

M. G. K. MENON, *et al.*

1° Dicembre 1963

Il Nuovo Cimento

Serie X. Vol. 30, pag. 1208-1219

Cosmic-Ray Intensity at Great Depths and Neutrino Experiments.

M. G. K. MENON, P. V. RAMANA MURTHY, B. V. SREEKANTAN

Tata Institute of Fundamental Research - Bombay

S. MIYAKE

Osaka City University - Osaka

(ricevuto il 17 Giugno 1963)

Summary. — A group from the Tata Institute of Fundamental Research, Bombay, has recently completed measurements on cosmic-ray intensities deep underground up to depths of 8400 m w.e. On the basis of these observations it is suggested that, for investigations on naturally occurring neutrinos, there are great advantages to be gained by performing the experiments at considerable depths — around 9000 ft. — below the earth's surface, essentially because of the very low background which is encountered at such depths. Some features relevant to neutrino physics which emerge from the measurements already made and the design of future experiments to detect cosmic ray produced and extra terrestrial neutrinos are discussed.

1. - Introduction.

An experiment has recently been completed by a group from the Tata Institute of Fundamental Research ⁽¹⁾, in which cosmic-ray intensities deep underground have been measured at depths larger than 800 m w.e. (metres of water equivalent) and up to a maximum depth of 8400 m w.e. (9200 ft below surface) in the Kolar Gold Fields, Mysore State, South India. For this experiment counter telescopes designed specifically for detecting penetrating particles were used; each telescope consistend of two horizontal layers of plastic scintillators separated by a distance of 25 cm; each layer of scintillators had

⁽¹⁾ S. MIYAKE, V. S. NARASIMHAM and P. V. RAMANA MURTHY: to be published.

an area of 1.62 m² and a thickness of 6 cm; in the gap between the scintillators, and extending beyond the edges of the scintillators by at least 30 cm, there was a layer of lead 5 cm thick. Some of the experimental aspects and the preliminary results up to a depth of 4280 m w.e. were briefly reported by MIYAKE, NARASIMHAM and RAMANA MURTHY at the International Conference on Cosmic Rays (Kyoto) 1961 (2). Experimental details including the precautions which were taken, particularly to eliminate contributions due to the radioactive background, and the procedures which were adopted for evaluation of the vertical flux values from the observed counting rates have been given by RAMANA MURTHY (3). In the following Table I the flux values obtained by MIYAKE, NARASIMHAM and RAMANA MURTHY (1) for the various depths and other relevant data are presented.

TABLE I.

Depth from surface (m)	Depth from the top of atmosphere (m w.e.)	Time of observation (h min)	No. of counts observed	Vertical intensity particles (*) / cm ² s sr
270	816	60 20	10152	$(2.51 \pm 0.15) \cdot 10^{-6}$
600	1812	100 28	1029	$(1.77 \pm 0.07) \cdot 10^{-7}$
1130	3410	211 45	142	$(1.42 \pm 0.14) \cdot 10^{-8}$
1415	4280	944 06	127	$(3.24 \pm 0.35) \cdot 10^{-9}$
2110	6380 (**)	1496 40	18	$(1.92 \pm 0.47) \cdot 10^{-10}$
2760	8400 (**)	1440 00	none	$\left\{ \begin{array}{l} < 10^{-11} \text{ for « atmos-} \\ & \text{pheric » muons (***)} \\ < 1.5 \cdot 10^{-12} \text{ for muons} \\ & \text{from neutrinos} \end{array} \right.$

Area of each telescope = 1.5 m²,
Effective solid angle for isotropic radiation = 3.7 sr.

(*) The particles detected by the counter telescopes are essentially muons since there is a layer of lead 5 cm thick between the scintillators which cuts out most of the electrons. The threshold for a muon to be detected by the apparatus is ~100 MeV.

(**) Two telescopes, each of area 1.5 m², were operated at these depths.

(***) The difference of about a factor of ten in the two upper limits given is due to the widely different angular distributions of muons arising from these two sources; this is discussed more fully in the text.

Apart from providing valuable information on certain aspects of cosmic-ray physics, such as the energy spectrum of muons at sea level and the variation

(2) S. MIYAKE, V. S. NARASIMHAM and P. V. RAMANA MURTHY: *Proc. Phys. Soc. (Japan)*, **17**, 318 (1962).

(3) P. V. RAMANA MURTHY: *Ph. D. Thesis* (Bombay, 1962): mimeographed copies available from Tata Institute of Fundamental Research.

of the energy losses of muons at high energies ⁽¹⁾, as also the characteristics of nuclear collisions at ultra-high energies ⁽⁴⁾, these experimental results have a bearing on certain aspects of neutrino physics ^(*) which we would like to discuss in this paper. These intensity measurements, which constitute the only reliable measurements with reasonable accuracy at such large depths, are especially important for the design of future experiments involving the detection of neutrinos incident on the earth from various sources.

It can be seen from Table I that the intensity of the penetrating component recorded by the telescopes falls off continuously at a fast rate with increasing depth. Such a decrease in the intensity of cosmic-ray muons is expected for several reasons: the primary cosmic-ray intensity continuously decreases with increasing energy; the probability of decay of pions into muons decreases with increasing energy owing to relativistic elongation effects and competition between nuclear interaction and decay; and the energy losses of muons as a result of electromagnetic processes like bremsstrahlung, pair production etc., increase. *At very large depths, therefore, it is to be expected that, the contribution to the intensity, by muons produced in the atmosphere (hereafter referred to as « atmospheric » muons), drops off to such a low value that the contribution due to the charged particles produced locally by neutrinos very near the apparatus will become dominant. The question is at what depth does this really happen.* Since the attenuation mean free path of neutrinos is of the order of a few 10^4 earth diameters, the intensity of neutrinos will not vary in the least with depth and so the charged particle intensity in equilibrium with neutrinos must remain constant with depth. It is clear from Table I that the intensity of the charged penetrating component is still decreasing even at depths around 6400 m w.e. and so, *the contribution from neutrino interactions has not become significant even at these depths.* Whether neutrino-induced muons will predominate over atmospheric muons at 8400 m w.e. cannot as yet be answered.

However, the absence of any counts at the depth of 8400 m w.e. has, by itself, considerable significance and this is discussed in what follows.

2. - Neutrino intensities and neutrino interactions.

Neutrinos and antineutrinos are produced in the atmosphere through the decay of pions and muons and other unstable particles produced by cosmic rays. It has been shown by several authors that the flux of neutrinos con-

⁽⁴⁾ V. S. NARASIMHAM and P. V. RAMANA MURTHY: to be published.

^(*) Much of the background relevant to what follows in this paper has been covered in a series of seminars held at the Joint Institute for Nuclear Research, Dubna (Dubna preprint 1960, D-577: *On High-Energy Neutrino Physics*).

tinuously incident on the earth from extra-terrestrial sources is at least a factor of hundred less than the neutrinos produced in the atmosphere through the decay of cosmic-ray secondaries. This is, of course, an important point which needs to be checked experimentally. For the present, we shall assume that this is so.

ZATSEPIN and KUZMIN (5) have made a careful evaluation of the flux and energy spectrum of neutrinos that arise from the decay of pions and muons in the atmosphere. Using these flux values, the expected counting rates in

TABLE II.

Type of interaction	Cross-section	No. of counts expected
1. $\nu + n \rightarrow p + \mu^-$ $\bar{\nu} + p \rightarrow n + \mu^+$	$\sigma_\nu \approx 1.5 \cdot 10^{-38} E_\nu \cdot \text{cm}^2$ $\sigma_{\bar{\nu}} \approx 0.5 \cdot 10^{-38} E_{\bar{\nu}} \cdot \text{cm}^2$ (E_ν in GeV)	~ 0.60
2. Same as 1	If above linear increase of cross-section in (1) is cut-off at lengths $l \sim \hbar/m_N c$ ($\sim 2 \cdot 10^{-14}$ cm)	~ 0.10
3. $\nu_\mu + X \rightarrow W^+ + \mu^- + X'$ and W^+ decays in a very short time to $\nu'_\mu + \mu^+$ $\bar{\nu}_\mu + X \rightarrow W^- + \mu^+ + X'$ $\rightarrow \bar{\nu}'_\mu + \mu^- + \mu^+ + X'$ W is an intermediate boson of mass M_W LEE and YANG (6)	(a) $M_W = \text{K-meson mass}$ (b) $M_W = \text{proton mass}$	(a) ~ 1.5 (b) ~ 0.15
4. $\bar{\nu} + e^- \rightarrow W \rightarrow \mu^- + \bar{\nu}$ GLASHOW (7)	(a) $m_W = \text{K-meson mass}$ (b) $m_W = \text{proton mass}$	(a) ~ 360 (b) ~ 18

the telescopes, of area 3 square metres and solid angle 3.7 sr, over a period of 60 days (1440 hours), have been calculated on the basis of different theoretical hypotheses for the interaction of neutrinos. The expected rates are given

(5) G. T. ZATSEPIN and V. A. KUZMIN: *Sov. Phys. JETP*, **14**, 1294 (1962); see also an earlier paper of M. A. MARKOV and I. M. ZHELEZHNYKH: *Nucl. Phys.*, **27**, 385 (1961).

(6) T. D. LEE and C. N. YANG: *Phys. Rev. Lett.*, **4**, 307 (1960).

(7) S. L. GLASHOW: *Phys. Rev.*, **118**, 316 (1960).

in Table II. These take into account the recently established result of DANBY *et al.* ⁽⁸⁾ that $\nu_\mu \neq \nu_e$ ^(*).

The first hypothesis is that ν - \mathcal{N} interactions are of the type $\nu + \mathcal{N} \rightarrow \mathcal{N}' + \mu$ and the cross-section for this type of interaction grows linearly with the laboratory energy of the neutrino and has a value of about 10^{-38} cm² at 1 GeV.

The second hypothesis is that the four-fermion interactions are cut off at lengths $l \sim \hbar/m_{\mathcal{N}}c \sim 2 \cdot 10^{-14}$ cm due to form factor effects; this leads to a constant cross-section at energies above 1 GeV instead of the cross-section increasing linearly with energy.

The third hypothesis is that the weak interactions are mediated ⁽⁶⁾ by intermediate bosons of mass, m_w .

The fourth hypothesis is the one proposed by GLASHOW ⁽⁷⁾ involving the resonant scattering of antineutrinos on electrons leading to the formation of intermediate bosons, of mass greater than the K-meson mass, which decay into muons in a very short time. The counting rates listed in Table II are based on the values given by GLASHOW of 2/day·m² if $M_w = M_K$ and 0.1/day·m² if $M_w = M_{\mathcal{N}}$; M_K and $M_{\mathcal{N}}$ are the masses of the K-meson and nucleon respectively. These numbers were obtained by GLASHOW at a time when there was no evidence that $\nu_\mu \neq \nu_e$.

The expected rates may be contrasted with the experimental observation that no counts were observed in 1440 hours with a detector area of 3 m².

A few remarks ^(**) need to be made regarding the fourth hypothesis of resonant scattering of antineutrinos with intermediate boson production. On the basis of our present knowledge that $\nu_e \neq \nu_\mu$, we can consider only $\bar{\nu}_e$ for this reaction. Electron antineutrinos are produced in the decay of negative muons but since the muon lifetime is rather long, the $\bar{\nu}_e$ flux from this source is very small; there are other sources such as K_{e3} and K_2^0 decays, but then K-mesons are much less abundant than pions. Taking this into account the expected counting rates in Table II for the fourth hypothesis have to be decreased by a factor of a few $\cdot 10^{-3}$ and become comparable to the values expected for process 3 (in Table II). Thus all that can be said is that if intermediate bosons exist, with a mass in the region of ≤ 1 GeV, our results strongly support the observation that $\nu_e \neq \nu_\mu$. Beyond this, the rather interesting sug-

⁽⁸⁾ G. DANBY, J. M. GAILLARD, K. GOULIANOS, L. M. LEDERMAN, N. MISTRY, M. SCHWARTZ and J. STEINBERGER: *Phys. Rev. Lett.*, **9**, 36 (1962).

^(*) Throughout this paper, unless otherwise stated, when we speak of neutrinos (antineutrinos) we mean the muon neutrinos (antineutrinos); further, we make no distinction between neutrinos and antineutrinos since we do not distinguish experimentally the charge of the muon which they can give rise to in interactions.

^(**) These remarks are based on discussions at the Bangalore Summer School in Theoretical Physics (1963). Since then Dr. GLASHOW has also kindly written to us to the same effect.

gestion of GLASHOW, of resonance scattering, with the greatly enhanced cross-section that it provides, cannot be studied at present in view of the small flux of $\bar{\nu}_e$.

It should also be remarked that we have not taken into consideration « inelastic » neutrino interactions, *i.e.* those which lead to the production of strongly interacting particles.

The observed cross-section for the interaction of neutrinos of energy of the order of 1 GeV is certainly less than 10^{-37} cm². It is interesting that an important conclusion such as this follows from a very simple experiment on the intensity of penetrating particles deep underground. The limit which we give, *i.e.*, that the cross-section is less than 10^{-37} cm² is in agreement with the recent findings of DANBY *et al.* (8) that this cross-section has a value of $\sim 10^{-38}$ cm². Accepting the latter value it would appear that we are fairly close to the detection of neutrino interactions (see expected counting rates in Table II); the actual detection will depend on the « atmospheric » muon background which can be estimated only by performing a similar experiment with a larger detector area \times time factor. The fact that the counting rate was zero in 180 m²·days makes it hopeful that the background will indeed be low enough to detect neutrino interactions, particularly since the steep angular distribution of the « atmospheric » muons can be used in a powerful way to discriminate against them as discussed further on.

3. — Anomalous scattering of neutrinos.

PONTECORVO and CHUDAKOV (9) used our observations at 6380 m w.e. to set an upper limit of $\sigma_{\nu N} < 10^{-34}$ cm² for the *anomalous* scattering which can give rise to high-energy recoil protons in the reaction $\nu + N \rightarrow \nu + N$; they point out that such an anomalous interaction of the muon neutrino is to be expected if the muon itself possessed an anomalous interaction; and that the experiment which has been carried out to determine the value of $(g-2)$ for the muon still allowed the possibility of an appreciable anomalous muon interaction.

For the evaluation of this anomalous scattering cross-section, PONTECORVO and CHUDAKOV have used our flux value of $1.62 \cdot 10^{-10}$ cm⁻² s⁻¹ sr⁻¹ obtained at 6380 m w.e. (*). It is to be emphasized, however, that this flux was deduced from the counting rate on the assumption that the particles have a steep

(9) B. PONTECORVO and A. E. CHUDAKOV: *Proc. International Conference on High-Energy Physics* (CERN, 1962), p. 638.

(*) The flux value of $1.62 \cdot 10^{-10}$ cm⁻² s⁻¹ sr⁻¹ for 6380 m w.e. is contained in a preprint circulated by us after the Kyoto Conference; the final value of $1.92 \cdot 10^{-10}$ cm⁻² s⁻¹ sr⁻¹ given in Table I is not very different.

angular distribution, which is the case for cosmic-ray «atmospheric» muons. In this case the area \times solid angle factor of the telescopes employed at this depth is of the order of $0.9 \text{ m}^2 \text{ sr}$. But for an isotropic radiation, like neutrinos of energy 1 GeV , the area \times solid angle factor of the same apparatus is about $5.8 \text{ m}^2 \text{ sr}$. Because of this reason, the upper limit given by PONTECORVO and CHUDAKOV has to be lowered by a factor of six. Our more recent observation that no count was registered at 8400 m w.e. tells us further that the upper limit deduced from the rate at 6380 m w.e. can safely be lowered by another factor of ten. This leads to a cross-section $\sigma_{\nu N}$ for anomalous neutrino-nucleon scattering of less than $1.5 \cdot 10^{-36} \text{ cm}^2$; from this it follows ⁽⁹⁾ that the upper limit for the constant F of the effective four-fermion anomalous neutrino-nucleon interaction is

$$F < \frac{5 \cdot 10^{-5}}{M^2} \quad (M = \text{nucleon mass}),$$

which is very close to the weak interaction constant $G (=10^{-5}/M^2)$. Therefore, the possibility that muon neutrinos (and correspondingly muons themselves) possess such an anomalous interaction is greatly reduced by the observation at 8400 m w.e.

4. — Energy-density of neutrinos.

PONTECORVO and CHUDAKOV ⁽⁹⁾ have also deduced the upper limit for the energy-density of neutrinos and antineutrinos (of energy greater than 1 GeV), in the universe from our observations at 6380 m w.e. , assuming that the cross-section for the production of muons by neutrinos in processes such as $\nu + N \rightarrow N + \mu$ is about 10^{-38} cm^2 . (The recent results of DANBY *et al.* ⁽⁸⁾ indicate strongly that the interaction cross-section of neutrinos of energy of the order of a few GeV is consistent with the theoretical expectation of 10^{-38} cm^2 .) The upper limit for the neutrino-antineutrino energy-density in the universe set by PONTECORVO and CHUDAKOV is 10^{-5} MeV/cm^3 .

If we take into account the effect of solid angle discussed in Section 3 and also the observation that no counts were observed at 8400 m w.e. the upper limit for the energy density of neutrinos and antineutrinos (of energy $\geq 1 \text{ GeV}$) in the universe turns out to be $1.5 \cdot 10^{-7} \text{ MeV/cm}^3$, which is five orders of magnitude lower than the corresponding energy-density of nucleons in the universe. In this paper we do not wish to go into the various implications of this upper limit; there is a useful discussion on this point by PONTECORVO and SMORODINSKY ⁽¹⁰⁾.

⁽¹⁰⁾ B. PONTECORVO and YA. SMORODINSKY: *Sov. Phys. JETP*, **14**(1), 1731 (1962).

5. - Life-time of the proton.

REINES, COWAN and GOLDBABER⁽¹¹⁾ have discussed the manner in which one can, in experiments of this type, obtain lower limits for the life-time of the proton, which would provide a sort of figure of merit for the law of conservation of baryons. They estimated a life-time of $>10^{21}$ years for the free proton and $>10^{22}$ years for bound protons which form part of nuclei; the latter figure is indicative of the absence of nucleon destroying collisions within nuclei; they have for these life-times considered all decays of the proton which are consistent with the laws of conservation of charge, energy, momentum and angular momentum. REINES and GIAMATI⁽¹²⁾ have improved considerably these figures for the proton life-time and give values of $>1.5 \cdot 10^{26}$ years for free protons and $> \text{few} \cdot 10^{27}$ years for bound protons on the basis of their observations at a depth of 585 m w.e. in a salt mine. REINES and GIAMATI have given in their paper⁽¹²⁾ a detailed discussion of the various aspects involved and all the earlier work concerning this problem.

It may appear that our observations at great depths would allow us to deduce figures for the proton life-time even better than the above. This, however, is not the case. Even though the telescopes recorded no count in a period of 60 days at the largest depth of 8400 m.w.e., the counting rates of individual scintillator layers composing the telescope were quite high—about 10/minute; the exact rates depended on the bias of the discriminators used. Previous investigations⁽¹³⁾ in the same mines have shown that the mines are radioactive at all depths and this radioactivity is due to γ -rays from ThC'. Therefore, an appreciable fraction of the counting rate of individual scintillator layers at 8400 m w.e. arises from local radioactivity. With this counting rate we can only deduce lower limits of $2.7 \cdot 10^{20}$ years for the life-time of the free proton and $2 \cdot 10^{21}$ years for the life-time of bound protons. This life-time is for decay by all charged modes.

From our experiment using the *coincidence* counting rate we can set a lower limit to the life-time of the proton in which one of the decay products is a muon. Coincidences can be caused in the telescope only by muons of energy greater than 100 MeV. From the result that no coincidence count was registered in 60 days at 8400 m w.e. we can set a lower limit of $5 \cdot 10^{25}$ years for the decay of protons into muons of energy greater than 100 MeV, in the case of free protons, and $4 \cdot 10^{26}$ years in the case of bound protons. If we consider the

(11) F. A. REINES, C. L. COWAN and M. GOLDBABER: *Phys. Rev.*, **96**, 1157 (1954).

(12) F. A. REINES and C. C. GIAMATI: *Proc. Conference on Nuclear Electronics*, vol. 1 (Belgrade, 1961), p. 47; also *Phys. Rev.*, **126**, 2178 (1962).

(13) B. V. SREEKANTAN and S. NARANAN: *Proc. Ind. Acad. Sci.*, **36**, 97 (1952).

possibility of the protons decaying into muons of much higher energy, which is energetically quite feasible (say muons of energy 300 MeV), then we have to consider the bound protons in the surrounding rock also up to a rock thickness of ~ 30 cm; this leads to a lower limit of $3 \cdot 10^{28}$ years for the decay of bound protons (into muons of energy 300 MeV or more). Questions relating to the decays of neutrons with breakdown of the law of conservation of baryons and decays involving pions as decay products can also be considered in a similar manner.

6. - Future experiments.

We shall now discuss some aspects which relate to the design of future experiments involving the detection of neutrinos deep underground.

a) *The intermediate boson.* Consider first the observation that no count has been recorded by 3 m^2 of counter telescope in a period of operation of 60 days. From an extrapolation of the cosmic-ray «atmospheric» muon intensity observed at 4280 m w.e. and 6380 m w.e., it can be seen that about 1 to 2 counts due to «atmospheric» muons should have been recorded at 8400 m w.e. It is possible that no count was registered because of statistical fluctuations. On the other hand, it may be that the cosmic-ray «atmospheric» muon intensity has really dropped off by several orders of magnitude and that no count is to be expected; in fact, an extrapolation based on all the available data would suggest that the expectation of $1 \div 2$ counts is on the high side. As can be seen from Table II, if the cross-section for neutrino interactions is as high as is to be expected on the basis of the production of intermediate bosons of mass near the K-meson mass, then one or two counts due to neutrino-produced muons should have been observed at 8400 m w.e. The observation that no count has been registered may again be due to a statistical fluctuation.

It is obvious that a follow-up experiment at a depth around 8400 m w.e. with area \times time of operation increased by a factor of 50 will certainly tell us whether intermediate bosons with mass of the order of that of the K-meson are produced or not; if no counts are recorded in this case, it will be clear that the intermediate boson, if it exists, has a mass considerably larger than the mass of the K-meson. A relatively simple experiment with a negative answer can thus yield a result of interest. On the other hand, if the counting rate turns out to be finite in such an experiment, then visual detectors like neon hodoscopes, spark chambers etc., will help to find out whether the events observed are due to «atmospheric» muons or caused by muons resulting from neutrino interactions in the surrounding rock. Such a separation becomes possible because of the widely different angular distributions of the two types of events,

viz. « atmospheric » muons would have a $\cos^n\theta$ angular dependence with $n \sim 6$ or 7 ⁽¹⁾ whilst neutrino-produced muons would have a $\cos^{-\delta}\theta$ angular dependence with $0 < |\delta| < 1$. The simplest and most obvious manner in which one can use these widely different angular distributions to discriminate against « atmospheric » muons, without recourse to visual detectors, would be to demand coincidences between parallel detector areas kept in the vertical plane; « atmospheric » muons arriving essentially in the vertical direction will not give rise to coincidences whilst the isotropic neutrino-produced muons will. The experiment is certainly a feasible one.

b) Extra-terrestrial neutrinos. The problem of detecting extra-terrestrial neutrinos has been discussed by many authors (see for example MORRISON ⁽¹⁴⁾). If they can be detected it would open up a new and important field of neutrino astronomy.

Experiments which have been envisaged for the detection of neutrinos underground either involve elaborate anticoincidence arrangements ⁽¹⁵⁾ or nano-second timing devices ⁽¹⁶⁾.

Our recent experiment has yielded a negative result in $180 \text{ meter}^2 \cdot \text{days}$ at 8400 m w.e. If this is not due to a statistical fluctuation and can be taken as an indication that the « atmospheric » muon background is indeed low, then, particularly if the neutrino interaction cross-section increases with energy, it might be feasible to work with simple large-area detectors deep underground in the manner discussed in Section 6-*a* to record neutrinos from extra-terrestrial sources. Thus it may be feasible to record the sudden increase of neutrino intensity that is expected to occur in the eventuality of a supernova explosion.

If we assume the cross-section for neutrino interactions to be the theoretical cross-section expected on the basis of intermediate boson production (with $m_w = m_K$), then in our present apparatus of 3 m^2 , we expect 1.5 counts due to neutrino interactions in a period of 60 days with a cosmic-ray neutrino flux of $2.4 \cdot 10^{-1} / \text{cm}^2 \cdot \text{s}$. Thus to register one count a traversal of $\sim 10^6$ neutrinos/ cm^2 is necessary through the entire 3 m^2 area of the telescopes. Let us now suppose that we are interested in registering the increase in the intensity of neutrinos in the GeV energy range due to the explosion of a supernova at a distance of about 1000 light years (10^{21} cm). To be sure that there has been a genuine increase we should get a large departure from our normal counting rate—for example, one count a day over a 10-day period, when the normal counting rate is one

⁽¹⁴⁾ P. MORRISON: *Scientific American* **207**, no. 2, 90 (1962).

⁽¹⁵⁾ F. A. REINES: *Proc. International Conference on Instrumentation for High-Energy Physics* (Berkeley, 1960), p. 212.

⁽¹⁶⁾ V. A. KUZMIN, M. A. MARKOV, G. T. ZATSEPIN and I. M. ZHELEZNYKH: *Proc. Phys. Soc. (Japan)*, **17**, 353 (1962).

count in 60 days. For this at least $\sim 10^6$ neutrinos/cm² should pass through the telescopes per day for this period. This leads to a requirement of an output of 10^{49} neutrinos per day for a period of 10 days corresponding to a total release of 10^{50} neutrinos in the explosion of the supernova. CHIU (17) has estimated that under certain hypotheses one could expect a release of about 10^{48} neutrinos in the energy region of 10 to 20 GeV in the explosion of some types of supernovae (*). These numbers must be treated with caution and purely serve as an indication that if the neutrino cross-section tends to increase with energy then it will be experimentally feasible to detect neutrinos from such astrophysical events by using large detector areas (hundreds of square metres) at the deepest depths available, *i.e.*, ~ 9000 ft. below ground.

c) Interactions due to electron neutrinos (ν_e). We have already stated in Section 1 that the apparatus used thus far detects particles which are capable of penetrating 5 cm of lead. These are mainly muons. It is, however, possible to redesign the equipment to distinguish separately electrons which pass through it with a view to study interactions caused by electron neutrinos (ν_e). Regarding this the following remarks can be made: As far as muon neutrinos are concerned, the interactions produced by them in the rock surrounding the apparatus up to a thickness of 2 to 3 metres can be utilised, since muons of energy 1 GeV produced in these interactions can easily penetrate that amount of rock. The useful thickness increases with increasing energy. However, in the case of the interactions of electron neutrinos (ν_e) the effective thickness of the rock that can be utilised is very limited. The radiation length in rock is about 27 g/cm², which corresponds to a thickness of about 10 cm. Even if one assumes that 1 GeV electrons can be detected after 5 or 6 radiation lengths through the rock it is clear that one cannot utilize more than about half a metre of rock surrounding the apparatus. Therefore, even if one has the means of identifying the charged particle which is registered as an electron, the number of ν_e -induced interactions that can be detected will be at least a factor of 5 down compared to ν_μ interactions; in addition, the flux of ν_e neutrinos is much less than the flux of ν_μ neutrinos. Considering these aspects, the detection of electron neutrinos is considerably less probable than that of the muon neutrinos.

(17) H. Y. CHIU: *International Science and Technology*, no. 8 (1962), p. 26.

(*) *Note added in proofs.* — If these arise from the annihilation of electron-positron pairs, they are expected to be of the ν_e type, for which, as discussed below in Section 6-c, the detection efficiency will be down by a factor of 5 compared to ν_μ 's. On the other hand there are also mechanisms which can give rise to ν_μ type neutrinos.

7. — Concluding remarks.

In conclusion we would like to emphasize that our recently completed experiment already indicates that deep underground studies (at depths of the order of 9000 ft. below the earth's surface) have many interesting possibilities in the field of neutrino physics, involving observations on cosmic-ray-produced and extra-terrestrial neutrinos. The Kolar Gold Fields in Mysore State are well suited for such experiments. It would be necessary to increase the area \times time factor by fifty to a hundred compared to what we have used. By taking coincidences between large detector areas kept parallel to each other and in the vertical plane it should be possible to discriminate strongly against the essentially vertical « atmospheric » muons whilst still detecting the isotropic neutrino-produced muons. The use of visual detectors would enable one to remove some of the ambiguities in interpretation that may otherwise arise.

RIASSUNTO (*)

Un gruppo del Tata Institute of Fundamental Research, Bombay, ha recentemente completato le misure delle intensità dei raggi cosmici sotterra sino a profondità di 8400 m a.e. Sulla base di queste osservazioni si suggerisce che si potrebbero ottenere grandi vantaggi eseguendo esperimenti a considerevoli profondità — circa 9000 ft. — sotto la superficie, essenzialmente grazie al bassissimo fondo che si riscontra a queste profondità. Si discutono alcune caratteristiche, interessanti per la fisica del neutrino, che emergono dalle misure già fatte ed il progetto di nuovi esperimenti per rivelare i raggi cosmici prodotti ed i neutrini extra terrestri.

(*) Traduzione a cura della Redazione.

M. G. K. MENON, *et al.*

1° Dicembre 1963

Il Nuovo Cimento

Serie X, Vol. 30, pag. 1208-1219

ON THE POSSIBILITY OF EXPERIMENTS WITH
NATURAL NEUTRINOS DEEP UNDERGROUND

M. G. K. MENON, P. V. RAMANA MURTHY and B. V. SREEKANTAN

Tata Institute of Fundamental Research, Bombay-5, India

and

S. MIYAKE

Osaka City University, Osaka, Japan

Received 10 June 1963

Measurements on the cosmic ray muon intensity at very large depths underground, in the Kolar Gold Fields (Mysore State, India), up to a maximum depth of 8400 m.w.e. (metres of water equivalent), have recently been carried out by Miyake, Narasimham and Ramana Murthy^{1,2}). Scintillation counter telescopes designed specifically for detecting penetrating particles were used for these observations.

127 counts were recorded in 944 hours with an effective telescope area of 1.5 m² at a depth of 4280 m.w.e., and 18 counts in 1496 hours with 3 m² at 6380 m.w.e. At the greatest depth of 8400 m.w.e. (9200 feet below surface), *no count* was registered in an operating period of 1440 hours with an effective area of 3m², i.e., in an exposure of ~ 180 m²-days.

This observation, that *no count* was recorded in 180 m²-days at 8400 m.w.e., is of particular significance for the design of experiments for the detection of "natural" - cosmic ray - neutrinos; (in what follows, we use the word neutrinos to denote neutrinos + anti-neutrinos).

The penetrating component deep underground consists primarily of "atmospheric" muons which arise from the decay of pions and kaons produced by cos-

mic rays in the atmosphere. The intensity of "atmospheric" muons is expected to decrease continuously with increasing depth due to the combined effect of several causes: increasing energy losses of muons at high energies, decrease in the decay probability of pions owing to relativistic effects, and steepening of the primary cosmic ray spectrum. At *very large* depths underground one can expect that the intensity of "atmospheric" muons will drop off to such an extent that the intensity of muons produced by neutrino interactions in the matter surrounding the detector assembly will dominate. Once this happens, the muon intensity will remain constant with depth, since there is no change in the intensity of neutrinos with depth.

It is evident from the recent work^{1,2}) of the Tata Institute group at the Kolar Gold Fields that even at depths around 6400 m.w.e., the contribution from neutrino produced muons has not started to dominate; we cannot yet say what the position is at 8400 m.w.e.

An important point to be borne in mind is that the muons from the two sources have widely different angular distributions. The atmospheric

muons, at great depths underground, have a steep angular distribution and arrive essentially in the vertical direction, whilst the neutrino beam, (at energies in the GeV energy range), is almost isotropic, and so will be the muons which arise from the interactions of these neutrinos. At 8400 m.w.e., where no count was registered, the apparatus employed had an (effective area) \times (solid angle) factor of $1.8 \text{ m}^2\text{-sterad}$ for the almost vertically incident atmospheric muons and $11.6 \text{ m}^2\text{-sterad}$ for isotropically incident muons (such as those from neutrino interactions).

By extrapolating the intensities recorded at 4280 m.w.e. and 6380 m.w.e., we estimate that 1-2 counts should have been recorded in the apparatus due to atmospheric muons alone. The fact that no count was registered may have been the result of a fluctuation or may have been caused by a further rapid decrease in the atmospheric muon intensity; if the latter is the case, it is of great interest from the point of view of neutrino experiments at these depths; using all of the available information there is some indication that the expectation of 1-2 counts may be on the high side.

The neutrinos and anti-neutrinos that can give rise to muons deep underground arise principally from the decay of pions and muons in the atmosphere. The flux of neutrinos and anti-neutrinos which arises in this manner has been evaluated rather carefully by Zatsepin and Kuzmin³⁾. Using the flux values for muon neutrinos (ν_μ), given by Zatsepin and Kuzmin, and using the most favourable cross section for the interaction of neutrinos in the GeV energy region i.e. through the production of intermediate bosons⁴⁾ W^\pm in reactions of the type: $\nu_\mu + X \rightarrow W^+ + \mu^- + X'$ and their rapid decay $W^+ \rightarrow \nu_\mu + \mu^+$ resulting in $\nu_\mu + \mu^+ + \mu^- + X'$, with the mass of the intermediate boson assumed to be equal to that of the K-meson, we estimate that 1.5 counts should have been registered by the apparatus due to neutrino induced muons. In this and in what follows it is assumed that $\nu_\mu \neq \nu_e$ which appears to be established by Danby et al.⁵⁾

(It might be emphasized here that the apparatus was specifically designed to record atmospheric muons and therefore the layers of plastic scintillators comprising the telescope were mounted horizontally. If instead an 'isotropic' detector had been used, the expected counting rate due to atmospheric muons would have been the same but that due to neutrino induced muons would have been ~ 5 instead of ~ 1.5 .)

There cannot be much ambiguity in our knowledge concerning the flux of cosmic ray neutrinos (see for example the discussion by Zatsepin and Kuzmin). The observation that no count was registered at 8400 m.w.e. when ~ 1.5 was expected due to neutrino induced muons may have been the result

of a fluctuation. Or the cross section for neutrino interactions may not be as high as that which we have taken on the basis of the production of intermediate bosons with mass about that of the K-meson. For example, if the mass of the intermediate boson is about that of the proton then the expected number of counts would be only ~ 0.15 . Again, if intermediate boson production does not occur, we would expect ~ 0.6 counts on the basis that the neutrino interaction cross section increases linearly with neutrino energy, $E_{\nu\mu}$, and has a value $\sim 10^{-38} \text{ cm}^2$ at $E_{\nu\mu} \sim 1 \text{ GeV}$. The recent experiment of Danby et al.⁵⁾ strongly indicates that the neutrino interaction cross section $\sigma_{\nu\mu}$ is $\sim 10^{-38} \text{ cm}^2$ at $E_{\nu\mu} \sim 1 \text{ GeV}$. It is of course possible that the cross section does not increase further with the neutrino energy because of form factor induced cut-off effects; for a cut-off corresponding to lengths $\sim \hbar/m_{Nc} \sim 2 \times 10^{-14} \text{ cm}$, the expected number of counts would be ~ 0.15 . It would thus appear that ~ 0.15 counts is the minimum to be expected and we are therefore within a factor of ten in detecting neutrinos deep underground.

A follow-up experiment at 8400 m.w.e. (or deeper), with (area) \times (time of operation) enhanced by a factor of 50-100 compared to the experiment recently, completed should not only fix the atmospheric muon intensity at this depth but also throw light on the behaviour of the neutrino interaction cross section at high energies. It should certainly tell us whether intermediate bosons with mass about that of the K-meson are produced or not.

Since the atmospheric muons are incident essentially vertically it is clear that by demanding coincidences between parallel detector layers mounted in the vertical plane one can discriminate strongly against them. Such an array will continue to register equally well neutrino induced muons. In fact, such vertical arrays have an additional advantage arising from the fact that the flux of neutrinos and anti-neutrinos, particularly at high energies, increases to a certain extent at large zenith angles as shown by Zatsepin and Kuzmin.

In view of the above, it seems possible to carry out experiments involving natural neutrinos deep underground (at depths around 9000 ft below surface in the Kolar Gold Fields, South India) using parallel detector layers in coincidence mounted vertically and with exposures of the order of $10^4 \text{ m}^2\text{-days}$.

References

- 1) S. Miyake, V. S. Narasimham and P. V. Ramana Murthy: Proc. Phys. Soc. (Japan) 3 (1962) 318.
- 2) S. Miyake, V. S. Narasimham and P. V. Ramana Murthy, to be published

- 3) G.T. Zatsepin and V.A. Kuzmin: Soviet Physics JETP, 14 (1962) 1294.
- 4) T.D. Lee and C.N. Yang: Phys. Rev. Letters 4 (1960) 307.
- 5) G. Danby et al., Phys. Rev. Letters 9 (1962) 36.

* * * * *

A TOTAL ABSORPTION SPECTROMETER FOR MEASURING THE ENERGIES OF NUCLEAR INTERACTING PARTICLES OF THE COSMIC RADIATION IN THE ENERGY RANGE OF A FEW GeV TO A FEW HUNDRED GeV

P. V. RAMANA MURTHY, B. V. SREEKANTAN, A. SUBRAMANIAN and S. D. VERMA*

Tata Institute of Fundamental Research, Bombay

Received 3 January 1963

The instrument referred to as a "total absorption spectrometer" (area 1.4 m² and solid angle = 0.25 steradians) has been constructed for measuring the energies of nuclear interacting particles of the cosmic radiation in the energy range of a few

GeV to a few hundred GeV. The general features of the design, construction and the procedure used for calibration are discussed as also the factors which govern the accuracy ($\approx 20\%$) of energy measurement.

1. Introduction

A dependable and reasonably accurate measurement of the energies of cosmic ray particles becomes increasingly difficult as one proceeds to higher and higher energies. A good method at lower energies is that in which the curvatures of charged particles traversing magnetic fields are measured using detectors like cloud chambers¹), gas filled counters²), nuclear emulsions³) and spark counters⁴); this works successfully upto energies of the order of about 10¹² eV. However, this technique suffers from the serious limitation that the apertures of the instruments are inevitably small and since the flux of cosmic ray particles decreases enormously at high energies, it becomes impracticable to use such magnetic spectrographs for experiments which involve large collection of data. While in principle it should be possible to construct large aperture spectrographs, the cost of construction and operation becomes prohibitively expensive when they have to be designed for work at energies greater than 10¹¹ eV. Another disadvantage of the magnetic spectrograph is that it cannot be used for determining the energies of neutral particles.

In the case of nuclear interacting particles, several methods, all of which depend in some way or the

other on the characteristics of the collisions, and on the properties of the secondaries produced in the collisions, have been evolved. For instance, one of the most common method is to determine the energy of the primary interacting particle from the angular distribution of the secondaries produced in the collision; for this it is necessary to assume that there is symmetry in the angular distribution of the secondaries in the centre of mass system of the colliding particle with respect to a plane perpendicular to the direction of the incident particle; the accuracy of energy determination depends on the secondary multiplicity and on the correlations that may exist between the secondary particles. In another method, the energy going into neutral pions is determined by following the electro-magnetic cascades which they give rise to. To determine the primary energy, it is then necessary to make an assumption regarding the inelasticity – the fraction

¹) J. Pine, R. J. Davisson and K. Greisen, *Nuovo Cimento* **14** (1959) 1181.

J. E. R. Holmes, B. G. Owen and A. L. Rodgers, *Proc. Phys. Soc.* **78** (1961) 496.

²) G. Brooke, P. J. Hayman, F. E. Taylor and A. W. Wolfendale, *Proc. Intern. Conf. on Cosmic Rays and Earth Storm* **3** (1962) 311.

³) A. J. Apostolakis and I. Macpherson, *Proc. Phys. Soc.* **A70** (1957) 154.

⁴) A. I. Alikhanyan, V. N. Bolotov, V. H. Volynsky, M. I. Dayon, M. I. Devishev, L. F. Klimanova, G. A. Maikyan, K. M. Matevosyan and A. P. Shmeleva, *Abstracts Intern. Conf. on Cosmic Rays and Earth Storm J-III-6-2* (1961).

* Now on study leave at the University of Chicago, Chicago, U.S.A.

of energy transferred to pions in the collision; there are also other implied assumptions concerning charge independence i.e. the number of charged pions produced in a collision is equal to twice the number of neutral pions produced and also that the electromagnetic cascades observed are all due to neutral pions directly produced in the primary collision. Yet another method is to determine the energies of the secondaries by assuming a constant value for the transverse momentum and then to sum up the energies of charged secondaries to get the primary energy, after correcting for neutrals. Due to fluctuations in the characteristics of collisions, and also since the values of the parameters used are uncertain, all these methods lead most often to erroneous values for energy in individual cases. *In fact one of the central problems in high energy physics is the determination of these parameters themselves and their fluctuations.* Hence it is necessary to use a method for energy determination which is independent of the characteristics of the nuclear collision itself.

A few years ago a method was proposed by Grigorov *et al.*⁵⁾ which is applicable only to nuclear interacting particles, but which is independent of collision characteristics to a great extent, though not completely. In this method, the nuclear interacting particle is allowed to pass through an appreciable amount of condensed matter (~ 1000 g/cm²); the particle interacts several times in this medium losing energy to secondary particles which are mostly pions. The charged pions further interact and produce more pions and thus lead to the development of a nuclear cascade. The neutral pions produced in the various collisions decay instantaneously into γ -rays and lead to electromagnetic cascades. Energy is thus fed continuously into the electromagnetic cascade from the nuclear cascade. The nucleonic and electromagnetic cascade particles lose their energy all of the time by ionisation in the medium; the low energy charged particles—slow pions and protons and the heavy fragments are in fact brought to rest in the medium. Thus, if the absorber is of the order of several interaction mean free paths, practically all the energy of the primary particle is transformed into energy of ionisation in the medium, which then has

to be measured. This method has been appropriately termed "Calorimetric" by the authors and several versions of calorimeters have been constructed by them. In the most recent version they have used 800 g/cm² of iron in the absorber, and ionisation chambers have been placed in layers every successive 80 g/cm² of the absorber; the ionisation chambers sample the energy loss in the medium. This calorimeter is being used for determining the energy of nuclear interacting particles of energy greater than 10^{11} eV. During 1959–1960, we constructed a total absorption spectrometer⁶⁾ which operates on the same principle as the calorimeter of Grigorov *et al.* This total absorption spectrometer (TAS) which has an effective area of 1.4 sq meter and a solid angle of acceptance of 0.25 steradians is being used a mountain altitude, in conjunction with a multiplate cloud chamber and an air Čerenkov counter⁷⁾ for the study of the characteristics of nuclear interactions at high energies⁸⁾. It is also being operated with an extensive air shower (EAS) array for the study of the nuclear interacting component in EAS.

In this paper we present details of the design, construction and calibration of this instrument. We have discussed at the end the factors which govern the accuracy of determination of energy—(which is $\pm 20\%$) with this device.

2. Design Features

The total absorption spectrometer consists of two parts:

- a. the *absorber*—in which the energy of the primary nuclear interacting particle is transformed mostly into energy of ionisation;
- b. the *probes*—the radiation detectors which sample at various depths in the absorber the track

⁵⁾ N. L. Grigorov, V. Murzin and I. Rapoport, Soviet Physics JETP 7 (1958) 348.

N. L. Grigorov, N. A. Kondratiev, A. I. Savelieva, V. A. Sobinyakov, A. V. Podgurskaya and V. Ya. Shestoporov, Proc. Moscow Cosmic Ray Conf. 1 (1959) 130.

⁶⁾ P. V. Ramana Murthy, B. V. Sreekantan and A. Subramanian, Proc. Cosmic Ray Symposium, Ahmedabad (1960) p. 49.

⁷⁾ A. Subramanian and S. D. Verma, Proc. Cosmic Ray Symposium, Ahmedabad (1960) p. 43.

⁸⁾ Siddheshwar Lal, R. Raghavan, B. V. Sreekantan, A. Subramanian and S. D. Verma, Proc. Intern. Conf. on Cosmic Rays and Earth Storm 3 (1962) 390.

lengths of the cascades initiated by the nuclear interacting particle.

Let us first consider the factors which govern the choice of material for the absorber. Obviously, the material should be one in which the maximum number of collisions takes place in the minimum thickness of absorber; also the fraction of energy α transferred to pions should be a maximum in each collision. In the appendix a calculation has been made to show the effect of the inelasticity parameter α on the rapidity of absorption of energy of a nucleon. Fig. 1 is a graphical illustration of this

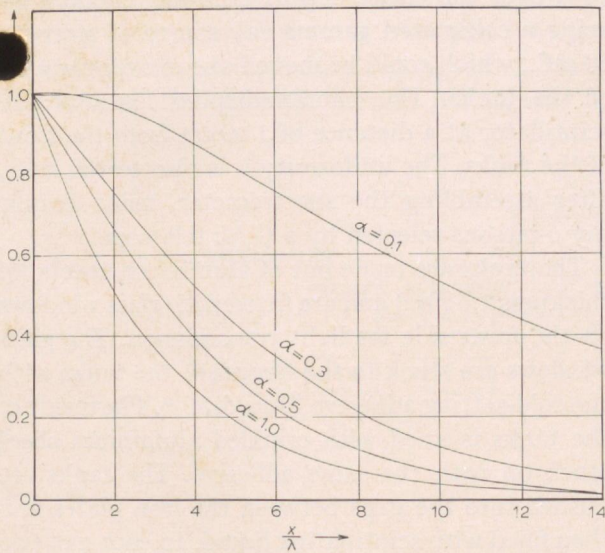


Fig. 1. Curves showing the dependence of the fraction of energy of an incident nucleon retained in N -particles in a cascade developing in a condensed medium as calculated in the appendix

calculation. If the value of α is about 0.5, then a thickness of absorber equal to six interaction mean free paths is necessary for absorption, on the average, of about 80% of the energy of the incident nucleon*. Since the value of α is likely to be $\geq 0.5^9$ in materials of high atomic weight like iron or lead, it is obviously preferable to fabricate the spectrometer from such materials. To keep the height of the spectrometer rather small, which is necessary if the aperture has to be large, the material chosen should have a short interaction mean free path. For

* If the incident particle happens to be a pion, the value of α may be taken as 1, in which case 88% of the incident energy is absorbed in TAS as shown in the appendix.

lead the interaction mean free path is about 15 cm and for iron it is about 12 cm and, therefore, iron is a better choice for the absorber than lead. It will be seen from the next two paragraphs that iron is a better choice from the other points of view also.

The main process by which energy is absorbed is through the development of electromagnetic cascades initiated by γ -rays which result mostly from the decay of neutral pions. It is, therefore, necessary to sample the soft cascades as well as possible — which means that the sampling must be done every few radiation lengths. By using the cascades curves under approximation B¹⁰) for energies greater than one GeV, and doing an arbitrary sampling every two radiation lengths, one finds that the energy of the cascades can be determined to an accuracy better than 10%. In our spectrometer, in a total thickness of 750 g/cm² (iron), we have 25 layers of scintillators to sample the energy loss, each after about 30 g/cm² of absorber; we thus sample the ionisation loss every two radiation lengths. If we had used lead instead of iron, then we would have had to use ~ 1200 g/cm² to have the same number of interaction mean free paths (i.e. 7.5) and if we had to sample every two radiation lengths, then we would have had 92 sampling layers.

As regards the probe, the basic requirement is that it should not affect the course of the electron-photon shower development in the material used as the absorber. This is achieved if the stopping power of the probe is small compared to the critical energy of electrons in the absorber; also the thickness of the probe should be a small fraction of a radiation length. Ionisation chambers are ideal as probes: and these have been so used by Grigorov *et al.*⁵⁾. However, for a large number of striations and with a spectrometer of large area, the number of ion chambers required is large, and there is corresponding complexity in the associated electronic circuitry. Instead we have used liquid scintillation counters of small thickness (< 2.2 g/cm²) as

⁹⁾ C. P. Babayan, N. L. Grigorov, M. M. Dubrovin, L. G. Mischenko, V. S. Murzin, L. I. Sarychevya, V. A. Sobiniakov and I. D. Rapoport, Proc. Moscow Cosmic Ray Conf. **1** (1959) 174.

¹⁰⁾ B. Rossi, High Energy Particles (Prentice-Hall, 1952) p. 258.

probes. Since the critical energy in iron is 21 MeV, the disturbance produced by the scintillators is very small. In this respect also, iron is preferable to lead as absorber since the critical energy in lead is only 7.6 MeV.

3. Details of Construction

Fig. 2 shows a cross sectional view of the spectrometer. The spectrometer consists of 25 layers of iron each of area $120 \times 120 \text{ cm}^2$ and thickness 3.75 cm (30 g/cm^2). The iron plates are stacked one

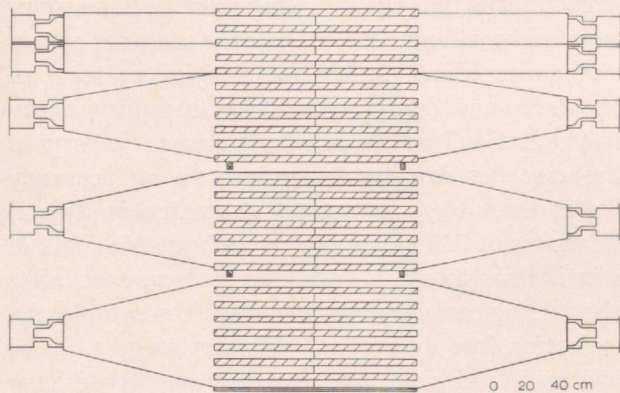


Fig. 2. A cross sectional view of the total absorption spectrometer and the arrangement of photomultipliers.

above the other on spacers, also of iron, in such a way that there is a gap of 4 cm between adjacent layers. The total height of the spectrometer is about 2.5 metres. In the gaps between the iron plates there are liquid scintillation tanks of horizontal dimensions $114 \times 64 \text{ cm}^2$. The height of the tanks varies in a step-wise manner from 1.9 cm at the front to 3.2 cm at the rear (fig. 3). This step-wise design makes it possible to obtain uniform light

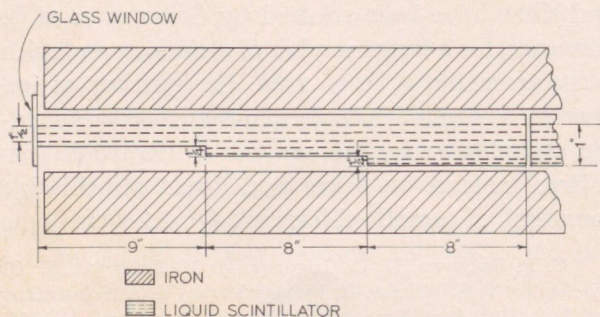


Fig. 3. An enlarged view of the section of two adjacent layers of the spectrometer showing the details of design of the liquid scintillation tank.

response at the photomultipliers from all parts of the scintillator. Light from the rear of the tank suffers attenuation due to absorption in the liquid and at the walls of the tank and to compensate for this a corresponding increased thickness of liquid is provided at the rear in which more light is produced per particle. Trial experiments showed that a simple tilt of the tanks to get a varying liquid level does not give the required uniformity when the height of the tanks has to be as small as 3 cm. The step-wise design was adopted after trials and has a uniformity of light response better than 10% over the entire depth. This was checked by using a collimated gamma ray source of strength 50 mC., which could be moved about over the area of the tanks. The photomultiplier looks at the scintillator at a distance of 1 metre from the front of the tanks. The uniformity was also tested later, after assembling the spectrometer, using cosmic ray μ -mesons selected by a G.M. telescope.

The tanks are made out of aluminium sheets (of thickness 1.6 mm) and are fitted with glass windows on the front side for light transmission. The glass windows are stuck to the flanges of the tanks with the cold-setting adhesive "Araldite"*. The inside of the tanks is lined with crinkled aluminium sheet stuck on with the same adhesive. The tanks are pushed into the gaps between the iron plates and then filled with scintillating liquid. In each gap two tanks are fitted in from opposite sides such that the rear edges of the tanks are in contact in the middle of the spectrometer. Thus there are 50 scintillation tanks in all between the 25 layers of iron plates. Each tank is filled with toluene in which is dissolved 3.5 g/litre of para-terphenyl and 5 mg/litre of POPOP.

The photomultipliers (Dumont 6364-5" diameter) that view the tanks from opposite ends are arranged as shown in the fig. 2. There are 5 photomultipliers on each side. Reckoning from the top, the first two tanks are viewed by one photomultiplier, the next two by the second photomultiplier, the next six by the third, the following seven tanks

* Araldite is not wholly resistant to toluene; the adhesive, after it has set, buckles under constant contact with toluene or its vapour making the tank leaky after a few months. The rate of replacement was about one tank per week.

by the fourth and the last eight tanks by the fifth photomultiplier. This arrangement serves to distinguish between the incidence of nuclear interacting particles and electron-photon cascades on the spectrometer. The first two sections can be used, for example, to measure the energy flow in the soft component of air showers.

4. Operational Details

The spectrometer is designed to measure energies over a range of 10^4 . The photomultipliers are operated at a relatively low voltage (~ 900 volts) for this purpose, and the associated electronic circuitry—the amplifiers and the pulse height display system correspondingly designed. A block diagram of the display system is shown in fig. 4.

The calibration was carried out using a G.M. telescope consisting of three trays of counters, one on top of the spectrometer, another half way through it and the third below the spectrometer. The triple coincidence pulses triggered the sweeps of the oscilloscopes on which the pulse heights are recorded (fig. 4). About 150 pulses were analysed each time to get the mean pulse height. The calibration was repeated once in a fortnight. The gains of all amplifiers were checked daily and constancy of gain was ensured to within 10%. A collision loss, (for relativistic μ -mesons), of 48 MeV per layer of iron and scintillator was used for relating the pulse heights to energy loss. In using this calibration, obtained from penetrating particles, for determining the energy of cascades and nuclear interacting particles, we have to make the assumption that

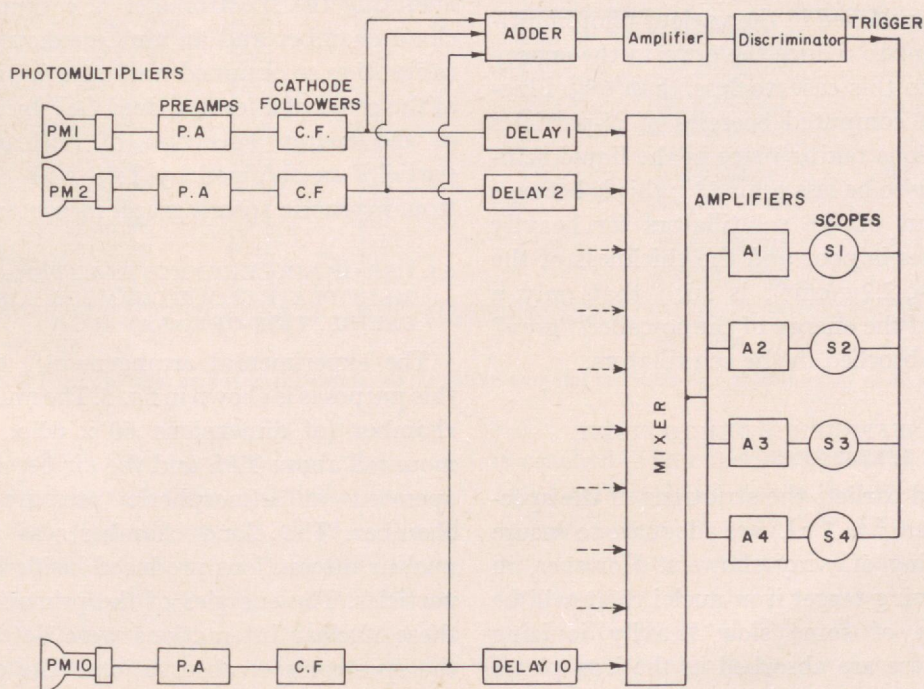


Fig. 4. A block diagram of the circuitry associated with the spectrometer.

The relationship between the pulse heights recorded on the oscilloscopes and the energy losses in the corresponding sections of the spectrometer is established by recording pulse heights corresponding to the passage through the spectrometer of single μ -mesons which lose energy only by ionisa-

tion. There is a constant ratio between the ionisation loss in the liquid scintillator and the iron plate immediately above it. This assumption leads to some errors in the determination of the energy of nuclear interacting particles and is discussed in the next section.

5. Errors in the Measurement of Energy

The energy of nuclear interacting particles determined from the total absorption spectrometer, is subject to the following errors:

1. errors in calibration and measurement of pulse heights;
2. sampling inefficiency due to finite number of striations;
3. leakage of energy from the spectrometer due to the finite thickness of the spectrometer.

5.1. ERRORS IN CALIBRATION AND MEASUREMENT OF PULSE HEIGHTS

The errors due to (1) are estimated to be about 10%. The number of photo-electrons released in the cathodes of the photomultipliers for an energy loss of 1 GeV in the spectrometer is about 25. For energy losses greater than 10 GeV, the number of photo-electrons released in the various photomultipliers is sufficient to reduce the error in the energy estimates due to this case to less than 6%. Fluctuations in the computed energies of N-particles due to interactions taking place in the liquid scintillators is likely to be less than 5%; this is because the light output of the scintillators for heavily ionizing particles is poor and the thickness of the scintillators, ($< 2.2 \text{ g/cm}^2$), is such that only a small fraction of the energy of the so-called "grey" secondaries is absorbed in the scintillators.

5.2. SAMPLING INEFFICIENCY DUE TO FINITE NUMBER OF STRIATIONS

As mentioned earlier, the striations of the spectrometer ($30 \text{ g/cm}^2 \approx 2 \text{ r.l.}$) are adequate to ensure efficient sampling of γ -ray showers. However, in collisions involving target iron nuclei there will be the production of some slow heavily ionizing secondaries; these are absorbed in the iron plates before they can enter the scintillators and this type of energy loss remains unsampled. While it is possible to make a fairly good estimate of the amount of energy that goes unsampled per collision by this mode, using the data available from interactions in nuclear emulsions, the *number* of such collisions in the entire absorber is hard to estimate. The number of collisions critically depends on the details of the development of the nuclear cascade.

5.3. LEAKAGE OF ENERGY FROM THE SPECTROMETER DUE TO THE FINITE THICKNESS OF THE SPECTROMETER

As already mentioned the amount of leakage of energy from the spectrometer because of its finite thickness depends on the value of the inelasticity parameter α and the interaction mean free path of nuclear interacting particles in iron. It is shown in section 6.3 that this leakage is negligible at low energies and reaches a value of about 15% at energies greater than 10^{12} eV .

6. Calibration of the Spectrometer

The errors due to sampling inefficiency and leakage of energy from the spectrometer discussed above are more of a systematic nature and difficult to estimate. However, it was possible to calibrate the spectrometer directly at about 40 GeV by operating the spectrometer in conjunction with a cloud chamber and an air Čerenkov counter. The calibration so obtained was extended upto energies of the order of a few hundred GeV by a comparison of the energy spectrum of nuclear interacting particles as obtained by TAS with that obtained from magnetic spectrograph measurements.

6.1. USE OF AIR ČERENKOV COUNTER AND MULTIPLATE CLOUD CHAMBER FOR THE CALIBRATION OF TAS AT 43 GeV

The experimental arrangement⁸⁾ employed for this purposes is shown in fig. 5. The multiplate cloud chamber (of dimensions $60 \times 60 \times 20 \text{ cm}^3$) was mounted above TAS and the air Čerenkov counter operated at atmospheric pressure above the chamber. The cloud chamber was triggered for nuclear interactions produced inside it by charged particles. The energies of the primaries producing these nuclear interactions were determined from the spectrometer observations. The observed efficiency of the air Čerenkov counter for charged nuclear interacting particles was plotted as a function of the energy recorded in TAS.

The charged N-particles at mountain altitude consist of both protons and pions. Protons give Čerenkov radiation in air at atmospheric pressure only when their energy exceeds the threshold energy of 43 GeV (at 2.2 km), whereas pions give rise to Čerenkov radiation when their energy exceeds

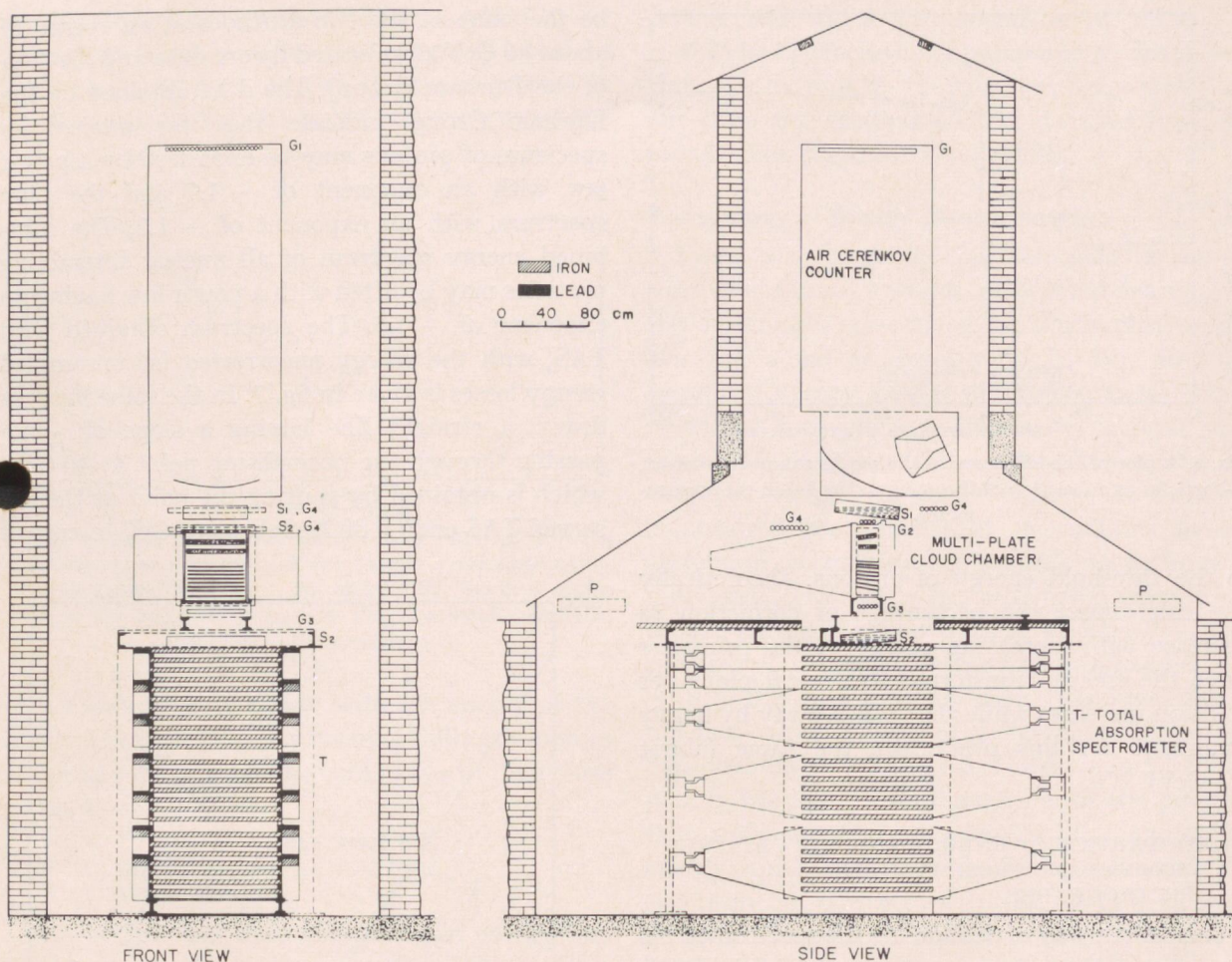


Fig. 5. Experimental arrangement employed for calibrating the spectrometer at an energy of 43 GeV.

GeV. Because of this, the efficiency of the air Čerenkov counter should show a definite increase around an *actual* primary energy of 43 GeV and attain a value which will remain constant thereafter with increasing energy. Fig. 6 gives the experimentally determined efficiency vs. energy plot, with the energy *uncorrected* for unsampled losses. Though the experimental points do not show a clear cut break in the efficiency curve, it can be seen that for energies lower than 20 GeV, *as recorded by the spectrometer*, the efficiency is around 33% and for energies much greater than 40 GeV the efficiency reaches a saturation value of $\sim 85\%$. The physical situation i.e., the threshold effect of protons discussed above, demands that there must be a break before the saturation value for efficiency

is reached. The experimental data of fig. 6 can be fitted with such a break in the efficiency at about a *recorded energy* of ~ 22 GeV. This means that the correction due to unsampled energy losses in the spectrometer is $43 - 22 = 21$ GeV, when the incident energy is 43 GeV. The solid line that is drawn in the same figure is *not* the best fit curve for the experimental points, but the curve that is expected on the assumption that the relative percentage of pions and protons is the same above and below the threshold value. From this data the abundance of pions is estimated to be $36 \pm 7\%$ of the charged N-particles unaccompanied by air showers at 2.2 km. The Čerenkov efficiency method gives the correction for the unsampled energy losses at a particular energy only i.e., that corresponding

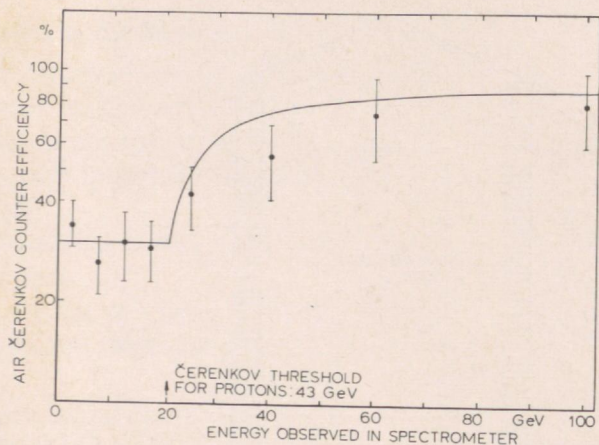


Fig. 6. A plot of the efficiency of the air Čerenkov counter for N-particles as a function of the energy sampled in the spectrometer.

to the threshold energy of protons. Theoretically one can expect the percentage of correction to decrease with increasing energy of the primaries since the energy transferred to neutral pions per collision increases while that taken away by heavy fragments remains practically the same (about 0.5 GeV).

6.2. COMPARISON OF ENERGY SPECTRA OBTAINED FROM TAS AND FROM MAGNETIC SPECTROGRAPHS

A clear cut way of calibrating the spectrometer is to compare the energy spectrum obtained with it with that obtained from a magnetic spectrograph at the same altitude of observation. TAS was operated at a mountain altitude of 2.2 km and there are no results available on the spectra of nuclear interacting particles with magnetic spectrographs at mountain altitudes. Recently the Durham Group¹¹⁾ have obtained the momentum spectrum of nuclear interacting particles upto 200 GeV at sea level. We have compared this sea level spectrum with that obtained with TAS* at 2.2 km assuming that the spectrum does not change from 2.2 km to sea level. From this we have obtained the variation of the correction factor as a function of the energy of the incident particle in the range 10 to 100 GeV. [In this connection it may be of interest to note that the proportion of pions to protons (≈ 0.6) seems to

* TAS is shielded on all sides by 5 cm iron and 2.5 cm of lead to remove the contamination by soft component.

be the same at the two altitudes at an energy of about 40 GeV as indicated by our data and the data of the Durham Group]. The data obtained by the Durham Group, indicate that the momentum spectrum of protons may be expressed by a power law with an exponent of -1.7 and the pion spectrum with an exponent of -1.2 . The combined energy spectrum of all nuclear interacting particles may be fitted with a power law having an exponent of -1.5 . The spectrum obtained with TAS, with the energy uncorrected for unsampled energy losses is given in fig. 7. In the same figure is drawn a straight line having a slope of -1.5 passing through the normalising point at 40 GeV which is obtained by shifting the point at the observed TAS energy of 20 GeV to 40 GeV to correct

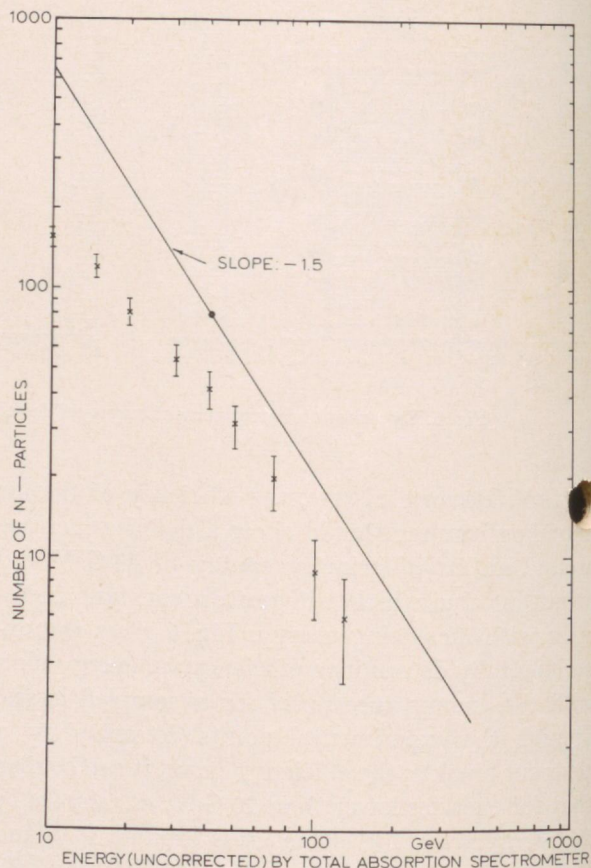


Fig. 7. Comparison of the integral energy spectrum of N-particles measured by the spectrometer and by a magnetic spectrograph.

¹¹⁾ A. W. Wolfendale, private communication (1962).

for unsampled energy losses. The variation of the correction factor as a function of energy obtained by a comparison of the two spectra is plotted in fig. 8. It is seen that the systematic corrections due

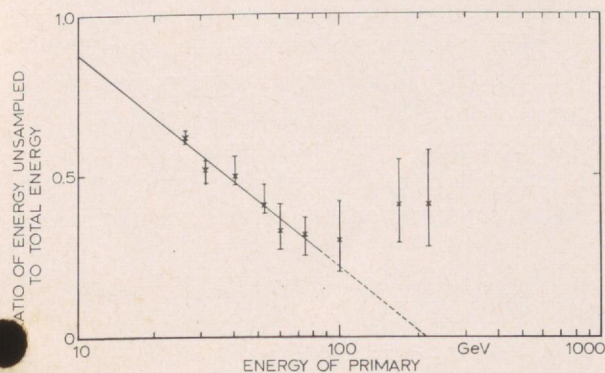


Fig. 8. Variation in the fraction of energy unsampled in the spectrometer as a function of the energy of the incident N-particles deduced from fig. 7. The straight line has been drawn to show the trend of decrease in the fractional unsampled energy loss in the spectrometer.

to 5.2 and 5.3 vary slowly with the energy of the incident particle. Fig. 9 is the final calibration curve obtained after fitting a smooth curve to the points in fig. 8.

6.3. LEAKAGE OF ENERGY FROM THE SPECTROMETER

At energies less than 100 GeV, the energy loss distribution in the various sections of the spectrometer shows that practically all of the energy is absorbed in the spectrometer itself. For higher energies, leakage of energy from the spectrometer becomes important as indicated by fig. 8 itself. At energies much greater than 100 GeV, one should expect that the leakage would practically be the only source of unsampled energy loss and this would be a constant fraction of the incident energy, depending only on the value of the inelasticity parameter α . To determine the fractional energy loss by leakage more exactly than can be done by using fig. 7, (in which the statistical errors are large at the high energy points), we determine the mean fractional energy loss in the last section of the spectrometer for cases of N-particles of energy ≥ 1000 GeV unaccompanied by large air showers, incident on the spectrometer. This mean fractional energy loss in the last section is found to be

0.17 ± 0.05 which corresponds to a value 0.75 ± 0.25 for the inelasticity parameter α ; this in turn gives a value of $0.15 \pm_{0.03}^{0.05}$ for the energy that leaks out from the spectrometer as deduced from the calculations found in the appendix.

7. Accuracy of Energy Measurements

From the foregoing considerations it can be concluded that at energies less than about 50 GeV, the systematic corrections for unsampled energy loss are equal in magnitude to the observed (sampled) energy loss in the spectrometer. These fractional corrections progressively decrease with increasing energy of the incident N-particles, as expected on general considerations. It must be emphasised that statistical fluctuations in the systematic corrections are unlikely to be large in individual cases since the unsampled energy loss occurs through many nuclear collisions in the spectrometer. After allowing for a random error of $\pm 10\%$ due to 5.1, an additional random error of not more than $\pm 10\%$ of the estimated energy is expected due to 5.2 and 5.3. The error in 5.3 comes mainly because of the fluctuation in the point of first collision. At high energies, the unsampled energy which is mainly the leakage through the spectrometer, is expected to tail off to a value of $\approx 15\%$. Thus a statistical error of $\pm 15\%$ can be attributed to the energy measurements of N-particles with the spectrometer in individual cases.

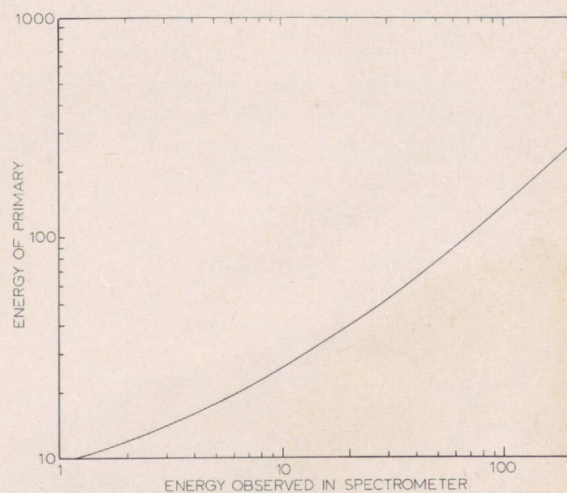


Fig. 9. The calibration curve for the spectrometer in the energy region 10 to about 100 GeV, deduced from a smooth curve fitted to the points plotted in fig. 8.

The uncertainties in the evaluation of the systematic corrections themselves will contribute a further error of $\pm 5\%$ on the estimated incident energy. Therefore, it can be concluded that the accuracy of energy determination of N-particles of energy greater than ≈ 30 GeV, with this instrument is about $\pm 20\%$, and this is practically independent of energy.

Acknowledgements

It gives us great pleasure to thank Prof. M. G. K. Menon for his interest in this project and for helpful discussions at various stages.

We are indebted to Dr. A. W. Wolfendale of the University of Durham for making available to us the results on the spectra of protons and pions at sea level, prior to publication.

We wish to express our thanks to Messrs. Siddheshwar Lal and R. Raghavan who were actively associated in the work connected with the calibration of the spectrometer using the cloud chamber. Our thanks are due to Messrs. A. R. Apte and M. A. Kalgaonkar and the late K. F. Dinshaw for their valuable help in setting up the spectrometer and in its operation over extended periods.

Appendix

A simple calculation is made here on the absorption of energy through the production of neutral pions in the case of a nucleon incident on a large homogeneous absorber. It is assumed that a nucleon on colliding with a nucleus of the medium transfers a fraction α of its energy to pions, one

third of which will be neutral. It is further assumed that a charged pion on colliding with a nucleus of the absorber transfers all its energy to secondary pions, a third of which will be neutral. Energy losses of charged N-particles by ionisation and energy dissipated in nuclear disintegration through the production of slow heavy fragments etc. are ignored. If E_0 is the energy of the incident nucleon, $E_N(x)$ the energy of the nucleon at depth x , $E_\pi(x)$, the energy flux of charged pions at depth x , the diffusion equation for the energies can be written as

$$dE_N(x)/dx = -E_N(x) \alpha/\lambda \quad - \quad (1)$$

and

$$dE_\pi(x)/dx = \frac{2}{3} E_N(x) \alpha/\lambda - E_\pi(x) /3\lambda$$

the solutions of which are

$$E_N(x) = E_0 \exp(-\alpha x/\lambda) \quad - \quad (3)$$

and

$$E_\pi(x) = \frac{2\alpha E_0}{1-3\alpha} \left\{ \exp\left(-\frac{\alpha x}{\lambda}\right) - \exp\left(-\frac{x}{3\lambda}\right) \right\} \quad (4)$$

from which the fraction of the primary energy E_0 retained by the nucleon and charged pions is given by

$$\frac{E_N(x) + E_\pi(x)}{E_0} = \exp\left(-\frac{\alpha x}{\lambda}\right) + \frac{2\alpha}{1-3\alpha} \times \left\{ \exp\left(-\frac{\alpha x}{\lambda}\right) - \exp\left(-\frac{x}{3\lambda}\right) \right\}. \quad (5)$$

In fig. 1, the above fraction is plotted for various values of α as a function of x .