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RATIO OF PIONS TO PROTONS AND RATIO OF NEUTRAL TO CHARGED INTERACTING PARTICLES AT MOUNTAIN ALTITUDE OF 800 gm/cm²

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Abstract

Using a combined set-up of a multiplate cloud chamber, an air Cerenkov counter and a total absorption spectrometer, the ratio of pions to protons not associated with large air showers has been determined to be $0 \cdot 50 \pm \cdot 07$ in the energy region 20–40 GeV at an altitude of 800 gm/cm². In the same energy region the ratio of neutral to charged particles is found to be $0 \cdot 66 \pm \cdot 07$. From the ratio of neutrons to protons deduced from these measurements (*i.e.*, $0 \cdot 99 \pm \cdot 11$), it is concluded that most of the charge excess of nuclear active particles of energies > 20 GeV at mountain altitudes and sea-level is due to pions.

1. Introduction

Experimental determination of the relative proportion of neutral to charged particles among the nuclear interacting particles at mountain altitudes and sea-level and the determination of the ratio of pions to protons is of particular interest in understanding the development and absorption of the nuclear cascades initiated by high energy cosmic ray primaries in the atmosphere. These ratios depend on various characteristics of high energy collisions in air like inelasticity, multiplicity, interaction cross-section, the extent of regeneration of pions by pions, probability of charge persistence of nucleons and pions, etc.,—parameters which enter into the diffusion equations describing the development and absorption of the nuclear cascades in the atmosphere. Since many of these parameters are not yet determined at high energies from a direct study of nuclear interactions, knowledge of the ratio of neutral to charged interacting particles, the ratio of pions to protons and the variation of these ratios with energy and altitude would help considerably in fixing at least some *limits* on the values of some of the parameters.

While several experiments have been carried out before to determine the ratio of neutral to charged particles, there has been no experiment reported so far in which the proportion of *pions to protons* has been determined at mountain altitudes. There exists a considerable amount of disparity in the value that has been obtained for the ratio of neutral to charged particles by different workers.[1] The value varies from 0·04 to 1·0. In none of these experiments the energy of the nuclear interacting particles has been determined reliably.

Using a combined set-up[2] of a multiplate cloud chamber, an air Cerenkov counter and a total absorption spectrometer, we have determined the ratio of neutral to charged interacting particles and also the ratio of pions to protons at an altitude of 800 gm/cm^2.

2. EXPERIMENTAL DETAILS

The experiment was principally designed to study the detailed characteristics of nuclear interactions produced by pions and nucleons of energy greater than 20 GeV and has been described elsewhere.[2] The experimental arrangement consisted of a multiplate cloud chamber with an air Cerenkov counter above and a total absorption spectrometer below. The cloud chamber was triggered with a selection system which selected only charged interacting particles for part of the run and made no distinction between charged and neutral interacting particles for the rest of the operating period. Triggering of the cloud chamber by nuclear interacting particles associated with large air showers or by particles in the cores of small air showers was prevented by a system of anti-coincidence counters of total effective area about a square meter placed by the side of the cloud chamber. The nuclear interacting particles were identified by the interactions they produced in the cloud chamber or by the characteristic development of nuclear cascades initiated in the spectrometer.* The air Cerenkov counter[3] which was operated at atmospheric pressure and had a threshold value of 45 for the Lorentz factor of the charged particles, enabled the classification of the charged interacting particles into *pions* and *protons* in the energy range 20–40 GeV. The energy of nuclear interacting particle was determined in individual cases to an accuracy of ± 20% with the total absorption spectrometer.[4]

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* The latter criterion of selection was used only in the determination of the ratio of pions to protons (Sec. 3 *a*).

3. EXPERIMENTAL RESULTS

(*a*) *Ratio of pions to protons.*—During the period (4500 hours) when the cloud chamber was triggered exclusively for nuclear interacting particles 427 events were recorded for which the charged primary was well within the solid angle of the air Cerenkov counter above the cloud chamber and for which the estimated energy from the total absorption spectrometer was in the energy range 20–40 GeV. Out of these, in 91 cases the air Cerenkov counter gave pulses indicating that the particles were pions. This number has to be corrected for spurious association of pulses from the Cerenkov counting system. A correction of about 1% arises from chance coincidence and another 1% from other background pulses due to knock-on electrons produced in the air column of the air Cerenkov counter passing through the front glass of the photomultiplier producing Cerenkov radiation there. This latter correction was determined by observing coincidences associated with the passage of μ-mesons through the Cerenkov counter while its photomultiplier was covered with black paper. These corrections reduce the number of pion events to 82. The air Cerenkov counter had an efficiency for extreme relativistic particles of $82 \pm 6\%$; there was an additional inefficiency of about 10% due to saturation effects in the recording system. Taking account of these facts we finally obtain the number of pion events to be 113 in a total of 427 events. This gives the ratio of pions to protons as $0{\cdot}50 \pm {\cdot}07$ in the energy region of 20–40 GeV.

(*b*) *Ratio of neutral to charged particles* (*N*/*C*).—During the period of 4650 hours when the chamber was triggered for both charged and neutral interacting particles 567 (above 20 GeV) nuclear interactions were recorded in the chamber for which one could unambiguously determine whether the interaction was produced by a charged or a neutral particle. Out of the 567 cases in 412 cases the energy of the interaction as determined with the total absorption spectrometer was in the range 20–40 GeV. In these 412 cases it was found that 248 were due to charged primaries giving a value of $0{\cdot}66 \pm {\cdot}07$ for the N/C ratio at energies 20–40 GeV. In the remaining 155 cases for which the energy was higher than 40 GeV (median energy 60 GeV), 103 interactions were due to charged primaries leading to a value of $0{\cdot}52 \pm {\cdot}09$ for the N/C ratio.

(*c*) *Ratio of neutrons to protons and probability of charge persistence.*—Using the ratio of neutral to charged particles and the ratio of pions to protons we could determine the ratio of neutrons to protons in the energy range 20–40 GeV. The value of this ratio comes out to be $0{\cdot}99 \pm {\cdot}11$, Assuming that the cosmic ray primaries are all protons, the ratio of neutrons to protons at an atmospheric depth of X gm/cm^2 can be written as

$$\frac{N}{P} = \frac{1 - \exp.\left[-2\,\epsilon X\left(\frac{1}{\lambda_{int}} - \frac{1}{\lambda_{abs}}\right)\right]}{1 + \exp.\left[-2\,\epsilon X\left(\frac{1}{\lambda_{int}} - \frac{1}{\lambda_{abs}}\right)\right]} \tag{1}$$

where

ϵ = probability of charge exchange in an inelastic collision of a nucleon with an air-nucleus, assumed to be energy independent;

λ_{int} = interaction mean free path of nuclear interacting particles in air;

λ_{abs} = the absorption mean free path of nucleons in the atmosphere.

In Table I we have given the expected ratio of N/P at an altitude of 800 gm/cm^2 for various values of the parameters ϵ and λ_{int} using a value for λ_{abs} as 120 gm/cm^2.

If we take into account the presence of heavy nuclei in addition to protons in the primary cosmic ray beam and consider the fragmentation of these nuclei at the top of the atmosphere, then formula (1) needs to be replaced by the approximate formula (72% protons and 28% neutrons).

TABLE I

ϵ	Expected ratio N/P at 800 gm/cm^2			
	$\lambda_{int} = 72$ gm/cm^2	$\lambda_{int} = 80$ gm/cm^2	$\lambda_{int} = 85$ gm/cm^2	$\lambda_{int} = 90$ gm/cm^2
0·5	0·98 (0·99)	0·94	0·87	0·80
0·4	0·94 (0·96)	0·88	0·80	0·71
0·3	0·87 (0·89)	0·78	0·68	0·58
0·2	0·71 (0·79)	0·60	0·50	0·43

$$\frac{N}{P} = \frac{0{\cdot}72\left[1 - \exp.\left(-2\,\epsilon X\left\{\frac{1}{\lambda_{int}} - \frac{1}{\lambda_{abs}}\right\}\right)\right] + 0{\cdot}28}{0{\cdot}72\left[1 + \exp.\left(-2\,\epsilon X\left\{\frac{1}{\lambda_{int}} - \frac{1}{\lambda_{abs}}\right\}\right)\right] + 0{\cdot}28}\,. \tag{2}$$

In Table I values for the N/P ratio calculated on the basis of formula (2) are given in the second column within brackets. It is seen that the values obtained according to formula (2) are always higher than those according to formula (1).

It is seen from Table I that the observed value of $0\cdot99 \pm \cdot11$ for N/P excludes the probability of charge persistence, *i.e.*, $(1 - \epsilon)$ being higher than 80% and may as well be close to 50% if λ_{int} is taken $= 90$ gm/cm^2 for nucleons of energies ~ 100 GeV (nucleons in the observed energy range of 20–40 GeV are expected to arise from the collision of nucleons of energy ~ 100 GeV in the atmosphere).

4. COMPARISON WITH OTHER EXPERIMENTS AND DISCUSSION

(*a*) *Ratio of pions to protons.*—There are no experimental results on the ratio of pions to protons at mountain altitudes with which we can compare our results. However, it may be pointed out that the evaluation by the Durham group[5] with magnetic spectrograph of the vertical intensity of pions and protons at sea-level indicates a ratio of $\pi/P = 0\cdot5 \pm \cdot11$ at an energy of 27 GeV. This compares well with our value of $0\cdot50 \pm \cdot07$ at 800 gm/cm^2.

(*b*) *Neutral to charged ratio.*—As stated in Section 1, the ratio of neutral to charged interacting particles has been determined earlier by many workers[1] at different altitudes. The experimental systems used by different workers to identify nuclear interacting particles are different (*see* Tables II and III). Brown *et al.* used nuclear emulsions; Greisen and Walker, and Farrow used ionisation chambers in conjunction with GM counter trays; Cervasi *et al.* and Khrimian used arrays of GM counters alone; Gottlieb, Deutschmann and Lal *et al.* have used multiplate cloud chambers.

In all experiments in which visual detectors like nuclear emulsions or cloud chambers have not been used, it must be emphasised that the identification of both the *charge* and the *interacting nature* of the particles are subjected to large uncertainties. The identification of charge in these experiments is based upon the presence or absence of a pulse from an array of hodoscoped GM counters placed over the apparatus meant for detecting nuclear interacting particles. Corrections due to (*i*) inefficiency of GM counter arrays, (ii) backward projected secondaries and (iii) association of air showers will be necessary and these corrections are quite appreciable (*see* Greisen and Walker). Since the association of air showers increases with energy, in these experiments, only part of the data will be useful for evaluating the N/C ratio. For example, in the experiment of Farrow at energies greater than 200 GeV, only ~ 10% of the interactions recorded could be used for the determination of the N/C ratio.

TABLE II

Authors	Altitude of observation gm/cm^2	Detector for nuclear interacting particles	Criteria for classification (energy or multiplicity)	N/C
Greisen and Walker (1953)	680	Ion chamber	(a) $0{\cdot}5a$–$1{\cdot}4a$ $1{\cdot}4a$–$4a$ $4a$–∞ $a=55$ GeV based on median energy estimate	0·82±0·17
Farrow (1957) ..	626 703 790	Ion chamber	200 GeV ,, ,,	0·74±0·15 0·65±0·15 0·56±0·36
Cervasi *et al.* (1955) ..	680	GM counters	10 GeV	0·77±0·035
Khrimian (1959) ..	720	GM counters	30 GeV	0·83±0·11
Brown *et al.* (1949) ..	670	Nuclear emulsions	$n_s \geqslant 3$	0·72±0·14
Gottlieb (1951) ..	650	Cloud chamber	≥100 GeV	0·04 to 0·16
Siddheswar Lal *et al.* (1962)	800	Cloud chamber	20–150 GeV (median energy 55 GeV)	0·69±0·13
Present experiment ..	800	Cloud chamber with total absorption spectrometer	20–40 GeV >40 GeV (median energy ~60 GeV)	0·66±0·07 0·52±0·09

TABLE III

Results obtained by Deutschmann[1]

Altitude: 730 gm/cm^2 (Cloud Chamber)

E_{π_0} GeV	0·0– 0·4	0·5– 0·9	1·0– 1·9	2·0– 2·9	3·0– 3·9	4·0– 4·9	5·0– 9·4	9·5– 16·4	16·5– 29·9	30– ∞
N/C	0·435 ±0·09	0·435 ±0·10	0·635 ±0·11	0·416 ±0·08	0·416 ±0·08	0·37 ±0·10	0·416 ±0·08	0·37 ±0·12	0·167 $(^2/_{12})$	0·125 $(^1/_8)$

Because of these considerations, it is evident that particularly from the point of view of determination of the neutral to charged ratio of nuclear interacting particles and the variation of this ratio with energy, one cannot place much reliance on experiments in which visual detectors have not been used. Therefore, for purposes of discussion we consider only experiments in which either cloud chambers or nuclear emulsions have been used.

In experiments in which cloud chambers have been used, there is absolutely no uncertainty regarding the identification of the charge or the interacting nature of the particles. However, partial rejection of data due to air shower association will still arise either due to the selection system incorporating anti-coincidences to remove strong association with air showers (as in the present experiment) or due to the rejection of cloud chamber photographs in which associated particles are seen (as in the analysis of Gottlieb). It is to be expected that the ratio of neutral to charged particles determined by rejecting the *associated cases* will represent the *upper limit* of the ratio for *all* nuclear interacting particles since pions should be more in concentration if at all, in the associated than in the unassociated events.

In the experiment of Gottlieb no attempt was made to estimate the energy of the nuclear interacting particles using the cloud chamber photographs themselves. From considerations of the flux of nuclear interacting particles reported, Greisen and Walker have pointed out that the mean energy of the interactions recorded in Gottlieb's experiment should be higher than 100 GeV. Therefore, the value of less than 0·2 obtained by Gottlieb probably corresponds to energies above 100 GeV. In the experiment of Lal *et al.* the energy of nuclear interacting particles has been estimated using the angular distribution method of Castagnoli *et al.*[6] From our experiment in which we have compared the energy estimates obtained by the angular distribution method with that obtained from the total absorption spectrometer, we find that the energy estimates in the angular distribution method are overestimated by a factor of about 1·4 (at energies of the order of 50 GeV). Therefore, we feel that the ratio of 0·69 ± ·13 reported by Lal *et al.* for a median energy of 55 GeV actually corresponds to a median energy of about 40 GeV and is therefore in agreement with the present experiment. In the experiment of Deutschmann, the events have been grouped according to the energy going into the π°-component and the variation of N/C ratio with energy studied. It becomes therefore difficult to compare the results of Deutschmann with the present experiment. Nevertheless, there is a clear indication of a decrease of the neutral to charged ratio with increasing energy in the experiment of Deutschmann also. The low value of 0·435 reported by Deutschmann for energies of π°-mesons less than 0·9

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In this paper we report on the detailed features of this group of events in an attempt to understand the process involved in the production of these events. We shall henceforth refer to these events as "collimated". These events are defined to be those which lead to an estimate of primary energy from the angular distribution of the secondaries (at least 3 in all including neutral pions) by the method discussed in I in excess of 8 times the energy estimated from the response of the total absorption spectrometer.

II. (*a*) EFFECT OF THE NATURE OF THE PRIMARY AND THE TARGET MATERIAL ON THE FREQUENCY OF OCCURRENCE OF THE COLLIMATED EVENTS

In Table I the relative frequencies of occurrence of collimated events is given for different primary particles in targets of carbon and brass. Pions were distinguished from protons upto an energy of 50 GeV† by using the air Cerenkov counter. Kaons are expected to be negligible compared to pions in the cosmic radiation. Uncharged primaries have been assumed to be neutrons. The median energy of the primaries was about 28 GeV with a cut-off at 15 GeV.

TABLE I

Frequency of collimated events

Target Primaries	Carbon	Brass
Protons	0/43	0/57
Pions	5/21	0/21
Neutrons	5/123	5/200
All charged particles	25/700	5/350

Table I indicates that roughly 25%‡ of the pion induced interactions in carbon are collimated. However, if one considers the results given in the fourth row in Table I and makes use of the fact that the ratio of pions to protons among charged primaries is $0{\cdot}50 \pm 0{\cdot}07$,[2] one obtains a lower figure of 10% for the frequency of this kind of collisions among pion inter-

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† Although the threshold energy for protons in the counter was 45 GeV, the effective threshold energy could be raised to 50 GeV due to poor efficiency of detection near the threshold.

‡ "However there seems to be a dependence of frequency of these events of the primary energy as indicated in Section III. Part of the higher frequency among the identified pion events may be due to the higher energy in the selection of events in the initial period of data collection. See Part I (1)",

actions. The latter figure is statistically more accurate and we take this as a better representative of the true frequency rather than the first estimate of 25%. In arriving at this estimate, it has been assumed that collisions produced by protons do not give rise to the collimated events which is consistent with the data in Table I.

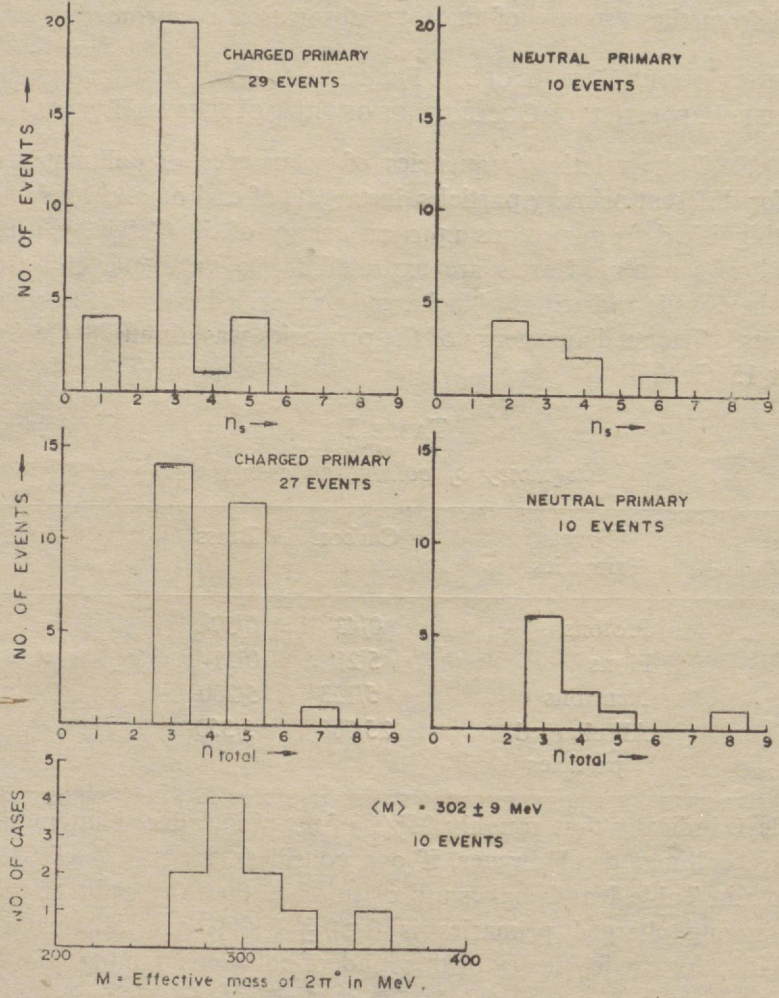

FIG. 1. The distribution of various quantities observed in the collimated events.

While protons seem not to produce these events, neutral primaries (neutrons) have been seen to be associated with some collimated events. However, this difference is not very significant statistically. If there is indeed such a difference between proton and neutron primaries, it would point to charge asymmetry, if any, of nuclear interactions. As discussed in Section III, the collimated nuclear interactions produced by neutral primaries do not exhibit certain features seen among the collimated events induced by charged primaries.

Finally, it is interesting to note that the relative frequency of these events is somewhat lower in brass than in carbon. The ratio of the frequencies in brass and carbon is $0{\cdot}4 \pm 0{\cdot}2$. It should be mentioned that the thickness of target plates in the two cases were $\lesssim 1/10$ of nuclear collision mean free path,[1] so that the above reduction is not attributable to secondary collisions taking place within the same target layer and masking the occurrence of collimated events.

(*b*) SPECIAL FEATURES OF THE COLLIMATED EVENTS

Two important features of the collimated events are: (*a*) charged and total (including π°) multiplicity distributions in the forward direction in the c.m. system of the incoming particle and a nucleon in the target material and (*b*) the transverse momentum distribution of γ-rays associated with the events. The former is shown in Fig. 1 and the latter in Fig. 2. The method used to estimate the number of π°'s in an event is to match the γ-rays into pairs from π°'s and count each of the unmatched ones as due to one neutral pion. It has been shown[3] that the detection efficiency for π° -mesons produced in the forward direction in the case of collimated events is close to unity.

The occurrence of odd multiplicities in both the charged and total multiplicity distributions is striking in the case of interactions induced by charged primaries. Another feature is the low mean energy of the neutral pions in comparison to the energy of the incident particle. The mean energy of π°'s in these events is $1{\cdot}7$ GeV whereas the mean energy of the primaries which gave rise to these π°'s is 50 GeV. The mean fraction of primary energy transferred to neutral pions, $\langle K_{\pi^\circ} \rangle = 0{\cdot}06$. This latter figure suggests that the incident particle which survives the collision retains most of the incident energy ($\sim 80\%$) since we can assume $\langle K_{\pi^\circ\pm} \rangle = 3 \langle K_{\pi^\circ} \rangle$. Based on these features it was suggested earlier[5] that a reaction of the following type would be applicable to the pion interactions:

$$\pi^\pm + N \rightarrow \pi^\pm + S_n + N \text{ or } N^*$$

where N stands for a nucleon in the target nucleus, N* an excited state of the target nucleon and S_n a system of *n* pions where *n* is even. The incident pion is assumed to retain its identity after the collision by losing only a small fraction of its energy. In some cases of collimated events, backward going relativistic secondaries were observed in the laboratory system which suggest the excitation of the target nucleon to an isobaric state.

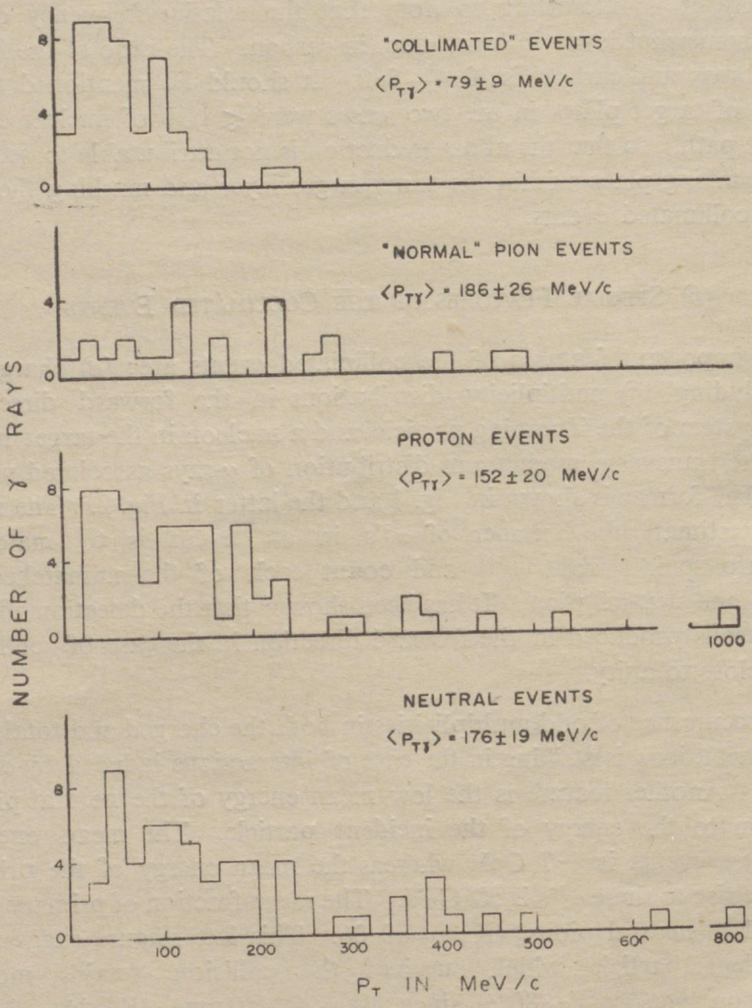

FIG. 2. The distribution of transverse momenta of γ-rays in different classes of events. The average value of the transverse momenta are given in the inset.

Further insight into the properties of S_n is gained by studying the transverse mometum distribution of γ-rays associated with the events (Fig. 2). The mean transverse momentum of γ-rays in the case of collimated events is significantly lower than in other events. This low value in turn points to a low value for the average of transverse momentum of neutral pions emitted from S_n. In fact the distribution of effective masses of two neutral pions from cases of S_2 and S_n given in Fig. 1 shows an average of 302 ± 9 MeV. This effective mass is close to the effective mass (317 ± 6 MeV) of di-pions in the ABC effect.[4] The ABC effect is an enhancement in the reaction cross-section $p + d \rightarrow He^3 + 2\pi$ corresponding to an effective mass of the 2π system at an energy of ~ 300 MeV. Since the enhancement is seen in only the neutral 2π system, the isospin attributed to the system is zero. A difficulty in the understanding of the ABC effect is the fact that it is seen in only the above reaction quoted. Searches for the ABC effect in other reactions like $\gamma\, p$ and $\pi\, p$ have proved fruitless.[6] It may be, for some unknown reason, that the target has to be a nucleus for producing the ABC effect. The ratio of neutral to charged pions that are attributable to S_n is found to be $0{\cdot}74 \pm 0{\cdot}18$.* This and the earlier observations about the multiplicity distributions are consistent with an isospin assignment of zero to S_2.

III. DISCUSSION OF THE RESULTS

From the foregoing, it appears that collimated events induced by charged primaries are preferentially originated by pions and in these events additional pions produced in the "forward direction" occur in pairs of charged and neutral pions. The effective mass of these di-pions seems close to that observed in the ABC effect. The events appear more frequently in carbon than in brass. Although collimated events have been seen to be induced by neutral primaries, these do not seem to have the characteristic multiplicity distribution observed in the case of interactions induced by charged primaries (Fig. 1). Therefore we infer that the collimated events with the characteristic features elucidated above are induced by pions only.

Collimated events can in general be due to diffraction dissociation,[7] Coulomb dissociation[8] or due to "glancing collisions" involving one pion exchange.[9] However, none of these mechanisms seems to be involved in producing the events reported here. The argument against diffraction or Coulomb dissociation is the large disparity in energies of the outgoing particles in the forward direction, *viz.*, there is probably one outgoing charged secondary carrying away $\sim 80\%$ of the incident energy. In a dissociation

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* The ratio of neutral to charged pions expected is $0{\cdot}5$ for the decay into two pions of a system with isospin zero; but corrected for phase space difference due to the different rest masses of charged and neutral pions this ratio is enhanced to $0{\cdot}7$ in the case of S_2 with the above-quoted mass.

phenomenon, the incident pion, excited to a higher mass state and decaying into a number of pions, should have equipartition of the incident energy among the secondaries. In some events there appears to be a large energy transfer to the target nucleon as evidenced by the occurrence of a relativistic secondary at large angles. In a coherent dissociation phenomenon the target nucleus will not break up. Further, Coulomb dissociation is ruled out from the fall of the frequency of events in brass compared to carbon; it should be the reverse if Coulomb dissociation is involved because this has a Z^2 effect. One pion exchange is excluded from the fact that outgoing forward multiplicities are odd, whereas it should be even from conservation of G-parity. However, the relative ratio of collimated events in brass and carbon evaluated earlier in II (*a*), *i.e.* $0 \cdot 4 \pm 0 \cdot 2$ is consistent with the idea of peripheral nature of the collisions [only 20% of the incident energy is radiated as pointed out in II (*b*)]. The total inelastic cross-section would vary as $A^{2/3}$ where A is the mass number of a nucleus whereas the area of periphery of constant thickness of a nucleus would vary as $A^{1/3}$. Therefore, frequency of peripheral events to all events will vary as $A^{-1/3}$. Thus between brass and carbon one expects a relative ratio of $(12/64)^{1/3} = 0 \cdot 6$.

Phenomena similar to the one reported here have not been observed at accelerator energies so far. It appears that collimated events as per our definition based on the angular distribution of secondaries only, do seem to be induced by protons in emulsion at about 27 GeV/c at a frequency of about

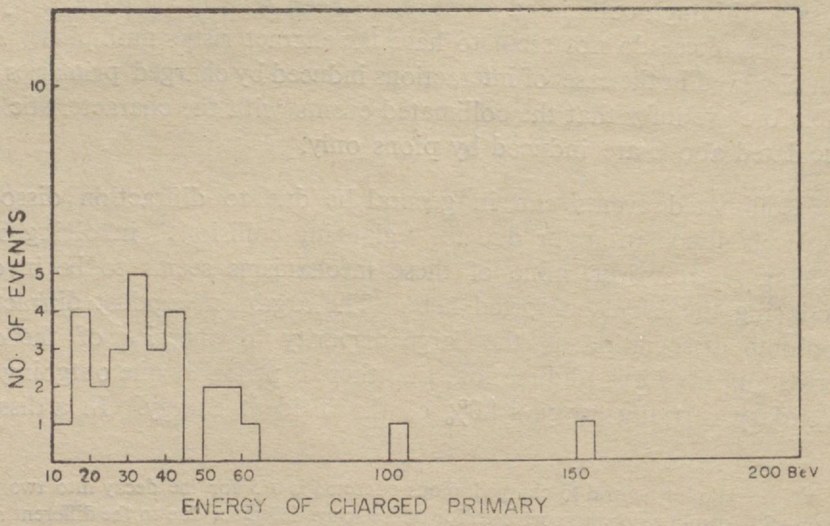

FIG. 3. The distribution in energy of the charged primaries producing the collimated event in carbon and brass as obtained with the aid of the total absorption spectrometer.[1]

1·5 – 3% in all interactions in emulsion and at a somewhat higher frequency of 3–5% in collisions against light nuclei of emulsion (C, N, O).* However, the detailed features of these events are unknown so that we cannot say that these events have characteristics similar to the events reported here. Interactions of pions have been studied upto 17 GeV/c[10] in heavy liquid bubble chambers with no report of finding events similar to ours. The median energy of the events observed by us is 35 GeV. The distribution in energy of the charged primaries of these events is given in Fig. 3. There seems to be an energy dependence in the production of these events. For collisions in carbon induced by charged primaries the ratio of collimated events to all is $0\cdot03 \pm 0\cdot01$ at energies < 30 GeV whereas the corresponding figure for energies > 30 GeV is $0\cdot09 \pm 0\cdot03$. Further investigations on the interactions of pions in carbon at energies 30–60 GeV from the 70 GeV proton Serpukov accrelerator will be interesting. A study on the role of the target (proton or nucleus) could throw further light on the phenomena reported here.

IV. Conclusion

A class of nuclear interactions, characterised by extreme collimation of the secondaries in the forward direction in the laboratory system, seem to be induced preferentially by pions. These events appear to be relatively more frequent in carbon than in brass. An energy dependence in the frequency of production of these events is indicated. It is possible to explain these collisions in terms of peripheral production of pions in pairs, the di-pion system being similar to that observed in the ABC effect. In these collisions, the incident primary surviving the collision appears to retain ~80% of its energy. It is not possible to invoke diffraction dissociation, Coulomb dissociation or one pion exchange mechanisms to explain the events.

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OBSERVATIONS ON THE NUCLEAR INTERACTIONS OF COSMIC RAY PIONS AND NUCLEONS AT ENERGIES $\gtrsim$ 20 GEV

Part II. The Extremely Collimated Nuclear Interactions

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ABSTRACT

Detailed features of extremely collimated nuclear interactions induced by cosmic ray particles in carbon and brass (belonging to group I as classified in Part I of this series of papers) are presented. These extremely collimated nuclear interactions seem to be preferentially induced by pions rather than by nucleons; also the relative frequency of these seems to be less when brass is used as target compared to the case with carbon as target. The distribution of multiplicities of secondary particles emitted in the forward direction show certain regularities in the case of interactions induced by charged primaries. Observations on the γ-rays associated with these events give support to the interpretation that in these inelastic collisions pions are produced in pairs in the forward direction with low transverse momentum. It is suggested that such a low energy di-pion system could be the same as found in the so-called ABC effect.

I. INTRODUCTION

IN Part I[1] of this series of papers (which shall be referred to as I hereafter), nuclear interactions observed in a multiplate cloud chamber operated in conjunction with an air Cerenkov counter and a total absorption spectrometer have been classified into different groups depending on the degree of angular collimation of the secondaries for a given energy of the primary. It was shown there that a group of nuclear interactions characterised by a high degree of angular collimation exists which cannot be explained as arising from simple fluctuations from isotropic emission of secondaries in the c.m. system.

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Nucleon-Antinucleon Production in High-Energy ($> 10^{12}$ eV) Hadron Collisions.

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In this paper we wish to present experimental results which show that in ultra-high-energy ($> 10^{12}$ eV) collisions of hadrons there is comparatively large production of nucleon-antinucleon pairs. At accelerator energies nucleon-antinucleon pairs constitute less than 1% of all produced particles with no indication of an increase with energy even up to 70 GeV (¹). The present results indicate a production of $\sim 14\%$ at energies $> 10^{12}$ eV, implying a rather rapid increase in the cross-section for production of nucleon-antinucleon ($\mathcal{N}\overline{\mathcal{N}}$) pairs at energies beyond 100 GeV.

The results have been obtained from a detailed study of the time structure of hadrons in extensive air showers carried out at Ootacamund (altitude 800 g cm^{-2}) during 1968-69. The hadron detector was a total-absorption spectrometer placed at the centre of an extensive air shower array comprising 20 scintillators distributed up to a distance of 40 m from the centre of the array for density determination and an additional four fast scintillators for the determination of the arrival angle. The array is designed to study the properties of air showers in the size range ($5 \cdot 10^4 \div 10^7$) particles. The total-absorption spectrometer is described in detail by Ramana Murthy *et al.* (²). It has been estimated that the measured hadron energy is accurate to about 30% in the present experiment. The arrival time of hadrons with respect to the shower front has been measured in units of 7 ns using a chronotron timing system and the error in the measured time can be approximated by a Gaussian with a half-width of 7 ns. Details of the experimental system and data analysis are given elsewhere (³).

The arrival time spectra obtained have been studied in relation to many air shower parameters, such as shower size, distance of the hadron from core, shape of the electron

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(¹) Yu. B. Bushnin, S. P. Denisov, S. V. Donskov, A. F. Dunaitsev, Yu. P. Gorin, V. A. Kachanov, Yu. S. Khodirev, V. I. Kotov, V. M. Kutyin, A. I. Petrukhin, Yu. D. Prokoshkin, E. A. Razuvaev, R. S. Shuvalov, D. A. Stoyanova, J. V. Allaby, F. Binon, A. N. Diddens, P. Duteil, G. Giacomelli, R. Meunier, J.-P. Peigneux, K. Schlupmann, M. Spighel, C. A. Stahlbrandt, J.-P. Stroot and A. M. Wetherell: *Phys. Lett.*, **29** B, 48 (1969); F. Binon, S. P. Denisov, P. Duteil, V. A. Kachanov, V. M. Kutyin, J. P. Peigneux, Yu. D. Prokoshkin, E. A. Razuvaev, R. S. Shuvalov, M. Spighel and J. P. Stroot: *Phys. Lett.*, **30** B, 506 (1969).

(²) P. V. Ramana Murthy, B. V. Sreekantan, A. Subramanian and S. D. Verma: *Nucl. Instr. Meth.*, **23**, 245 (1963).

(³) S. C. Tonwar: Thesis submitted for the Ph. D. degree of the University of Bombay (1970), unpublished.

lateral structure, etc. It has been seen that, while the time spectra of hadrons are highly sensitive to the energy of the hadrons as expected, there seems to be no correlation with the electron lateral structure or shower size within statistical errors. The studies also show that the spectra become slightly flatter for hadrons arriving at large distances from the shower core. However there is no significant dependence of the time spectra within 20 m. Thus the data for hadrons of the same energy have been combined for all showers of size $6.7\cdot10^4 \div 1.8\cdot10^6$ irrespective of electron lateral structure and having core distances smaller than 20 m. Only showers with zenith angle smaller than 30° have been considered to avoid contamination of the hadron detector by soft shower particles entering from the sides. In Fig. 1 are presented the arrival time spectra for hadrons of energy groups $(10\div20)$ GeV and $(20\div40)$ GeV in the form of histograms.

It is seen from Fig. 1 that the hadrons which are delayed by more than 10 ns constitute a significant fraction $(\sim10^{-2})$ even at energies higher than 10 GeV. Since for pions of energy >10 GeV the delay cannot be more than $(2\div3)$ ns relative to the

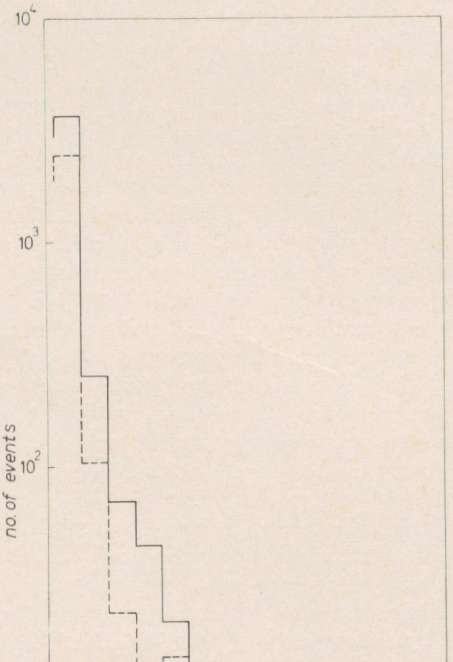

Fig. 1. – Arrival time distributions for hadrons contained within 20 metres of shower axis in showers of size N_e in the interval $6.7\cdot10^4 \div 1.8\cdot10^6$ for two hadron energy groups. R is the distance of the hadron from the shower axis. —— $(10\div20)$ GeV (4070 events), – – – $(20\div40)$ GeV (2600 events).

shower front, their characteristic delay being only < 0.3 ns/km, and the effective height of production ~ 1 km, a large fraction of the hadrons of energy 10 GeV or more which are delayed by more than 10 ns have to be particles heavier than pions—presumably nucleons. In order to deduce the extent of nucleon production in individual collisions of high energy, it is necessary to carry out a detailed calculation of the development and absorption of the hadron cascade in the atmosphere and compute the hadron arrival time spectra for various energies and compare the same with the experimentally obtained time structure. Since no unique model of high-energy collisions has been established it is necessary to carry out this computation on the basis of various models treating many interaction characteristics as free parameters. Monte Carlo methods have to be necessarily employed for these computations.

Among the many models tried out, it has been found that one particular model gives the best agreement with experimental results. This model has features that have been extracted from the isobar model proposed by PAL and PETERS (4) and the fireball model of COCCONI *et al.* (5). The secondary hadrons that have been considered are pions, kaons and nucleons ($\mathcal{N}\bar{\mathcal{N}}$). The main assumptions for the simulation of the hadronic cascade in the atmosphere made in the computation of the time structure are:

i) The mean free paths for collision of nucleons, kaons and pions with air nuclei are 80, 120 and 120 g cm^{-2} respectively and these are independent of the energy of the interacting particle.

ii) The interactions of the nucleons are characterized by an inelasticity parameter, while the kaon and pion interactions are completely inelastic. The nucleons lose only a fraction η ($= 0.2$) of their energy in any interaction and emerge in excited state in 70% of the collisions. The excited state decays into 1, 2 or 3 pions and a baryon depending on the interaction energy. For convenience the decay process has been assumed to take place in steps such that in each decay there are only two particles in the final state, each with momenta of 0.4 GeV/c in the rest frame of the decaying state. The excitation of the target nucleon is ignored as this is not likely to lead to a nucleon of energy > 5 GeV in the laboratory system.

iii) Apart from the isobar decay products, particles are also produced by the « pionization » process with a multiplicity n proportional to the center-of-mass energy. For nucleon interactions the average $\bar{n}$ is given by the relation $\bar{n} = 0.25\,E^{\frac{1}{2}}$ but for pion and kaon interactions the relation $\bar{n} = 1.0\,E^{\frac{1}{2}}$ is used. However, for an individual interaction the multiplicity n is determined from a distribution of the type $n \exp[-n^2/\alpha^2]$ suggested by BOZOKI *et al.* (6), where α is related to the average multiplicity.

iv) All the interactions are treated in the c.m. system. The energy and momentum of isobar particles are determined from kinematic considerations. For the « pionization » particles the following distributions for longitudinal momentum p_l^* and transverse momentum p_t have been used:

$$W_l(p_l^*) \sim \exp[-a p_l^*]\,\mathrm{d}p_l^*\,, \qquad W_t(p_t) \sim p_t^{\frac{3}{2}} \exp[-b p_t]\,\mathrm{d}p_t\,.$$

The average transverse momentum has been taken as 0.40, 0.49 and 0.59 GeV/c for pions, kaons and nucleons respectively. With p_l^* and p_t known for each particle it is easy to obtain the lateral distribution of these hadrons at any observational level.

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(4) Y. PAL and B. PETERS: *Mat. Fys. Medd. Dan. Vid. Selsk.*, **33**, No. 15 (1964).

(5) G. COCCONI *et al.*: UCRL-10022 (1962), p. 167.

(6) G. BOZOKI, E. GOMBOSI, M. POSCH and L. VANICSEK: *Nuovo Cimento*, **64** A, 881 (1969).

v) In nucleon-nucleon collisions the recoil nucleon has been assumed to have characteristics similar to those of the forward nucleon, except for its backward direction in c.m. system. In pion and kaon interactions, due to lack of available information an assumption has been made that the recoil nucleon behaves as a created particle going backwards in the c.m. system. The phenomenon of backward scattering in pion collisions has also been taken into account using suitable extrapolations from the proton momentum spectrum given by DARONIAN *et al.* (⁷) for 11 GeV/c π^--p interactions and assuming the E^{-2} type of energy dependence of the cross-section. These latter assumptions lead to an over-estimate of production of low-energy nucleons but are helpful in fixing the lower limit for the $\mathcal{N}\overline{\mathcal{N}}$ production cross-section at high energies.

vi) Among the particles produced in interactions, on the average, a fraction $f_{\mathcal{N}}$ has been assumed to be $\mathcal{N}\overline{\mathcal{N}}$ and another fraction f_{K} has been assumed to be kaons, charged as well as neutral. The function f_{K} has been assumed to increase with energy such that from a value of 0.02 at 10 GeV, it increases to about 0.15 at 500 GeV and saturates there. The function $f_{\mathcal{N}}$ has been assumed to vary with interaction energy E according to the relation

$$f_{\mathcal{N}} = 0.14(500/E + 1)^{-1}\,.$$

Thus $f_{\mathcal{N}}$ has a value of 0.003 at 10 GeV, 0.10 at 10^3 GeV and finally saturates at about 0.14 for energies $\sim 10^4$ GeV. In individual interactions, random process assigns the produced particle its identity as pion, kaon or nucleon within the constraints imposed by the values of $f_{\mathcal{N}}$ and f_{K}.

vii) The air showers have been simulated for proton primaries as well as heavy-nuclei primaries. In the latter case, the superposition assumption has been made, *i.e.* a shower of primary energy E_0 initiated by a nucleus of atomic number A has been considered equivalent to a superposition of A showers, each of energy E_0/A, initiated by nucleons.

First a calculation was made based on the assumptions i) to v) given above and assuming a constant production of only 1% of $\mathcal{N}\overline{\mathcal{N}}$'s at all energies as indicated by accelerator results up to 70 GeV. The results are shown in curve A) in Fig. 2, for hadrons of energy $(10\div 20)$ GeV in showers of average size of 10^5 particles initiated by primary protons of energy $3\cdot 10^{14}$ eV. The wide discrepancy with experimental results is quite obvious.

Since some of the observed showers could be due to heavy primaries, it is necessary to examine what the predicted time spectrum is for such showers. Curve B) in Fig. 2 corresponds to the case of ironlike primaries ($A = 50$). It is seen that while there is a slight flattening, the discrepancy with experimental results is still wide. As a next step an increase in the production of $\mathcal{N}\overline{\mathcal{N}}$ with energy was tried. Curve C) in Fig. 2 is based on such an increase. The increase in the proportion of $\mathcal{N}\overline{\mathcal{N}}$ with energy was taken to be given by the equation in vi) above. It is seen that the agreement between the experimental data and the calculated curve C) is very close indicating rather copious production (about 14%) of $\mathcal{N}\overline{\mathcal{N}}$ in high-energy collisions. Though the curve C) is somewhat steeper than the experimental data, much emphasis cannot be placed on the fit in the higher-delay region because of large statistical errors. It may be possible to improve the fit considerably with still higher $((20\div 25)\%)$ $\mathcal{N}\overline{\mathcal{N}}$ production at higher

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(⁷) P. DARONIAN *et al.*: *Proceedings of the Second Topical Conference on High-Energy Collisions of Hadrons, CERN*, Vol. **2** (1968), p. 226.

energies. However, keeping in view the constraints imposed by the measured values of charged-to-neutral ratios among hadrons in air showers, as discussed later, such an increase of $\mathcal{N}\overline{\mathcal{N}}$ has not been considered in the calculations. It may be mentioned that the emphasis here is on fixing the lower limit for nucleon production in high-energy hadron collisions.

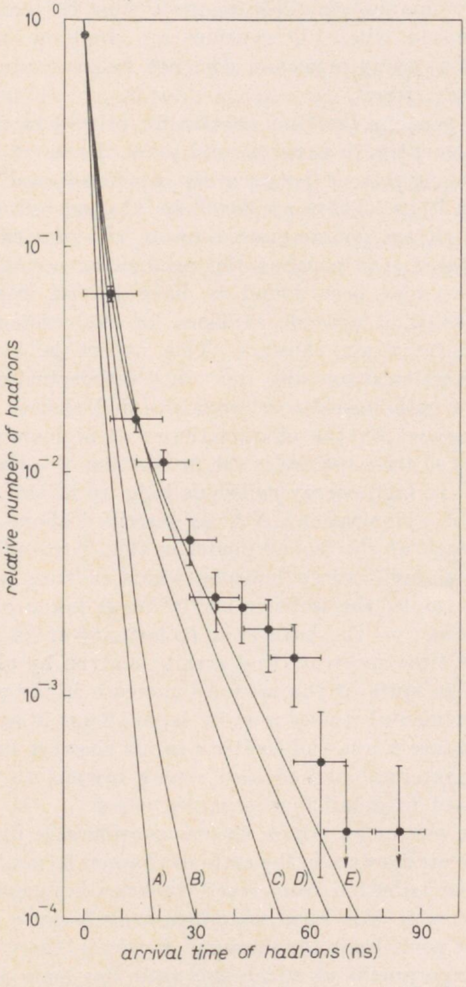

Fig. 2. – Comparison of the observed time spectra for hadrons of $(10\div20)$ GeV energy with spectra calculated using different models of high-energy hadron collisions. The statistical errors as well as the errors in the measured arrival time are shown on each experimental point except the zero-time point which is free of timing errors. $\overline{N}_e$ is the average shower size and R is the distance of the hadron from shower axis, $\overline{N}_e=10^5$, $R\leqslant 20$ m. ● experimental data, —— calculations.

In order to see the effect of primary composition on the time spectra in this model of increased $\mathcal{N}\overline{\mathcal{N}}$ production, a calculation has been made on the basis of an assumed primary composition:

$$\mathrm{H}:\mathrm{He}:\mathrm{C}:\mathrm{S}:\mathrm{Fe}=20:30:20:20:10\,,$$

which is somewhat different from the observed composition and which has a deliberate over-emphasis on the heavy primary component. The results are given in curve D). It is seen that the predicted number of hadrons is high in the $(10 \div 20)$ ns region compared to the curve C), while for larger delays curve D) falls below curve C). This rather odd behaviour is due to the fact that in heavy primary showers the delayed hadrons spread out to larger distances leaving the time spectra of hadrons within the 20 m circle practically unaffected. This suggests that the composition of air shower primaries can be ignored when observations are confined to hadrons within 20 m. Therefore the presence of heavy primaries does not help in reducing the extent of $\mathcal{N}\overline{\mathcal{N}}$ production to any great extent.

The model C) also predicts the time spectra for other hadron energy groups which are in reasonable agreement with experimental data. However for hadrons of energies above 20 GeV there is agreement between the predicted and observed spectra only up to delays of about 20 ns. There are few tens of observed events scattered in the $(20 \div 80)$ ns region which are not accounted for in the present picture of air shower development, which takes into account the production of $\mathcal{N}\overline{\mathcal{N}}$. These high-energy large-delay events have also been found to have special interaction characteristics and have been interpreted as possible evidence for the existence of heavy-mass particles (mass $\sim 10\ \text{GeV}/c^2$) in air showers. This aspect is discussed in detail elsewhere (3). The present calculations also reproduce satisfactorily the observed features of hadron time spectra with regard to shower size and shower core distance.

The primary requirement on the characteristics of high-energy collisions in order to reproduce the observed time spectra is the production of a large number of comparatively low-energy $\mathcal{N}\overline{\mathcal{N}}$ in high-energy collisions high up in the atmosphere. The isobar model together with the « pionization » $\mathcal{N}\overline{\mathcal{N}}$ as described above meet this requirement. The particular advantage of the isobar model is that it provides through the decay of the isobar additional high-energy hadrons which in turn produce more « pionization » $\mathcal{N}\overline{\mathcal{N}}$. If, for example, the isobaric excitation is taken out in the above model and calculations are made on the basis of an inelasticity of 0.4 ± 0.2 and a multiplicity proportional to $E^{\frac{1}{4}}$, the time spectrum that results is given by curve E) in Fig. 2. It is seen that in this case in spite of the assumed increase in the production of $\mathcal{N}\overline{\mathcal{N}}$, the discrepancy with experimental results is quite large. Thus it appears quite feasible on the basis of time structure studies of hadrons in air showers to role out many of the models of high-energy interactions and lend strong support to specific models. These aspects will be discussed in detail in a separate paper.

Another air shower parameter which throws considerable light on the composition of hadrons in extensive air showers is the ratio of charged to neutral hadrons at energies > 10 GeV, where the contribution from recoil nucleons is insignificant. However, it is rather difficult to determine this ratio unambiguously because of the over-abundance of nonhadronic charged particles in air showers. Recently, there have been a few multiplate cloud chamber experiments in which this ratio has been determined quite unambiguously. Hinotani (8) measures the C/N ratio as 2.9 at energies > 10 GeV. Chatterjee *et al.* (9) estimate the C/N ratio for hadrons of energy > 25 GeV in showers of size greater than 10^5 particles as 3.3 ± 0.8. Kameda *et al.* (10) give a value of $2.5^{+1.5}_{-0.5}$ for hadrons of energy > 500 GeV. If nucleon-antinucleon production is completely ignored then the C/N ratio will be very high (~ 100 or more depending

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(8) K. Hinotani: *Journ. Phys. Soc. Japan*, **17**, 24 (1962).

(9) B. K. Chatterjee *et al.*: *Proceedings of the Eleventh Symposium on Cosmic Rays, Astrophysics, Geophysics and Elementary-Particle Physics*, Vol. **2** (Delhi, 1969), p. 350.

(10) T. Kameda *et al.*: *Proceedings of the Ninth International Conference on Cosmic Rays*, Vol. **2** (London, 1965), p. 681.

on the number of pions and kaons in the shower at the observational level). If the fraction of nucleons is taken to be only 1% up to the highest energies then the C/N ratio in the model discussed above comes out to be ~ 12 for hadrons of energy > 10 GeV. However, the model which predicts the time spectrum given by curve C) in Fig. 2, in which the increase of the production of $\mathcal{N}\bar{\mathcal{N}}$ with energy is considered, gives a value for C/N of 3 for $E > 10$ GeV, and also for $E > 500$ GeV, in good agreement with the experimental results quoted above.

Conclusions. The experimental data on arrival time spectra and the charged-to-neutral ratio for hadrons associated with air showers conclusively show that nucleon-antinucleon pairs are produced in abundance ($\sim 14\%$) in high-energy hadron interactions ($> 10^{12}$ eV). Since machine results even at 70 GeV indicate production of only about 1% of nucleon-antinucleon pairs among secondaries, it follows that there must be a rapid increase in the production cross-section with energy between $(10^{11} \div 10^{12})$ eV. The time structure studies of hadrons in air showers lead to interesting guesses on the probable phenomenological picture of high-energy hadrons collisions.

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Time structure of hadrons in extensive air showers and models of high energy hadron interactions

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Abstract. The arrival time spectra of hadrons of energy 5–40 GeV in extensive air showers of size $6{\cdot}7 \times 10^4$–$1{\cdot}8 \times 10^6$ particles have been obtained in an experiment carried out at Ootacamund (800 g cm^{-2} altitude) during 1968–69 and compared with the predictions from Monte Carlo calculations based on two different models, the 'fireball' and 'isobar–pionization' models, of high energy collisions. The 'fireball' model predicts time spectra which are too steep compared to the observed ones. Variations within plausible limits of some of the parameters characterizing the hadron interactions like inelasticity, multiplicity, momentum distribution among secondaries and extent of nucleon–antinucleon ($N\bar{N}$) production do not succeed in reducing the discrepancy. The 'isobar–pionization' model on the other hand succeeds well in explaining the observed features of the arrival time spectra when increased $N\bar{N}$ production is taken into account. Thus it has been concluded that in high energy hadron collisions isobaric excitations of the interacting baryons play a very dominant role. The rapid increase in the cross section for the production of baryons in hadron collisions of energy greater than 10^{11} eV is also emphasized by this study.

1. Introduction

A rigorous theory of strong interactions of hadrons involving multiparticle production has not been formulated yet. Consequently few statistical (eg Fermi 1951, Landau 1953, Hagedorn 1965, Wayland *et al.* 1967, Wayland 1968) or phenomenological (eg Cocconi *et al.* 1962, Hasegawa 1961, Amati *et al.* 1962, Pal and Peters 1964, Koshiba 1969) models have been proposed which have been partly successful in fitting the experimental data available at accelerator energies ($<$ 70 GeV). Since these models have quite a few free parameters, which are energy dependent, it is necessary to have experimental results over a wide range of energies to establish the validity or the plausibility of any of these models. The prominent parameters that characterize high energy hadron collisions are interaction cross section, inelasticity, multiplicity, states of the colliding hadrons after interaction, angular distribution, transverse momentum distribution and composition of secondary particles. Cosmic ray experiments carried out at mountain altitudes using cloud chambers and ionization calorimeters and at balloon altitudes using nuclear emulsion stacks and recently calorimeters have given information on some of the parameters up to energies of approximately 10^{13} eV. The experiments of Grigorov *et al.* (1970) using calorimeters in satellites have yielded information on the dependence of the nucleon interaction cross section on energy in the 10^2–10^3 GeV energy region. At high energies ($> 10^{13}$ eV) studies of extensive air showers are the only means available for deducing the characteristics of hadron collisions.

The extensive air shower is the end product of a series of hadronic and electromagnetic interactions in the atmosphere, initiated by a primary cosmic ray proton or a heavy nucleus of ultra high energy ($> 10^{13}$ eV). At any observational level, mountain altitude or sea level, the air shower consists of three distinct components—the soft component (γ rays and electrons), the penetrating component (muons) and the interacting component (various types of hadrons like pions, kaons, nucleons, etc). The study of the detailed properties of these components and the correlations among them offers in principle a method, though indirect, for discerning the characteristics of high energy collisions. Some of these properties like the lateral distribution of electrons, the energy spectrum of hadrons, the energy spectrum of muons, and the variation of the number of hadrons and muons with shower size, have been studied experimentally by many workers and compared with the predictions from calculations based on different models of high energy hadron collisions. However, it has turned out that these properties are not sensitive enough to unambiguously reject or lend firm support to any particular model.

Another interesting property of air showers is the 'time structure' or the relative delay in the arrival time of the different constituents of air showers at the observational level. The time structure arises in the following way. The photons and the high energy electrons which travel with the velocity of light arrive first at the observational level. The early experiments of Bassi *et al.* (1953) showed that near the axis the soft component is contained in a narrow disc of 1–2 m thickness with the consequence that the relative delay between the soft particles is less than a few nanoseconds. The heavier particles like nucleons trail the shower front and their time lag increases as the production height of these particles above the observational level increases. A nucleon which has been produced say approximately 2 km above the observational level with an energy of about 10 GeV, gets delayed relative to the air shower front by as much as 32 ns. However, for pions of the same energy this delay is less than a nanosecond. Thus the time spectra of hadrons contain information about the relative composition of the particles at the observational level. The detailed time structure of hadrons at the observational level, however, is determined by several parameters like the production height distribution for hadrons and the energy spectrum of the hadrons apart from the composition of particles produced in high energy interactions and is thus sensitively related to the characteristics of these interactions.

Particles considerably heavier than the nucleon will naturally arrive with considerably larger delays with respect to the shower front. Since 1965 several experiments (Damgard *et al.* 1965, Chatterjee *et al.* 1965a, Bjornboe *et al.* 1968, Jones *et al.* 1967, Dardo *et al.* 1968, Tonwar *et al.* 1971a) have been carried out looking for delayed heavy mass particles in air showers. The experiment of the Tata Institute of Fundamental Research (TIFR) air shower group carried out in the summer of 1965 showed that the time structure study could not only reveal the presence of heavy mass particles, if they exist, but also could, if carried out with considerable refinement and improved statistics, establish the extent of nucleon–antinucleon ($N\bar{N}$) production (Chatterjee *et al.* 1965b) at high energies. In the present paper we wish to report the results of such a study carried out in 1968–69 and show how a comparison of the experimentally determined time structure of hadrons with the time structure functions calculated on the basis of different models of high energy interactions, has enabled us not only to determine the extent of $N\bar{N}$ production (Tonwar *et al.* 1971b) but also to come to some positive conclusions regarding the validity of the different models at high energies. The experimental results on time structure and the charged to neutral ratio of hadrons in air showers lend strong support to the 'isobar–pionization' models in complete exclusion of pure pionization models.

2. Experimental arrangement and results

The experiment on the time structure of the hadronic component of extensive air showers was carried out with the TIFR air shower array at Ootacamund (altitude 800 g cm^{-2}). The array comprises of 20 density detectors (plastic scintillators) of various sizes, spread around the hadron detector such that the farthest density detectors are located at about 40 m from the centre. There are four fast detectors (liquid scintillators) located at the corners of a rectangle of side 10 m which measure the relative delay between the particles in the shower front and thus determine the shower arrival direction. The hadron detector is a total absorption scintillation spectrometer (TASS) and consists of 750 g cm^{-2} of iron absorber in the form of 25 layers each of 30 g cm^{-2} interspersed with liquid scintillator tanks. Its design features and recording system have been discussed in detail by Ramana Murthy *et al.* (1963). In the present experiment nearly 300 g cm^{-2} of absorber in the top section of the spectrometer is not used to avoid contamination by the electron component as the latter may lead to an overestimation of hadron energy. Monte Carlo calculations have been performed to estimate the errors in the measured energy and the details of these calculations are discussed elsewhere (Tonwar 1970). It is estimated (Tonwar *et al.* 1971c) that the measured energies are accurate to about 30% for hadrons in the energy range 5–100 GeV. The contamination by low energy (say, $\sim$ 1 GeV) star like events occurring in the scintillation liquid to the number of high energy hadrons ($>$ 5 GeV) has been considered and shown (Tonwar *et al.* 1971c) to be negligible.

The arrival time of the hadron is measured by timing the hadron relative to the associated shower front. The measured time, in units of 7 ns, has a Gaussian type of error distribution with halfwidth of less than 7 ns (Tonwar *et al.* 1971c).

The data collected during 1968–69 have been classified into various groups according to the values of electron lateral structure parameter α, distance R of the hadron from the shower axis, shower size N_e and the hadron energy E_N. The time spectra for hadrons of different energies have been studied as a function of these parameters (Tonwar 1970, Tonwar *et al.* 1971c). While the spectra seem to be insensitive to the electron lateral structure as well as shower size, they show weak correlation with distance R and become flatter for hadrons located at larger distances from the shower axis. However, for hadrons contained within 20 m of the shower axis, the latter effect is negligible. It may be mentioned here that the errors in these shower parameters are too small to have any effect on the interpretation of the data. For example, it has been estimated (Tonwar 1970) that the uncertainty in the shower core location in the present data is less than ± 4 m. Considering these features the data have been combined together irrespective of the value of the parameters α, N_e and R except for some minimum or maximum limits on these values. These limits are as follows: $0{\cdot}4 < \alpha < 1{\cdot}9$, $6{\cdot}7 \times 10^4 < N_e < 1{\cdot}8 \times 10^6$ and $R \leqslant 20$ m. The time spectra obtained from these data for hadrons of three energy groups, 5–10 GeV, 10–20 GeV and 20–40 GeV are presented in figure 1. It is interesting to note from figure 1 that a significant fraction ($\sim 10^{-2}$) of hadrons of energy greater than 10 GeV is delayed by more than 10 ns which is not expected if the hadrons in air showers are predominantly pions.

3. Comparison of experimental results with theoretical predictions

The time spectra of hadrons have been calculated by the Monte Carlo method on the basis of different models of hadron collisions. The models considered here can be broadly classified into two groups.

(i) Fireball type: all the secondary particles are assumed to be decay products of two fireballs moving slowly in the centre of mass (cm) system in the same directions as the colliding hadrons. The nucleons are assumed to escape from the collision with decreased energy but in normal states. Typical examples of these types of models are those proposed by Cocconi *et al.* (1962) and Wayland *et al.* (1967).

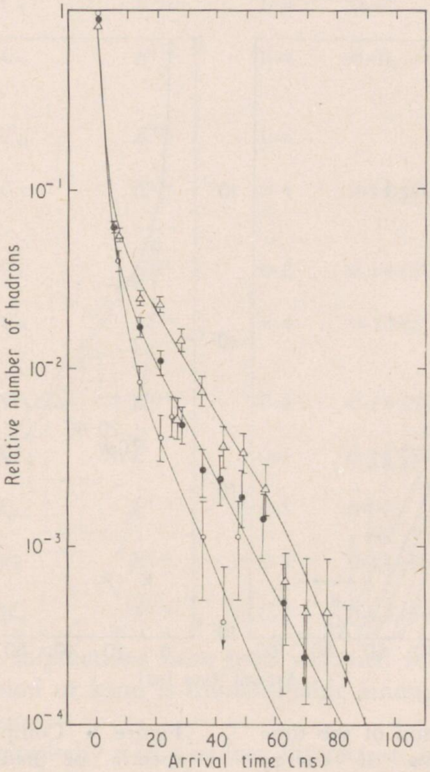

Figure 1. Arrival time spectra of hadrons of different energies falling within 20 m of axes of showers in the size range $6{\cdot}7 \times 10^4$–$1{\cdot}8 \times 10^6$ particles. The errors shown are statistical. The timing errors on the experimental points are shown later in figures 2 and 3 where the data is compared with calculations. The smooth lines which are just eye-fits have been drawn to illustrate the time structure dependence on hadron energy. ○ Hadron energy 5–10 GeV (4600 events); ● hadron energy 10–20 GeV (4070 events); △ hadron energy 20–40 GeV (2600 events).

(ii) Isobar type: the colliding nucleons emerge from the collision in excited states with very high probability. Also the nucleons lose only a small part of their energies in the interaction. This energy goes into the production of new particles which can be imagined as the decay product of a fireball at rest in the cm system or again as two fireballs moving rather slowly in the same system. The excited nucleons decay into two or more particles, including a baryon. Typical examples of such a model are those proposed by Pal and Peters (1964) and Koshiba (1969).

3.1. *Fireball type models*

First an attempt was made to see whether the experimentally observed time structure of hadrons could be reproduced by cascade calculations made within the

The recoil nucleon in pion–nucleon or kaon–nucleon interactions has been assumed to behave like a created particle and thus follows the distributions W_l^c and W_t^c as far as its longitudinal and transverse momenta are concerned. Though in kaon collisions the nucleon always goes backwards in the cm system, it has been assumed to emerge in the forward direction in a small fraction f_b of pion–nucleon interactions, to take into account the well known phenomenon of backward scattering. This fraction f_b has been assumed to decrease with energy E of the interacting pion according to the relation

$$f_b = 0{\cdot}05 \left(\frac{E}{10}\right)^{-2}.$$

The figure 0·05 has been chosen after considering the proton momentum spectra in π–p interactions reported by Daronian *et al.* (1968). These assumptions about the recoil phenomenon in pion or kaon collisions naturally lead to an overestimate of the recoil nucleon energy in the laboratory system and thus help in setting a lower limit for nucleon–antinucleon production in high energy hadron collisions. It is necessary to state that another assumption is implicit here according to which the hadron–nucleus interactions are essentially hadron–nucleon interactions.

C(vi) Among the particles produced in a hadron interaction a fraction f_K is considered to consist of kaons, charged as well as neutral. The fraction f_K is assumed to be energy dependent and follows the relation

$$f_K = 0{\cdot}14 \left(\frac{60}{E} + 1\right)^{-1}.$$

Thus while only 2% of the produced particles are kaons in collisions of hadrons of energy 10 GeV, this fraction increases to about 0·14 at 500 GeV where it gets saturated. All the prominent decay modes of kaons have been taken into account.

C(vii) The fraction of nucleon–antinucleons f_N has been assumed to be 1% of all the produced particles at all the energies. As will be discussed later the value of f_N is very significantly related to the hadron time spectra.

C(viii) The source particles of the air showers are assumed to be all nucleons.

These eight assumptions are sufficient to specify all the interaction details in the hadron cascade of the air showers. Among these assumptions those regarding the multiplicity $\bar{n}$ and p_{l*} distribution are akin to the assumptions in the model of Cocconi *et al.* (1962). It has been assumed that of all the pions produced in any interaction, on the average, one third are neutral. These neutral pions decay into two gamma rays, assumed to have equal energies, and generate the electromagnetic cascade. The contribution of each gamma ray to the number of electrons $N_e(E_\gamma, t)$ at the observational level is calculated using the relation given by Greisen (1956) as

$$N_e(E_\gamma, t) = 0{\cdot}31 \ln \left(\frac{E_\gamma}{E_0}\right)^{-1/2} \exp\{t(1-1{\cdot}5 \ln S)\}$$

where E_γ is the energy of the gamma ray, t is the amount of matter between the point of origin of the gamma ray and the observational level expressed in radiation lengths and E_0 (0·084 GeV) is the critical energy in air. S is the age parameter defined by the relation

$$S = 3t\left(t+2 \ln \frac{E_\gamma}{E_0}\right)^{-1}.$$

The contribution from all neutral pions produced at different levels to the size at the observational level is summed up to obtain the shower size.

With this model C_1, thirty showers were generated for a primary energy of 3×10^{14} eV. The average size for these showers is about 10^5 particles. It is seen from figure 2 that there is a wide discrepancy between the predicted time spectrum (C_1) and the observed one. This model predicts a charge to neutral (C/N) ratio among hadrons of energies greater than 10 GeV of about 11·4 which is too high compared to the experimental value of 2·9 given by Hinotani (1962). While the discrepancy regarding C/N suggests a higher nucleon content among hadrons in air showers, the discrepancy related to time spectra suggests in addition the need for producing relatively lower energy nucleons which can be expected to make the spectra flatter. Keeping the fraction f_N fixed at 1%, both these objectives are met to some extent if the shower originates from the collision of a heavy nucleus rather that a single nucleon. Thus in the next model C_2, the assumption C(viii) has been modified and the heavy nuclei (atomic number $A = 50$) have been taken as the source particles of air showers instead of nucleons. In calculations with heavy primaries the superposition assumption, which states that a shower initiated by a nucleus (A) of total energy E_0 is equivalent to a superimposition of A showers each initiated by a nucleon of energy E_0/A, has been made. The time spectrum predicted by this model C_2 (curve C_2 in figure 2), though flatter relative to that given by the previous model, is still too steep compared to the observed one. Also, though the predicted C/N ratio for hadrons of energy greater than 10 GeV decreases to a value of 8·5 with this model, the discrepancy with the experimental value (Hinotani 1962) still remains large. Considering the above discrepancies and the trend shown by the model C_2, it becomes necessary to assume that the fraction f_N of nucleon-antinucleons among the particles produced in high energy collisions, increases at higher energies. Thus in the next model C_3, the fraction f_N has been assumed to be energy dependent according to the relation

$$f_N = 0{\cdot}01\left(2\lg\frac{E}{10}+1\right). \qquad (1)$$

This relation makes nucleon-antinucelons to be 9% of all produced particles in collisions of hadrons of energy 10^5 GeV. In this model C_3, however, the primaries of air showers have been taken to be nucleons again as in model C_1. It is obvious that the assumption of pure heavy nuclei composition for primaries is too artificial and has been considered in model C_2 only to illustrate the effect of heavy nuclei primaries on hadron time spectra as well as C/N ratio. The predictions from the model C_3 are plotted in figure 2 as curve C_3. The hadron time spectrum for this model is distinctly flatter compared to the earlier two models, though still far short of fitting the observations. The discrepancy between the predicted C/N ratio and the measured values, however, narrows down considerably, thus suggesting the correctness of the hypothesis of increased nucleon–antinucleon production at higher energies. In order to improve the situation still further it has been assumed that the fraction f_N increases with energy at a faster rate than that given by the logarithmic relation used in model C_3. The relation used in the next set of calculations, labelled by model name C_4, is

$$f_N = 0{\cdot}14\left(\frac{500}{E}+1\right)^{-1}. \qquad (2)$$

This relation gives values of f_N as 0·003, 0·095, 0·14 at energies of 10, 10^3 and 10^5GeV respectively. It also assumes the saturation of the value of f_N at about 0·14 for energies greater than 10^{13} eV. The predicted time spectrum with this assumption is shown in figure 2 by curve C_4 which is clearly an improvement over the previous models when compared with observations. This model C_4 also predicts C/N ratios which are in good agreement with experimental values. For instance, this model gives a C/N ratio for hadrons of energy greater than 10 GeV of 2·6 compared to the observed (Hinotani 1962) value of 2·9. The predicted and observed (Kameda *et al.* 1965) C/N values for hadrons of energy greater than 500 GeV are 2·3 and $2{\cdot}5\ ^{+1\cdot5}_{-0\cdot5}$ respectively.

The results from the comparison of the calculations using model C_4 with observations indicate the need for decreasing the energy each hadron gets during the production process in such a way that it leads to the flattening of the time spectra without unduly affecting any other characteristic of air showers. This objective can be achieved in one of the following three ways. The first method achieves the objective by decreasing the available energy for the created particles while keeping their number in any interaction the same as before. This is possible if in nucleon–nucleon interactions the value of inelasticity is rather small (assumed to be 0·4 in model C_4). Thus in the next model C_5 the mean elasticity has been assumed to have the value of 0·2 with the fluctuations of similar type as specified in assumption C(ii) of model C_1. The predictions of this model, shown by the time spectrum plotted in figure 2 as curve C_5, justify the reasoning given above (as curve C_5 is flatter relative to C_4) but fail quantitatively to fit the observations. The second method of reducing the energy per particle in any creation process is indirect and consists of the assumption of heavy primaries as the dominant source of air showers. Assuming a composition of primary cosmic rays in the energy region around 3×10^{14} eV to be

$$\mathrm{P : He : C : S : Fe} = 20 : 30 : 20 : 20 : 10$$

the model C_6 (modification of C_4) predicts the time spectrum shown by the curve C_6 in figure 2. Again it is seen that the desired objective of flattening the time spectra is achieved but only to a limited extent. This may appear strange but it is possible to explain the failure of the model C_6 in flattening the spectra significantly in the following way. Since most of the hadrons in the relevant energy interval are produced relatively higher up in the case of heavy nuclei, they are naturally expected to be delayed more than the hadrons in showers initiated by lighter nuclei. However, due to this very fact they are also scattered far away from the axis of the shower due to the transverse momenta acquired in the interactions. Since the comparison with experimental data is restricted to time spectra for hadrons which are within 20 m of the shower axis, the heavy nuclei effect is neutralized by the transverse momenta effect and thus the hadron time spectra show little correlation, if any, with the composition of the primaries of air showers. It may also be mentioned that since the composition at these ultrahigh energies ($\sim 10^{15}$ eV) is not known experimentally, the relative composition assumed in model C_6 has been deliberately weighted towards heavier nuclei in order to exaggerate the effect of the composition.

Another possible method for reducing the average energy of the particles produced in high energy collisions as well as increasing their production heights consists of increasing the number of particles produced in any interaction. Since there is very little margin for any significant change in the assumed mean multiplicity at lower energies ($\sim$ 100 GeV) because of the available experimental data at these energies, the number of particles produced in any collision at higher energies can be increased only by assuming a faster increase of multiplicity with energy, for example, the relation of the type $\bar{n} \sim E^{1/2}$. However, as pointed out by many authors (eg Feinberg and Ivanenko 1969, Murthy *et al.* 1968), this energy dependence seems unlikely because various shower properties predicted by the calculations using this relation disagree with the available experimental data. It is necessary to point out here that this relation gives good agreement if the isobaric excitation is assumed for nucleon–nucleon interactions, as discussed later. Since in the present model excitations of the nucleons have not been considered, the relation $\bar{n} \sim E^{1/2}$ for multiplicity dependence has not been used to improve the fit of the predicted spectra with the experimental data.

It is evident from this study of the effects of various parameters of high energy interactions and composition of primary cosmic rays on time spectra of hadrons in air showers that the time spectra are sensitive only to the relative number of nucleons and other hadrons among the particles produced in high energy hadron collisions. It may seem possible to improve the fit to the experimental data with model C_4 if the nucleon production, as represented by the fraction f_N, is substantially increased, that is, f_N becomes as high as 0·4 at energies of the order of 10^4 GeV. However, there is a constraint imposed on the extent of nucleon production that can be assumed, by the existing experimental information on the value of C/N ratio among hadrons of different energies in air showers. It may be seen that for hadrons of energy greater than 500 GeV, the model C_3 which assumes the nucleonic component to be only 10% of all the secondaries in hadron interactions of 10^5 GeV energy, gives the C/N ratio as 4·21. The corresponding values from models C_4 and C_5 are 2·3 and 1·9. These values should be compared with the experimental value of $2\cdot5\ ^{+1\cdot5}_{-0\cdot5}$ given by Kameda *et al.* (1965). This clearly indicates that it is not advisable to increase the nucleon production beyond the value given by relation (2). Similar conclusions can be drawn from the comparisons of the values of the C/N ratio for hadrons of lower energies for which experimental data (Hinotani 1962, Chatterjee *et al.* 1969) exist.

In the fireball type of model as represented by the assumptions C(i) to C(viii), some more changes have been considered. As suggested by Wayland *et al.* (1967) in their 'two-temperature' model, the distributions of the longitudinal and transverse momenta of the particles emerging from hadron collisions have been assumed to be of the form

$$W_1{}^{\mathrm{w}}(p_{1*})\,\mathrm{d}p_{1*} = \frac{T}{m^2c^3}\frac{\Sigma_{K=1}^{\infty}(\exp(-K\mu_1/T)/K^{3/2})(1+K\mu_1/T)}{\Sigma_{K=1}^{\infty}\mathrm{K}_2(Kmc^2/T)/K}\,\mathrm{d}p_{1*}$$

$$W_1{}^{\mathrm{w}}(p_{\mathrm{t}})\,\mathrm{d}p_{\mathrm{t}} = \frac{p_{\mathrm{t}}\mu_2}{T_0m^2c^2}\frac{\Sigma_{K=1}^{\infty}\mathrm{K}_1(K\mu_2/T_0)}{\Sigma_{K=1}^{\infty}\mathrm{K}_2(Kmc^2/T_0)/K}\,\mathrm{d}p_{\mathrm{t}}$$

where $\mu_1{}^2 = p_{1*}{}^2+m^2$, $\mu_2{}^2 = p_{\mathrm{t}}{}^2+m^2$. Here T and T_0 are the temperatures characterizing the two momenta, m is the mass of the secondary particle and c is the velocity of light. K_1 and K_2 are the modified Bessel functions. The longitudinal temperature T increases with cm energy $E_0{}^*$ as $T = \text{constant}\,(E_0{}^*)^{1/4}$. The transverse temperature T_0 is independent of energy and its values have been taken for different types of particles as

$$(T_0)_{\text{nucleon}} = 0\cdot140\ \text{GeV} \qquad (T_0)_{\text{kaon}} = 0\cdot115\ \text{GeV}$$

$$(T_0)_{\text{pion}} = 0\cdot140\ \text{GeV}.$$

Of course, these expressions for W_1^w and W_t^w have been somewhat simplified in the calculations by making some assumptions in order to keep the computer time needed for generating a shower within reasonable limits. Thus the next model, called W_1, has only the assumption C(iv) different from model C_4 and predicts a time spectrum for hadrons of energy in the interval 10–20 GeV as shown in figure 2 by curve W_1 which follows exactly the curve C_4. This shows that minor changes in the momenta distributions for particles created in high energy interactions have no effect on the time spectra of hadrons. Similar conclusions can be drawn for many other properties of air showers.

It may be of interest to consider a change in the multiplicity–energy relation in this model W_1. Since some statistical theories (eg Hagedorn 1965) suggest a logarithmic dependence of mean multiplicity on the energy of the colliding hadron, model W_2 has been constructed from model W_1 by changing the relation $\bar{n} = 2{\cdot}7\, E^{1/4}$ to $\bar{n} = 1{\cdot}6 \ln E + 1{\cdot}1$. As the latter relation gives a lower number of secondary particles at higher energies relative to the $E^{1/4}$ law, it is expected that it will result in lowering the average height of production for hadrons of different energies and thus steepening the time spectra. This expectation is confirmed by the results of the calculations as shown in figure 2 by curve W_2. However, the difference between the two spectra W_1 and W_2 is rather small and it can be concluded that within the constraints imposed by the other assumptions of the present model, the predicted time spectra for hadrons are rather insensitive to the type of dependence of multiplicity on energy within certain limits.

All the models discussed so far belong to the fireball type since it has been assumed throughout that all the secondary particles are created from the decay of two fireballs. The nucleons have been assumed to emerge from the interaction region in their normal states but with diminished energy. It is clear from the discussion above that this picture of high energy hadron collisions is inadequate as far as the hadron time spectra are concerned. All these models predict time spectra that are too steep compared to the experimentally observed ones. It also seems evident from the discussion above above that while the predicted time spectra are insensitive to many interaction parameters like inelasticity, multiplicity and the shape of the momenta distribution, they are significantly affected by the assumed composition of the secondary particles, especially the relative amount of the nucleonic component.

In the second type of model, the isobar type, the main feature which is different from the models considered earlier, is the assumption of isobaric excitation of the nucleons in the nucleon–nucleon interactions. It has been assumed that in a majority of collisions, the colliding nucleons emerge from the interaction region in excited states and the latter subsequently decay into two or more particles. It is also assumed that the excited nucleons carry off the major part of the energy of the original nucleons, thus leaving only a small fraction of energy which goes into the pionization process. Thus such a collision results in the creation of a few high energy particles and many particles of much lower energy. This is in contrast with the situation in the fireball type of models where each nucleon–nucleon collision results in the creation of a single high energy nucleon and many intermediate energy particles. The isobar model used in the present calculations is based on the phenomenological model suggested by Pal and Peters (1964). The features of the nucleon excitation, as incorporated in the calculations can be briefly described as follows.

In 70% of the nucleon–nucleon collisions, the nucleons emerge in an excited state and the forward isobar in the laboratory system carries away 80% of the energy of the incident nucleon. The excited state decays into a nucleon and 1 to 3 pions depending on the interaction energy. For the sake of convenience the decay has been assumed to take place in steps such that each decay step gives rise to only two particles. Each particle in the rest frame of its parent state has been assumed to carry a momentum of 0·4 GeV/*c*. The laboratory momenta of these isobar decay products are thus computed kinematically after making the assumption that the isobars do not carry any transverse momenta. One third of the decay pions are assumed to be neutral. The pionization component gets only 20% of the energy of the incident nucleon. The number of particles produced by the pionization process is assumed to be linearly dependent on the cm energy of the colliding nucleons. Thus the mean multiplicity in a collision of a nucleon of energy E (laboratory system) is given by $\bar{n} = 0{\cdot}25\, E^{1/2}$. In the case of pion or kaon interactions, the mean multiplicity has been taken to be related to the energy E as $\bar{n} = 1{\cdot}0\, E^{1/2}$. It has been seen in a separate calculation that unless the recoil isobar gets transverse momentum much larger than 1 GeV/*c*, it has negligible probability of contributing any particle of energy greater than 5 GeV in the laboratory system. Since such a high value of transverse momentum seems unlikely to occur with any significant probability, the recoil isobar has been ignored in the present calculations. The rest of the details of the model have been assumed to be similar to those in model C.

With this isobar model the hadron time spectra have been calculated for two assumptions about the nucleon–antinucleon production. If it is assumed that the nucleonic component continues to be only 1% of all the secondaries irrespective of the interaction energy, the calculated time spectrum (curve P_1 in figure 2) for 10–20 GeV hadrons in showers of average size 10^5 is very similar to the predicted spectra from model C_1 of the fireball type. However, if the nucleonic component is assumed to increase with energy according to the relation (2) such that the nucleon–antinucleons constitute nearly 14% of the particles produced in collisions of hadrons of energy greater than 10^4 GeV, the calculated time spectrum is relatively very flat as shown by the curve P_2 in figure 2. It is evident that increase in the relative nucleon production is a necessity in this model also. Of all the models considered as yet the model P_2 seems to give the best fit to the observed time spectra. Though there are few experimental points which still lie above the predicted curve, this disagreement should not be overemphasized due to large statistical errors. It may be possible to improve the fit by increasing the nucleonic content from about 15% in the model P_2 to about 20% at higher energies. Such a change is highly unlikely to alter significantly any other characteristics of air showers including the C/N ratio. However, this case has not been considered here for the reason that the large errors in the present experimental data at large delays are not expected to allow any firm conclusion about the precise extent of nucleon production in the range 15–20%. With improved experimental data having better statistics as well as smaller timing errors it seems clearly possible to get a better estimate of the nucleon–antinucleon production in high energy hadron collisions.

As already pointed out a variant of the isobar model of Pal and Peters (1964) is the model proposed by Koshiba (1969). This model, called 'aleph + pionization' model, is based on the results from nuclear emulsion studies of families of high energy γ rays and other related phenomena. Koshiba has suggested that at energies of about 10^{12} eV and higher a new isobar 'aleph' is formed in nucleon–nucleon interactions whose mass is about 2 GeV/c^2 and which decays dominantly into kaons apart from a baryon. Thus the kaon to pion ratio among the decay products of 'aleph' is nearly unity. Further, the number of particles resulting from the pionization process have been suggested to increase with energy according to the quarter power law. This model has been incorporated into the present calculations but only partially in that only the latter suggestion about multiplicity has been used. The reason for ignoring the special decay properties of 'aleph' lies in the fact that at the highest energies, there is hardly any distinction between the kaon component and the pion component in the hadron cascade of an air shower provided the number of particles originating from the isobar decay is similar. As the latter condition is fulfilled, the only effect of ignoring the kaon contribution is likely to be felt on the high energy muon content of the air showers and not on the hadron time spectra. Thus model K_1 with all the features similar to the model P_2 except for the multiplicity law, assumed as $\bar{n} = 2{\cdot}7\, E^{1/4}$, can be considered a close approximation to the model suggested by Koshiba (1969). The predicted time spectrum for this model is shown in figure 2 by the curve K_1. The spectrum is obviously steeper than the one given by model P_2. This is not very surprising because of the reasons discussed earlier (decrease in the average production height). However, this study brings out an interesting possibility of distinguishing not only the model but also the possible multiplicity–energy relation if some other parameters like isobar decay channels can be reasonably well fixed on the basis of some experimental data. Also some reliable measurements on the kaon content of the hadronic component of the air showers can be useful. Some information on the kaon component can be obtained from a comparison of the calculations with the available data on high energy ($>$ 220 GeV) muons in air showers discussed by Sivaprasad (1971). However, at present the uncertainties in various parameters used in the calculations do not permit any definite conclusion regarding the kaon component.

Since the model P_2 remains the best model of all those considered in the present work for hadron energies of 10–20 GeV, it is interesting to see how the predictions of this model compare with experimental results for hadrons of other energies. In figure 3 are shown the predicted time spectra for hadrons of 5–10 GeV and 20–40 GeV along with the corresponding experimental data. The agreement is quite good for the lower energy hadrons if the assumption C(v) regarding recoil process and backward scattering is kept in view. However, for the higher energy group the predicted spectra disagree with the observations beyond about 15 ns. There are a few tens of events observed with energies of more than 20 GeV which are delayed by more than 25 ns. These events are discuseed in detail elsewhere (Tonwar *et al.* 1971a) and suggest the possible existence of heavy mass ($\sim$ 10 GeV/c^2) strongly interacting particles which have been predicted (see Gell-Mann 1964, Zweig 1964, Gursey *et al.* 1964, Maki 1964, Bacry *et al.* 1964) on the basis of higher symmetry schemes for elementary particles.

The 'isobar–pionization' model P_2 also reproduces satisfactorily other features of hadron time spectra. For instance it predicts the independence of the shape of time spectra of hadrons from shower size as observed experimentally. Also it gives good agreement for the observed correlation of time spectra with the distance of the hadron from the shower axis. It may also be mentioned that these calculations also predict many other properties of air showers which agree very well with the available data, for example, the energy spectrum of hadrons, the size dependence of the number of hadrons etc. The predicted C/N values for hadrons of threshold energies of 10, 25 and 500 GeV are 2·9, 3 and 3·2 respectively. These values should be compared with the corresponding observed values (Hinotani, 1962, Kameda *et al.* 1965, Chatterjee *et al.* 1969) of 2·9, $3{\cdot}3 \pm 0{\cdot}8$ and $2{\cdot}5\ ^{+1\cdot5}_{-0\cdot5}$. It is clear there is good agreement between the predicted C/N values and observed ones for hadrons of all energies.

Thus it is evident that while the fireball type of model, even with a reasonable amount of nucleon–antinucleon production is inadequate to explain the experimentally observed time structure of hadrons in air showers, the isobar–pionization type of model with a similar amount of nucleon–antinucleon production gives a fairly good fit to the experimental data. In the fireball model the surviving nucleons are the only high energy particles emerging from nucleon interactions; the other particles have relatively lower energies. Since the fraction of nucleon–antinucleons among secondaries is related to the energy of the colliding hadron, mainly these high energy nucleons are effective in producing nucleon–antinucleons, especially lower down in the atmosphere. However in the case of isobar–pionization models, the number of relatively high energy particles is higher at least up to a few kilometres above the observational level. Therefore the number of interactions producing a significant number of nucleon–antinucleons is correspondingly larger. Since the number of particles in each interaction is also large, the average energy per particle is smaller. These factors combined yield a higher number of low energy nucleons a few kilometres above the observational levels which naturally get delayed by relatively large amounts of time, thus leading to the flattening of the time spectra. It may be of interest to note that according to this picture, about 30–40 nucleon–antinucleons are produced in a nucleon–nucleon interaction of energy approximately 10^{15} eV having a total multiplicity of about 250 hadrons.

4. Conclusions

The present study shows that the arrival time spectra of hadrons in air showers are rather sensitive to the mechanism of particle production at high energies. With the data available at present on high energy hadron collisions, two distinct class of models have been proposed by various authors, the fireball type and the isobar–pionization type. Comparison of the time spectra calculated on the basis of these models with the observed spectra clearly shows that the fireball type of models are not favoured by the experimental data and the isobar type of models reasonably succeed in understanding the observations on time spectra. It is to be emphasized that it is necessary to increase the nucleon–antinucleon production relative to other particles in hadron collisions at higher energies to achieve a good fit for the time spectra and also to explain the results on the charged to neutral ratio among hadrons in air showers. Further detailed studies of time spectra of hadrons in air showers also hold the promise of establishing the existence of heavy mass hadrons (mass $\simeq 10$ GeV/c^2) which are predicted by the higher symmetry schemes for elementary particles since, in the present investigation, some of the data can most readily be accounted for by assuming the presence of such particles in the air showers.

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