OBSERVATIONS ON THE NUCLEAR INTERACTION OF COSMIC RAY PIONS AND NUCLEONS OF ENERGIES $\gtrsim$ 20 GeV

Part I. Experimental Details and Results Relating to Fluctuations in the Angular Distribution of the Secondary Particles Produced in Interactions in Carbon

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Received July 24, 1970

Abstract

In this paper, which is the first of a series entitled 'Observations on the Nuclear Interactions of Cosmic Ray Pions and Nucleons of Energy $\gtrsim$ 20 GeV', a description is given of the experimental arrangement, the types of data collected and the methods employed to analyse and classify the data. Results on the fluctuations in the angular distribution of the secondary particles produced in interactions in carbon are also presented and it is shown that these fluctuations are considerably larger in certain cases than what can be accounted for purely from statistical fluctuations in the isotropic and uncorrelated emission of secondaries in the c.m. system of the collision with a target nucleon and in others difficult to be understood on this basis if additional features of these interactions are also considered. It is suggested that 'correlated emission' of secondaries possibly due to final state interactions or multiparticle resonances with different 'Q-values' and other properties are perhaps the cause of the observed fluctuations; this is in contrast to the explanation in terms of simple motion of 'fire balls' in the c.m. system as has been generally discussed.

1. Introduction

A series of experiments have been carried out over the past few years at Ootacamund (altitude 2·2 km, atmospheric depth 800 gm/cm^2), India, to study in some detail the characteristics of nuclear interactions produced by cosmic ray pions and nucleons of energy > 20 GeV, in targets of carbon and brass. For these investigations an experimental arrangement comprising of a multiplate cloud chamber, a total absorption scintillation spectrometer and a large aperture air Cerenkov counter was employed. A brief description of this apparatus and some of the preliminary results obtained have been reported earlier at Conferences.[1–3] It is intended to publish in this journal the details of this extended investigation in a series of papers entitled 'Observations on the Nuclear Interactions of Cosmic Ray Pions and Nucleons of Energy $\gtrsim 20$ GeV'. In this paper, which is the first of this series, a complete description of the experimental arrangement, the method of analysis and classification of data are presented; some results on the angular distribution of the secondaries produced in interactions in carbon are also reported and discussed.

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement, the front and side views of which are shown in Fig. 1 *a*, consisted of a multiplate cloud chamber, with a total absorption scintillation spectrometer (TASS) below and an air Cerenkov counter above; a tray of Geiger counters, G_2 (38 cm × 18 cm), and a liquid scintillation counter S_1 (60 cm × 60 cm) were placed above and correspondingly G_3 (60 cm × 20 cm) and S_2 (45 cm × 100 cm) below the cloud chamber. A set of two trays of Geiger counters, G_4 (120 cm × 60 cm), were kept on either sides of the set-up to remove incident particles which come accompanied with air showers. In Fig. 1 *b* are given details concerning the cloud chamber, which had an useful volume of 60 cm × 60 cm × 19 cm. The multiplate assembly consisted of 5 brass plates, each 0·63 cm thick, one brass plate of thickness 1·9 cm and two lead plates each 1·27 cm thick offering 7·8 radiation lengths in all for a vertically incident γ-ray. For the first part of the experiment the chamber contained inside at the top a *producer* layer of two graphite blocks, each 4 cm thick and of density 1·6 gm/cm^2. For the later part of the experiment, these graphite producers were replaced by three brass plates each of 0·63 cm thick. A gap of ~ 12 cm was left between the producer layer and the plate assembly to ensure good resolution between the individual charged secondaries emerging from the *producer* and the γ-rays which start to materialise in the plate assembly; details concerning this aspect are contained in an earlier publication.[4]

The TASS, which is an energy-measuring device working on the principle of a calorimeter, and the air Cerenkov counter which has been used as a velocity selector have been described elsewhere[5, 6] in detail. With the help of TASS the energy of the primary particle producing a nuclear interaction in the *producer* layer could be determined to an accuracy of $\pm 20\%$. The air Cerenkov counter could distinguish between pions and protons with an efficiency of about 85% if the incident charged particle had an energy 10 GeV $\leqslant E \leqslant 45$ GeV; the two limits correspond approximately to the threshold

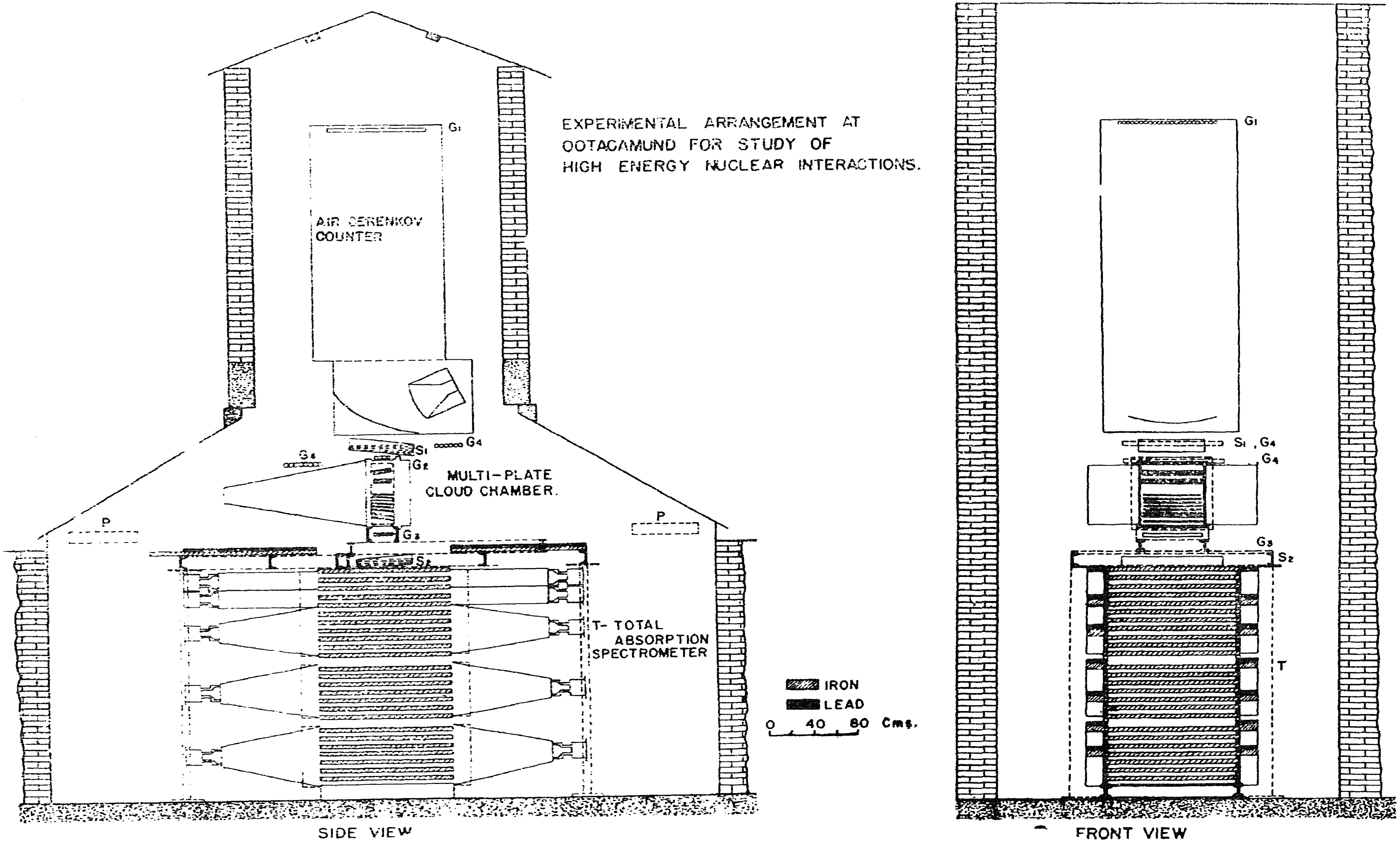


FIG. 1 *a*. Experimental **arrangement**: front and side views.

energy for pions and protons to emit Cerenkov radiation in air at an altitude of 800 gm/cm^2. Only a small fraction of the incident particles within the geometry of the apparatus except the Cerenkov counter passed through the air Cerenkov counter. Therefore the number of identified primaries, *viz.*, pions or protons, was relatively small.

3. SELECTION CRITERIA AND CATEGORIES OF INTERACTIONS

In the first series of experiments the objective was to record, in the cloud chamber, nuclear interactions produced by charged particles of energy greater than ~ 20 GeV. For this purpose, after some trials, the following selection criterion among the counters for triggering the cloud chamber was used:

$$G_2 + G_3 + S_2 (\geqslant 2) + \text{TASS}_{\text{min}} - G_4 - S_1 (\geqslant 2)$$

The number within brackets indicates the number of singly charged minmum ionising particles. By using $S_2 (\geqslant 2)$ in anticoincidence, the triggering was confined to cases where none or just one singly *charged* particle entered the chamber; and by demanding $S_2 (\geqslant 2)$ in coincidence, it was ensured that there was a nuclear interaction inside the cloud chamber. In the beginning a minimum of visible energy release of ~ 10 GeV was demanded from TASS. Later this was reduced to ~ 1 GeV to increase the efficiency of recording nuclear interactions, in the energy range ~ 20 GeV. When appropriate corrections are made[5] for the invisible part of the energy loss in the spectrometer a release of 1 GeV in TASS corresponds to a total energy of ~ 10 GeV for the incident interacting particle whereas an energy release of 10 GeV in TASS corresponds to an energy of ~ 30 GeV for the interacting particle.

In the second series when the chamber was triggered for both *charged* and *neutral* interacting particles, the Geiger tray G_2 was placed inside the cloud chamber just below the producing layer. For identification of particles by the air Cerenkov counter, only those cases were considered where there were signals from both the Cerenkov detector and the Geiger tray G_1 placed at the top of the air Cerenkov counter. It was also necessary that the criterion $S_1 (< 2)$ was satisfied. Indication of an association of this type was provided by a neon lamp placed near the panel of the four oscilloscopes that were used for recording the pulse amplitudes from the different sections of the TASS.

Four series of runs were taken with this multiplate detector array. The period of operation and the criteria adopted for triggering the chamber for

TABLE I

Details regarding the different series

Series	Period of operation	Target	Selection criteria	Hours of operation	No. of pictures collected	No. of nuclear interactions produced in the target	No. of useful showers
A	15—2-61 to 17—9-61	Graphite	Charged primary and 10 GeV in TASS *	1475	4593	138	49
B	18—9-61 to 21—1-62	do.	Charged primary with 1 GeV in TASS	1436	6632	331	215
C	22—2-62 to 13—7-62	do.	Charged and neutral primaries with $\sim$1 GeV in TASS†	1620	8005	527	311
D	22-11-62 to 16—8-63	Brass‡	Same as C	3034	12222	761	497

* For 200 hours, the selection system demanded a coincidence pulse from G_1 also.

† The minimum energy loss demanded in TASS was slightly greater than that in B.

‡ Interactions produced in brass have not been discussed in this paper.

each series, as also other details, are given in Table I. In the last column of the table is given the number of "useful" showers after rejecting various categories of events as listed below.

The following categories of interactions were rejected:

(i) When the interaction happened to be at the edge of the illuminated volume of the chamber;

(ii) where there was clear evidence for an interaction by one of the secondaries in the producer block itself;

(iii) when more than one particle was incident on the chamber, and passed right through it; in such cases the enrgey indicated by TASS could not be attributed to any one particular particle;

(iv) if the distribution in the energy released in different sections of TASS was indicative of the incidence of inclined particles which escaped the counter trays in anticoincidence as well as the chamber but passed through TASS, Excluding these types of interactions, all others were considered for detailed analysis.

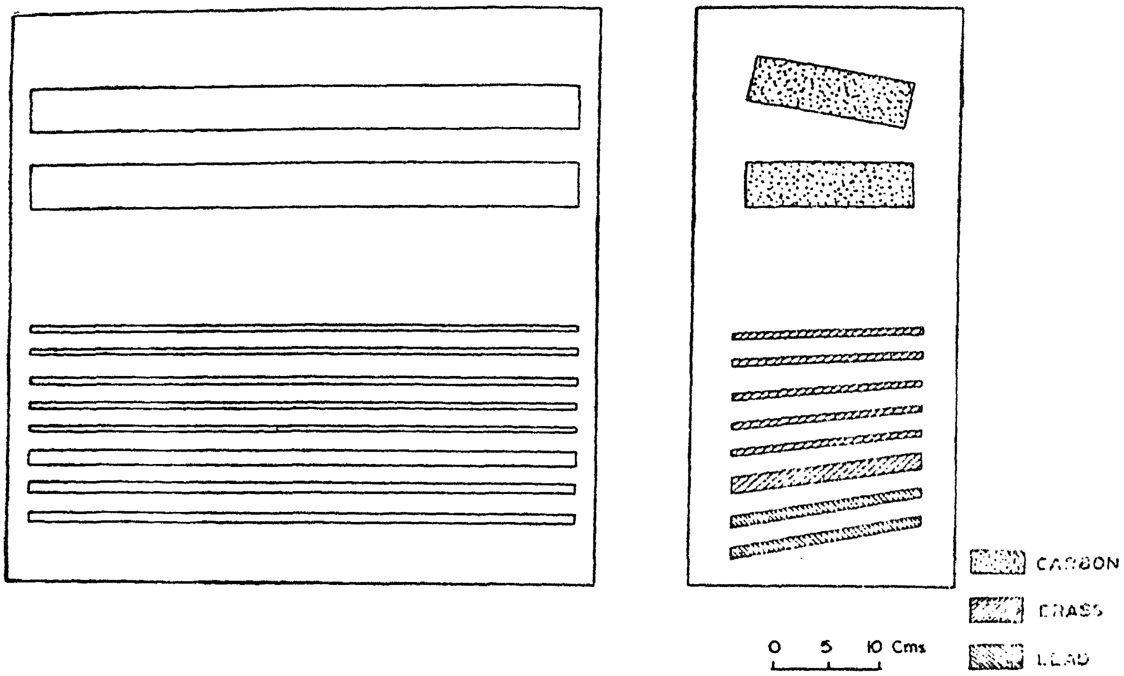


FIG. 1 *b*. A sketch of the cloud chamber seen in two views.

4. ANGULAR DISTRIBUTION OF THE SECONDARIES

(*a*) *Reconstruction of the event.*—The angular distribution of the secondary particle was obtained from a spatial reconstruction of the events by an analog method[7] using the co-ordinates of individual tracks measured in any two of the three views of the event; using this method the spatial direction of a track could be determined to within an accuracy of $\pm \frac{1}{2}°$. However, the main source of error in the angular distribution of the secondaries was due to the uncertainty in the direction of the primary particle as a result of distortion which was quite considerable in the top compartments. This error has been found to be $\sim 2 \cdot 5°$. An accuracy of $\sim 2 \cdot 5°$ is tolerable for interactions of energy < 50 GeV where the half-angle of the shower is $\gtrsim 10°$ but is rather large for interactions of energy $\gtrsim 100$ GeV or for extremely collimated events of lower energies. In such cases, and also in the cases of interactions produced by neutral particles, the direction of the primary particle was obtained by determining the centre of gravity of the shower particles. For determining the centre of gravity, very wide angle tracks were not included whereas high energy γ-rays were taken into account.

(*b*) *The E_c/E_0 plot.*—For each event the true energy (E_0) of the primary particle was obtained from TASS. The energy of the primary particle denoted by E_c was calculated from the angular distribution of the charged secondaries using the method of Castagnoli *et al.*[8] In the present analysis the energy estimated by this method has been used as a parameter which is related to the angular distribution of the secondaries. In using the Castagnoli *et al*'s method a track corresponding to the so-called "forward proton" (which is the follow through of the incident particle), was excluded from the observed secondaries if its angle of emission in the laboratory system happened to be $< 1/0{\cdot}7\,E_0$ (assuming transverse momentum of the nucleons ~ 1 Gev/c and inelasticity ~ 0·3). In this analysis only those events have been included which have charged multiplicity $n_s \geq 3$. The observed distributions of log E_c/E_0 for the various categories of events are shown in Fig. 2 (*a* to *d*). The expected distributions which are shown by broken curves in Fig. 2 have been calculated on the assumption of isotropic and uncorrelated emission of secondaries in the c.m. system (target assumed to be a nucleon) using the formula

$$P\left(\frac{E_c}{E_0}\right) = \frac{1}{\sqrt{2\pi}\,\sigma_0}\,\exp.\left[\frac{-\left(\log\frac{E_c}{E_0}\right)^2}{2\sigma_0^2}\right]$$

$\sigma_0 = 2\sigma/\sqrt{n_s}$ and n_s is the number of charged secondaries used in finding E_c. This Gaussian distribution is expected since the energy E_c, the Lorentz factor γ_c for the centre of isotropic emission of the secondaries, the nucleon mass M_n and σ are related by the following relations:

$$E_c = (2\gamma_c^2 - 1)\,M_n$$

$$\langle\log\gamma_c\rangle = \frac{1}{n_s}\sum_{i=1}^{n_s}\log\cot\theta_i \pm \frac{\sigma}{\sqrt{n_s}}$$

where θ_i is the angle of emission of the *in*th secondary in the laboratory system and log γ_c has been shown[8] to be distributed like a Gaussian with a standard deviation of $\sigma = 0{\cdot}39$ for isotropic emission of the secondaries in the c.m. system. In general it can be seen from Fig. 2 that the observed distributions are shifted towards the right with respect to the expected ones; this means that E_c has been *overestimated* with respect to E_0. If the dotted curves are shifted to the right by 0·15 on the log E_c/E_0 plot as represented by full curves in Fig. 2, there is agreement between the observed distributions and the calculated one expect for the tail region in Figs. 2 *a*, 2 *c* and 2 *d*. This shift of 0·15 corresponds to an average overestimate factor of $E_c/E_0 \simeq 1{\cdot}4$. Such an overestimate of 1·4 can be expected on the basis that the secondary pions have an energy ~ 300 MeV in the c.m. system[9,10];

this would imply that the ratio of the velocity of the c.m. system to that of the pions in that system, *i.e.*, β_c/β_π is not unity but $\sim 1 \cdot 1$.

(*c*) *Tail in the E_c/E_0 distribution.*—In the histograms of Fig. 2, we have shown the area corresponding to values of $E_c/E_0 \geqslant 8$ as a shaded one. This can be particularly seen in the case of the interactions of identified pions (Fig. 2 *c*) and to a lesser extent in the case of interactions due to neutral primaries (Fig. 2 *d*); it is, however, not present in the case of proton interactions.

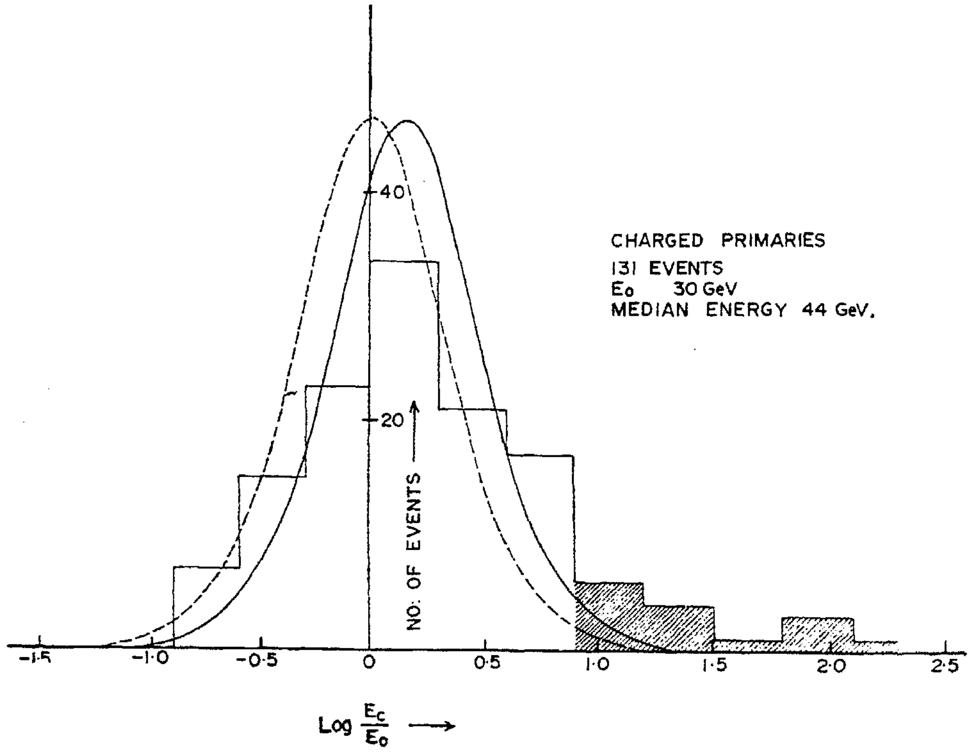


FIG. 2 (*a*)

There are 15 events beyond $\log E_c/E_0 = 0 \cdot 9$ in Fig. 2 *a* (interactions of charged primaries). Since events of low multiplicity can contribute appreciably to such a tail, we have estimated the probability that out of 54 events with $n_s \leqslant 4$, there are 15 events with $\log E_c/E_0 > 0 \cdot 9$; this works out to be 2×10^{-7}. Similarly, the probabilities for observing events in the shaded tail region in pion-induced events and in neutral primary induced events (Figs. 2 *c* and 2 *d*) are 10^{-3} and 5×10^{-3} respectively. These figures show that it is extremely unlikely that the observed tail in the distribution of E_c/E_0 can be explained as due to fluctuations from isotropy in the emission of the secondries in the c.m. system. *In other words there are anisotropic (or asymmetric) emission of secondaries in the c.m. system.*

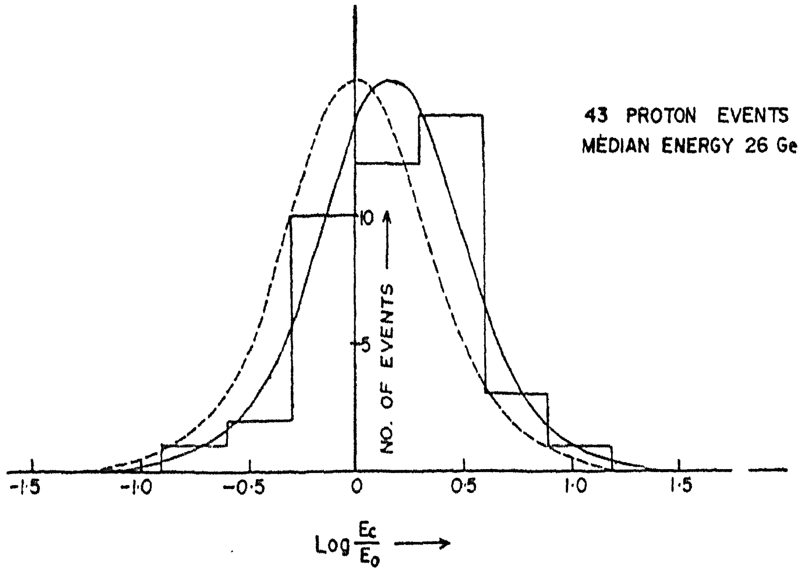


Fig. 2(b)

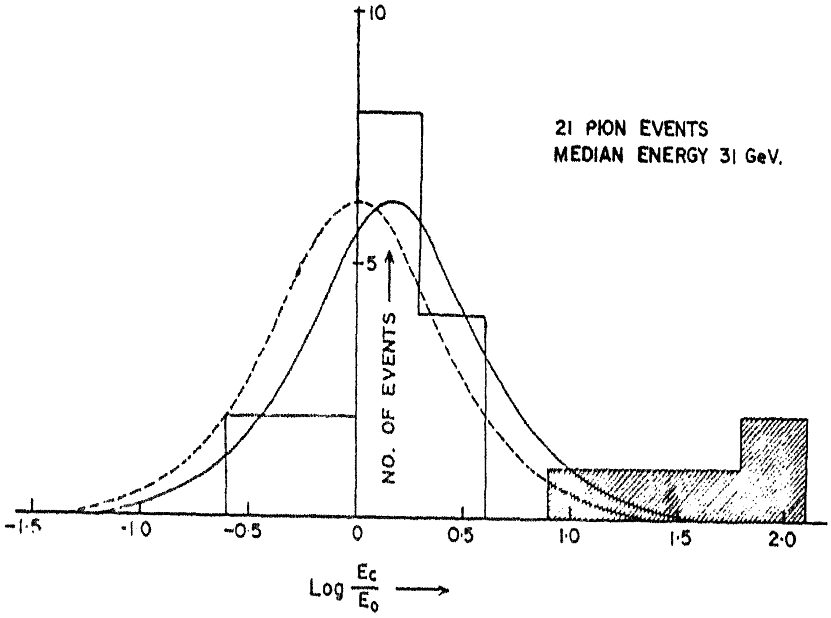


Fig. 2(c)

5. CLASSIFICATION OF EVENTS BY THE ANGULAR DISTRIBUTIONS OF THE SECONDARIES

The accepted events have been classified into four groups depending on the ratio E_c/E_0 which is a function of the degree of collimation of the charged secondaries. Events belonging to the tail of the distribution of E_c/E_0 (the shaded region in Fig. 2) form Group I. These events have been termed "anomalous events" and will be discussed in detail in a subsequent paper. The other three groups, *viz.*, II, III and IV consist of events with $2 < E_c/E_0 < 8$, $\frac{1}{2} < E_c/E_0 < 2$, and $E_c/E_0 < \frac{1}{2}$ respectively. In dividing in this manner, we have taken into account the fact that because the charged secondary multiplicity in these events is ~ 4, the inaccuracy in the estimation of E_C will be of the order of a factor of 2, higher or lower from the estimated value. The idea behind this classification and further study of the different groups as made below is to see whether Group II and Group IV events can be understood purely in terms of statistical fluctuations in the emission of secondaries or whether there are physical mechanisms involved in producing these groups of events.

6. ASYMMETRY IN THE EMISSION OF SECONDARIES

In Fig. 3 (*a*, *b*, *c*) the differential distributions

$$\frac{\triangle N}{\triangle \log (\gamma_{CN} \tan \theta)} \textit{ vs. } \log (\gamma_{CN} \tan \theta)$$

for events of Groups II, III and IV are shown. γ_{CN} is the Lorent z factor of the c.m. system with a nucleon as target [we assume that although the target is carbon, most of the collisions will be against a single nucleon. We have no evidence to the contrary from the distribution of E_C. Approximate equality of Group II and Group IV events (Table II) confirms our assumption] corresponding to an energy E_O of the incident primary; θ

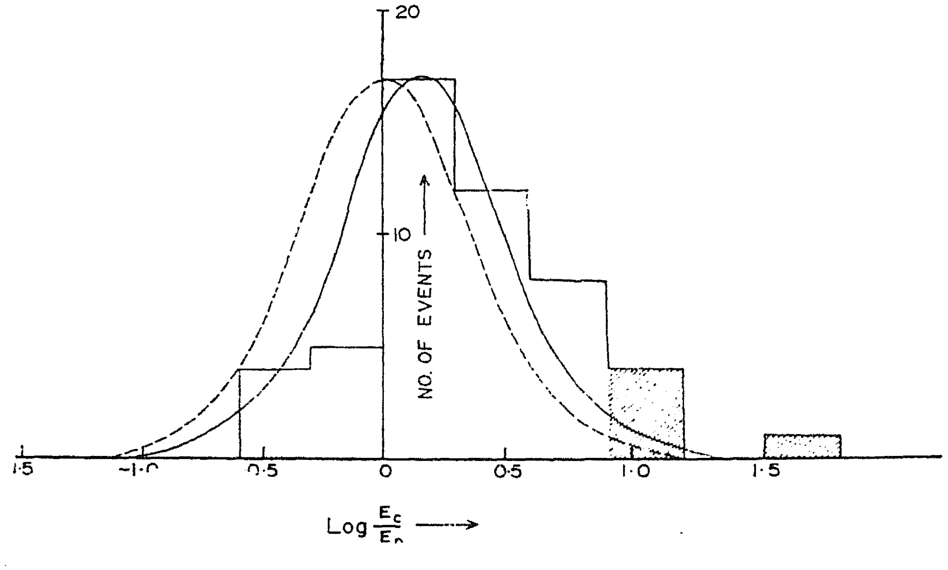
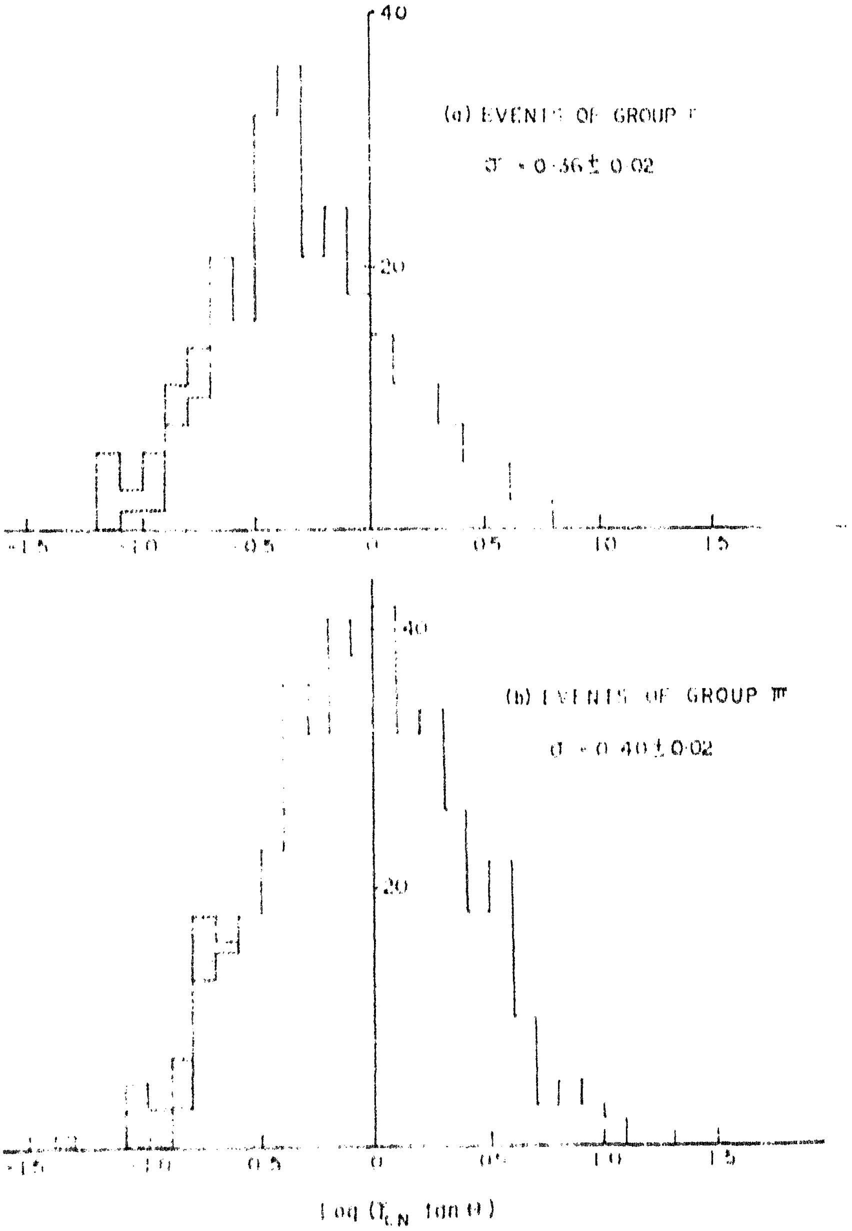


FIG. 2 (*d*)

FIG. 2 (*a* to *d*). Differential distribution of log E_c/E_0 for various categories of events (*i.e.*, those produced by charged primaries, protons, pions and neutral primaries respectively). E_c is the enrgy of the primary estimated from the angular distribution of the charged secondaries using the Castagnoli formula. E_0 is the true energy of the primary particle as determined by the total absorption scintillation spectrometer. Dotted and full curves show the expected distributions, *See* Section 4 (*b*) in text.

is the angle of emission of a secondary in the laboratory system. For isotropic emission of secondaries in the c.m. system, the root mean square width of the distribution in Fig. 3 should be $\sigma = 0{\cdot}30$ if $\beta_c/\beta_\pi = 1{\cdot}1$ and $\sigma = 0{\cdot}39$ if $\beta_c/\beta_\pi = 1{\cdot}0$ where β_c is the velocity of the c.m. system and β_π



Figs. 3(a) and 3(b)

the velocity of the individual secondaries in the c.m. system. If the events belonging to Group II and Group IV arise due to flucutation in the relative number of neutral and charged mesons in the forward and backward hemispheres in the c.m. system, then the distribution

$$\frac{\Delta N}{\Delta \log (\gamma_{\mathrm{CN}} \tan \theta)} \quad \textit{vs.} \quad (\log \gamma_{\mathrm{CN}} \tan \theta)$$

for these two groups will have a variance less than that for Group III. The width of the distribution in Fig. 3 for events of Group II is $0{\cdot}36 \pm 0{\cdot}02$, and for events of Group IV, 0·45 ± 0·3 whereas for Group III it is 0·40 ± ·02. There is, therefore, no indication of any strong fluctuations in the relative number of charged and neutral mesons which could cause the formation of Group II and Group JV events. Thus, there is an indication that sometimes there is a genuine asymmetry in the emission of secondaries in the c.m. system in nuclear collisions at these energies giving rise to the Group II and Group IV events. Further support to this view follows from the analysis given below.

TABLE II

Groups	II	III	IV
Fraction of total number of events in Group	0·3	0·5	0·2
Variance of the γ_{CN} tan θ distribution	0·36 ± 0·02	0·40 ± 0·02	0·45 ± 0·03
Ratio of neutral pions to charged secondaries n_{π^0}/ns_s in the forward hemisphere of the c.m. system.	0·4 ± 0·09	0·22 ± 0·05	0·7 ± 0·21
Average transverse momentum of γ-rays in the forward hemisphere in the c.m. system (in MeV/c)	135 ± 15	158 ± 19	105 ± 12

Some characteristic features of the events in the different groups are given in Table II. The ratio of neutral pions to charged secondaries has been evaluated for the different groups as shown in the third row of Table II. In determining n_{π^0}/n_s we have removed from the total number of charged secondaries the so-called "forward proton" on the basis of the criteria discussed earlier. The number of γ-rays divided by twice the number of charged secondaries (excluding forward protons), in the forward hemisphere in the c.m. system has been taken to be the ratio n_{π^0}/n_S. We have restricted to the forward hemisphere because the plate assembly in the chamber had almost unit efficiency for detection of γ-rays here. One would have expected a lower value of n_{π^0}/n_S for events belonging to Group II as compared to events belonging to Group II if Group II arose out of fluctuation in n_{π^0}/n_S.

For Group IV the larger value of n_{π^0}/n_S is compatible with the fluctuation hypothesis. However, the average transverse momentum of γ-rays is lower for the events belonging to Group IV as compared to those of Groups II and IV. This feature has no obvious relation to the fluctuation of n_{π^0}/n_S. It will be shown in the subsequent paper on the Group I events that the transverse momentum of γ-rays observed in these events is low, *i.e.*, 70 ± 8/6 MeV/c.

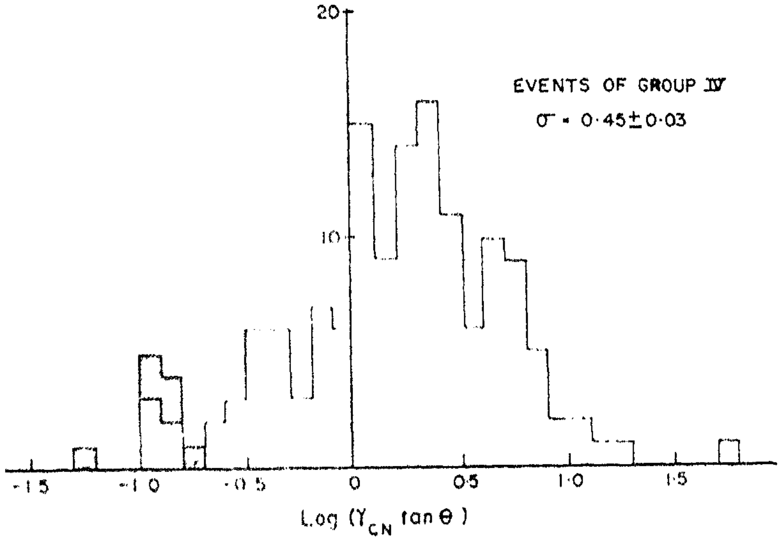


FIG. 3 (*c*)

FIG. 3 (*a*, *b*, *c*). Differential distribution of log (γ_{CN} tan θ) for events in different groups. γ_{CN} is the Lorentz factor for the nucleon-nucleon c.m. system, corresponding to an energy E_0 of the primary particle.

The shaded portion in these figures indicates the number of particles—the so-called "forward protons" which have been excluded whilst finding E_0.

Thus while a consistent explanation of all these features looks impossible on the basis of statistical fluctuations in the emission of secondaries in the c.m. system, it is feasible that a physical mechanism is responsible for the observed fluctuations. Dobrotin *et al.*[11] have classified events observed at ~ 300 GeV into the so-called forward and backward asymmetric events in nucleon-nucleon collisions in the c.m. system. These would correspond to our Group II and Group IV events. These asymmetries are interpreted as due to the motion of "fire-ball" in the forward or backward direction in the c.m. system without any other physical features involved. We would like to suggest here that one could expect correlations among the emission of secondaries due to multiparticle resonance and final state interactions. On this basis different values of n_{π^0}/n_S and mean transverse momentum of γ-rays could be associated with different meson clouds which, moving sometimes in opposite directions in the c.m. system, could give rise to the asymmetric events belonging to Groups II and IV.

7. CONCLUSION

From a study of the nuclear interactions produced in graphite by cosmic ray charged and neutral interacting particles of energy $\gtrsim 30$ GeV it is found that there exist a certain class of events which are "extremely collimated". In this paper it has been shown that such collimation cannot be understood on the basis of fluctuations in the angles of emission of the secondary particles in the c.m. system. Besides these events, the others have been grouped into three categories. It is shown that these groups are unlikely to arise from statistical fluctuations in the relative number of neutral and charged mesons in the two hemispheres of the c.m. system. It has been suggested that a possible cause of these fluctuations could be due to the formation of different resonant systems or corresponding final-stage interactions producing both very low energy and high energy secondaries. Oppositely moving meson clouds in the c.m. system with different "Q-values" and n_{π^0}/n_S ratio leading to correlated emission of secondaries could explain the fluctuations observed.

ACKNOWLEDGEMENTS

We wish to express our thanks to Prof. M. G. K. Menon for his continued interest in this work. We are indebted to Dr. P. V. Ramana Murthy and Dr. S. D. Verma who collaborated with us in the early phase of the experiments. It is a pleasure to record the valuable assistance given by Messrs. A. R. Apte, M.A., Kalgaonkar and S. G. Khairatkar in running the experiment at Ootacamund and Mr. N. V. Gopalakrishnan in the analysis of data.

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