in the figure. The efficiency of the Čerenkov counter to veto is quite high in such cases. Thus, almost all of the muons stopping in the apparatus beyond S_3 are precluded from triggering the apparatus. However, the number of photo-electrons emitted at the photocathodes is finite. From table 1 it is seen that the average number of photo-electrons emitted at all the six photocathodes due to Čerenkov radiation produced in water by an ultra-relativistic singly charged particle is $\bar{n} = (16{\cdot}6 \pm 0{\cdot}3)$. In addition it is to be noted that the Čerenkov yield is not a step function of the velocity and hence there is finite (though small) probability of Čerenkov signal not being generated even though a muon travels at $\beta > 0{\cdot}75$. These Čerenkov failure probabilities are given by

$$\eta(\beta) = e^{-6k \cdot \eta(\beta)} \tag{5}$$

when $n(\beta)$ is the Čerenkov yield (photons/cm) at a given velocity and k is the coefficient (in units of cm) which includes the average pathlength of a particle, the light collection efficiency, the photon conversion efficiency, etc. The value of k is experimentally determined to be 0·012 cms (see section 6·1). The factor 6 in the exponent corres-

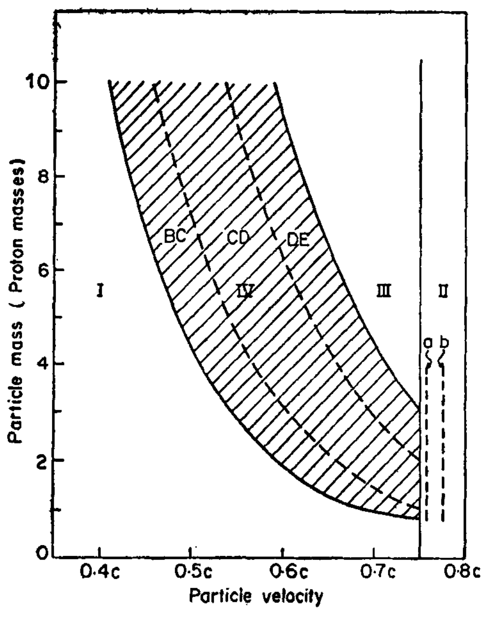

Figure 4. Sensitivity of the present experiment to particles of different masses (in units of proton masses) and velocities. The hatched area indicates the region in which the present experiment is sensitive. The sensitive region is in turn divided into three parts to show separately the regions of sensitivity for different types (BC, CD or DE types) of events that can be potentially recorded in the present experiment. For example, a BC type of event is one due to a heavy sub-relativistic particle stopping in the absorber located between the pair of trays B and C. The vertical dashed lines a and b depict the particle velocities 0·757c and 0·775c that correspond to the Čerenkov failure probabilities of 50 and 10 present respectively.

ponds to the number of photomultipliers used. η is given at the top of figure 3 for various β.

Figure 4 shows the sensitivity of the present experiment to particles of different masses, M and velocities β. The mass-velocity space in the figure is divided into 4 regions. The present experiment is sensitive to the region IV (shaded) only. Region I is forbidden because of the requirement that a particle must penetrate a minimum of 160 g cm^{-2} of Fe (equivalent), region II because the particle velocity must be less than 0·75 c and region III because the total range must be less than 550 g cm^{-2} of Fe to enable us to see the particle stop within the apparatus. The allowed region is further divided into three parts BC, CD and DE. If a particle stops in the absorber between the detectors B and C then we call it an event of the type BC; the possible range of masses and velocities are represented by the shaded area under BC. Also shown in the same figure are the broken lines a and b which represent 50% and 10% probability limits respectively for a charged particle failing to produce a Čerenkov signal even though $\beta > 0{\cdot}75$.

We expect heavy charged particles capable of being detected in this experiment to have been produced in the terrestrial atmosphere at heights $\geqslant 3$ km; for, the bulk of the cosmic ray interactions, strong electromagnetic or weak, take place at heights above 3 km. Assuming a relativistic time dilatation factor of 10, it is necessary that the particles have proper lifetime in their rest frames of $\geqslant 1$ μsec. Hence the present experiment is sensitive to particles with lifetimes greater than a microsecond and masses greater than that of a proton.

4. Analysis

A graduated perspex scale of length equal to that of a tray was attached one to each NFT tray. After each event, all the trays were photographed along with the scales, the latter being illuminated laterally. Both the views were photographed on a single frame of a 35 mm film using a system of mirrors to reflect the light from the different trays. Because of the wide disparity in the pathlengths of the NFT light (3·3 m to 5·5 m) and in the resulting demagnification factors of the various trays, it was not possible to judge the trajectory of a charged particle by a simple re-projection of the film. Hence each event was transcribed (position of the series of flashes in each tray read from the scales) on to a separate sheet wherein the relative positions of the trays were drawn to scale in both the views. As an example, figure 5 shows a sketch of an event of the type CD photographed in the present experiment. The scales shown in the figure symbolically represent the NFT trays.

An event recorded in the present experiment is accepted as a candidate for being a heavy mass sub-relativistic particle if and only if the following conditions were satisfied.

(i) The NFT photographs show single particle tracks in both the orthogonal views (West and South). Particles accompanied by another charged particle are therefore rejected.

(ii) At least trays A and B (in both views) should show flashes thereby ensuring that the particle was incident within a few degrees from the vertical and not from sides.

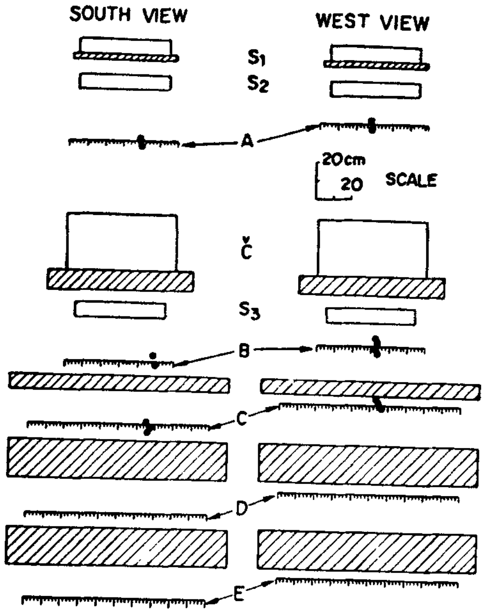

Figure 5. A sketch of an event of the type CD recorded in this experiment. The sub-relativistic particle is well within the geometry penetrating S_1, S_2, Č, S_3 and the first three iron absorbers. It stops in the absorber between the pair of NFTs C and D.

(iii) The oscilloscope photograph recording the signals from the Čerenkov detector should show no pulse to ensure that the event is not admitted due to the failure of appearance of a veto signal because of electronic dead-times.

5. Results

During 3000 hrs of observations nearly 18,720 events were recorded with an average rate of $(6{\cdot}24 \pm 0{\cdot}05)$ events/hr. The average rate of high energy muons passing through the telescope ($S_1S_2S_3$ rate) was (5820 ± 60) per hr. Most of the recorded events were due to the low energy electromagnetic component associated with high energy muons. Often there were no tracks at all in either view. There were 26 events of the types BC, 2 events of the type CD (one of which is shown in figure 5) and one event in which the particle passed straight through the telescope without stopping. All the remaining events were rejected by the selection criteria mentioned above.

6. Discussion and conclusions

6.1. *The single straight through event*

A single charged particle passed straight through the apparatus, satisfying the trigger criterion. The oscilloscope showed no Čerenkov pulse during this event. This event is interpreted as a case in which the Čerenkov detector failed to detect a highly relativistic charged particle (muon in this case). During the period of observation a total 6·53 million muons passed through S_1 and tray E geometry. Thus the Čerenkov failure probability can be calculated as:

$$\frac{1^{+1\cdot25}_{-0\cdot67}}{6\cdot53\times10^6} = 1\cdot53^{+1\cdot91}_{-1\cdot03}\times10^{-7}$$

This is in reasonable agreement with the inefficiency $(6\cdot2\pm1\cdot8)\times10^{-8}$ estimated from a study of the inefficiencies of individual photomultipliers (see section 3.2). Using this value of the inefficiency one can calculate the constant k in eq. (5). From figure 3, it can be seen that the Čerenkov yield of an ultra-relativistic ($\beta\approx1$) charged particle in water is 220 photons/cm; then

$$e^{-6k\cdot220}=1\cdot53\times10^{-7}$$

from which we find $k=0\cdot012$ cm. This is the value of k that was used in section 3.3 for calculating the Čerenkov failure probabilities for various lower values of β.

6.2. *Two events of the type CD*

We recall that an event of the type CD is one in which the charged particle showed tracks in both the views of the NFT trays A, B and C. Trays D and E showed no flashes though an extension of the track ABC passes through well within D and E, showing that the particle has stopped in the absorber Fe IV. The oscilloscope showed no pulse indicating that the particle velocity was $\leqslant0\cdot75c$. One such event is shown in figure 5.

One has to consider whether these events can be understood in terms of particle radiation already known to exist before attributing them to heavy leptons. From figure 4 it can be seen that particles with subprotonic masses cannot generate $S_1S_2S_3\bar{C}$ trigger if their velocity is less than 0·75c in Č detector. Hence pions and kaons cannot trigger the apparatus. Let us consider the contributions to CD type events from the other particle radiation known to exist at sea-level.

6.2.1. *Stopping protons:* It can be seen from figure 4 again that protons with velocity less than 0·75c cannot generate CD type events.

6.2.2. *Stopping deuterons:* The energy of a deuteron which is potentially capable of generating CD type events should lie in the range 740 MeV to 950 MeV depending on whether the particle stops at the top or at the bottom of the iron absorber Fe IV (see figure 1). Using the sea-level measurements by Ashton *et al* (1970) on the deuteron flux at sea-level it is estimated that the contribution by stopping deuterons to the CD type of events in our set-up is negligibly small.

6.2.3. *Stopping muons:* It is estimated that $\sim$1·51 million muons stopped during the period of observation in the absorber Fe IV. The velocities of these muons lie in the range 0·956 to 0·991 (as read from figure 3) depending on whether the muon stops at the top or bottom of the absorber respectively. The Čerenkov failure probabilities at these velocities as read from figure 3 are 10^{-6} and 3×10^{-7} respectively. The total number of CD type events generated by muons stopping in Fe IV coupled with Čerenkov failure probabilities then lie in the range 1·5 to 0·5 whereas the observed number is 2. Hence we interpret both the observed CD type of events as due to stopping muons.

6.3. *The 26 events of the type BC*

Sub-relativistic single charged particles stopping in the absorber Fe III in between the NFT trays B and C are called BC type events. In these events, trays A and B showed tracks in both the orthogonal views and the trays C, D and E did not show any, though an extension of the track AB passed through C, D and E. In addition the scope showed no pulse in these events.

Once again we consider the contributions of stopping protons, deuterons and muons to this category of events.

6.3.1. *Stopping protons:* The energy range of protons that stop in the matter between trays B and C is 480 MeV to 590 MeV depending on whether they stop at the top or bottom of the absorber. Let us consider the atmospheric protons arriving at the site and stopping in the absorber Fe III. Using the measurement of sea-level proton flux by Brooke and Wolfendale (1964) we calculated that protons could account for only 1·8 events of this type.

6.3.2. *Stopping deuterons:* Since the flux of deuterons at sea-level is an order of magnitude smaller than that of protons (Ashton *et al* 1970) the contribution to BC type of events from stopping deuterons is negligibly small.

6.3.3. *Stopping muons:* As in the case of CD type of events we estimated that $6{\cdot}3\times10^{5}$ muons have stopped during the period of observation in the absorber Fe III. The velocities of these muons are in the range 0·932 and 0·956 depending on whether the muon stops at the top or bottom of Fe III. The Čerenkov failure probabilities at these velocities are $2{\cdot}7\times10^{-6}$ and 10^{-6}. Then it can be estimated that the total number of events of the type BC caused by muons stopping in Fe III coupled with Čerenkov inefficiency are in the range 1·7 to 0·6 Hence atmost 2 events of the type BC can be attributed to stopping muons.

From the preceding discussion it is clear that we can account for only 2+2 (=4) events of the type BC as either due to stopping protons or stopping muons. Particle radiation at the surface cannot account for bulk of the events of the type BC. We now turn our attention to secondary sources of radiation that can possibly contribute to this type of events.

The formation of stars due to high energy muon interactions in emulsion exposed underground have been studied during early cosmic ray work (Kaneko *et al* 1955; George and Evans 1950). Often low energy protons are ejected from these stars, though, pions form a major component of these secondaries. The flux of stopping protons produced in such stars is reported by Kaneko *et al* (1955) as $(0{\cdot}015\pm0{\cdot}002)$ cm^{-3} day^{-1} at 17 hg cm^{-2} underground. Using this flux value we estimate the total number of BC type of events during the period of observation caused by stopping protons produced in nuclear interactions of high energy muons with the ' rock nuclei ' as (30 ± 4).* This is only a crude estimate since the energy spectrum of the secondary protons is not well-known. The number of BC type of events after subtracting the contribution from atmospheric stopping protons (2) and atmospheric stopping muons (2) is 22. This number can be compared with (30 ± 4) estimated above, of locally produced stopping protons. It is possible that in a few cases low energy secondaries (which are normally absorbed in a few grams of matter) produced simultaneously with the proton are sufficiently energetic and hence reach top tray (A). Such events get rejected by the event selection criteria. Also if the produced proton is emitted close to the parent muon (which is relativistic) both the proton and muon pass through the telescope; such events are vetoed by the Čerenkov detector. In view of these considerations the recorded BC type of events can be considered a lower limit on the number of locally produced stopping protons. Thus the agreement between the observed and expected number of BC type of events can be considered satisfactory.

From the foregoing discussion, it is clear that the observed heavy mass particle events can be interpreted in terms of the known particle radiation. If heavy leptons are present in cosmic radiation underground, they could have been seen in events of the type CD or DE whereas the observed two CD type of events could be fully accounted for as due to stopping muons. Hence we conclude that no heavy leptons are detected in the present experiment. We place an upper limit on the ratio of the flux of heavy leptons to that of all muons at this depth at $2{\cdot}12\times10^{-7}$ or in terms of absolute flux value, the upper limit on the flux of heavy leptons at 17·8 hg cm^{-2} underground (from top of atmosphere) is $1{\cdot}27\times10^{-9}$ cm^{-2} sec^{-1} st^{-1} (with 90% confidence) in the differential range 220 g cm^{-2} to 550 g cm^{-2} of iron.

Let us compare our results with other experiments to search for heavy mass particles both at the accelerators and using cosmic radiation.

As the heavy leptons are charged, they must couple to the electromagnetic field and be photoproduced in pairs. One such possibility is through the process 1·1. Barna *et al* (1968) at Stanford Linear Accelerator Centre (SLAC), USA, have searched for heavy leptons photoproduced by gamma rays of energy 18 GeV. They report an upper limit in the range $(1 \text{ to } 3)\times10^{-6}$ for the flux of long-lived heavy leptons (of mass 1–2 m_p) relative to that of muons, from their negative results. Experiments were also done to search for heavy leptons in p—Z interactions by Dorfan *et al* (1965), Appel *et al* (1974) and Cronin *et al* (1974) at Fermi National Accelerator Laboratory (FNAL), USA. These authors have used high energy proton beams incident on heavy nuclei to search for heavy leptons. They did not find any. The negative results were used to set some useful upper limits on the invariant cross-sections. There are also experiments on the production of heavy leptons in p-p collisions. Jovanovich *et al* (1975) at the European Centre for Nuclear Research (CERN) and Bintinger *et al* (1975) at FNAL have looked for slow massive particles produced in nucleon-nucleon interactions. The results are again negative. An experiment which sets a rather high lower limit on the mass of heavy leptons was by

* In calculating this number it was assumed that ~2% (see Jain *et al* 1970) of the protons produced have energies greater than the threshold energy (480 MeV) for generating BC type of events. Also it was assumed that these secondary protons are ejected isotropically.

Barish *et al* (1974) at FNAL. They tried to detect positively charged leptons (through their decay into *positive* muons) produced in a muonic neutrino beam experiment (the muonic neutrinos produce only *negative* muons). The few μ^+ events that were observed are consistent with the antineutrino contamination in the incident beam and no heavy leptons were detected. This experiment sets a lower limit on the mass of such particles to be around 8 GeV. It is possible that heavy muons have the same lepton number as the ordinary muons and one can expect heavy muons to be produced in the reactions:

$\nu_\mu + Z \rightarrow Z + M +$ hadrons, where M (heavy muon) decays into known leptons. An analysis of the bubble chamber (Gargamelle) data by Asratyan *et al* (1974) at CERN has set a lower limit on the mass of this particle M at 1·8 GeV.

The upper limit on the flux of heavy leptons obtained in the present experiment cannot be converted into limits on either the production cross-sections or heavy lepton mass as the production mechanism is not known and the target is spread over a large column of the atmosphere. Any such conversions will be too much model dependent to be useful.

However, our results can be compared with the upper limits obtained in cosmic ray experiments. Kasha *et al* (1968) have conducted an experiment at sea-level to search for singly charged heavy particles in cosmic radiation arriving at a zenith angle of 75°. From their negative results they set an upper limit on the flux at sea-level of singly charged heavy leptons in the velocity range $0{\cdot}5<\beta<0{\cdot}75$ at $2{\cdot}8\times10^{-8}$ cm^{-2} sec^{-1} st^{-1}. This is to be compared with the upper limit on the flux of heavy leptons at a depth of 7·6 hg cm^{-2} below ground, of $1{\cdot}27\times10^{-9}$ cm^{-2} st^{-1} sec^{-1} obtained in the present experiment. Ashton *et al* (1970) and Alcock *et al* (1974) have also searched for sub-relativistic massive particles in cosmic radiation at sea-level and underground (600 g cm^{-2}) respectively, and the results are negative.

However, there are some positive results on the basis of which the authors claimed to have detected the existence of heavy leptons. The 'Perl' events observed in e^+e^- storage rings at Stanford Positron Electron Annihilation Ring (SPEAR Perl *et al* 1976), USA, is one such example of positive results. The authors observed events with two non-collinear leptons (muon and electron) and no other charged particles. These events are interpreted as due to the following processes:

$$e^+ + e^- \rightarrow L^+ + L^- \text{ with the subsequent decays,}$$

$$L^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_L$$

$$\text{and} \quad L^+ \rightarrow e^+ + \nu_e + \bar{\nu}_L.$$

Also the electron-hadron final states observed in $e^+ e^-$ collisions by Braunschweig *et al* (1976) are interpreted as due to production and decay of heavy lepton pairs

$$L^- \rightarrow \bar{\nu}_L + \bar{\nu}_e + e^-$$

$$L^+ \rightarrow \bar{\nu}_L + \text{hadrons}$$

In a cosmic ray experiment carried out deep underground at Kolar Gold Fields (India), Krishnaswamy *et al* (1975) have recorded some events which are interpreted by the authors as evidence for the production (by neutrinos) and decay of charged heavy leptons. However, there is no independent confirmation of such phenomenon and it does appear that the cross-sections are rather high. In all these experiments, admittedly, one is dealing with very rare type of events. It is not, however, proven beyond doubt that the heavy leptons with fairly large lifetimes do exist.

It is concluded, therefore, that in many experiments both at the accelerators and in the cosmic radiation (including the present experiment) one did not see any evidence for the existence of heavy leptons. The few claims that are made for having detected heavy leptons again both at the accelerators and in the cosmic radiation need to be confirmed by independent experiments before being accepted as valid.

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