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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 $6{\cdot}7\times10^4$–$1{\cdot}8\times10^6$ 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 ($\mathrm{N\bar{N}}$) 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 $\mathrm{N\bar{N}}$ 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: $0{\cdot}4 < \alpha < 1{\cdot}9$, $6{\cdot}7\times10^4 < N_e < 1{\cdot}8\times10^6$ 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).

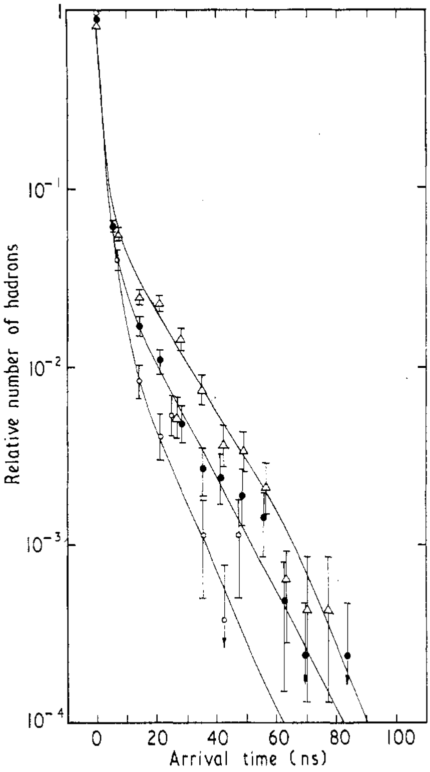
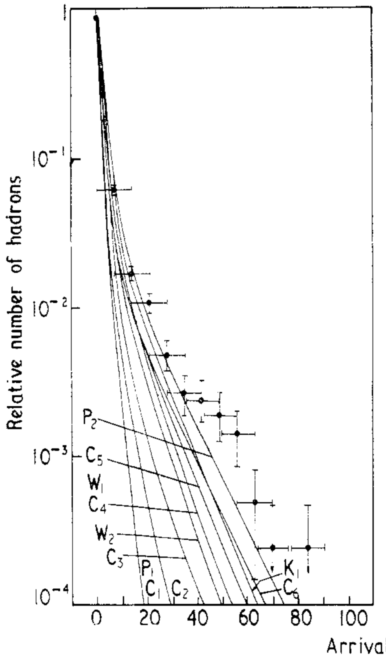


Figure 1. Arrival time spectra of hadrons of different energies falling within 20 m of axes of showers in the size range $6\cdot7\times10^4$–$1\cdot8\times10^6$ particles. The errors shown are statistical. The timing errors on the experimental points are shown later in figures 2 and 3 where the data 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 framework of pure fireball type models by varying the functional forms of the various interaction parameters or the composition of the primary particles initiating the air showers. Table 1 summarizes the salient features of the various models considered in the calculations. Figure 2 gives the time spectra for hadrons of 10–20 GeV obtained from these calculations for different models along with the experimental results.



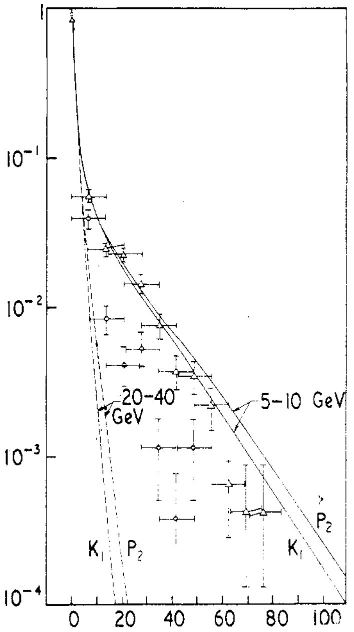


Figure 2. Comparison of the time spectra of hadrons of energy 10–20 GeV obtained from Monte Carlo calculations using different interaction models with the observations. The timing errors are Gaussian. The experimental data ⊹ is presented after folding the error distribution for the point corresponding to zero time.
$6{\cdot}7 \times 10^4 < N_e < 1{\cdot}8 \times 10^6$;
$R \leqslant 20$ m.

Figure 3. Comparison of the time spectra of hadrons of energies 5–10 and 20–40 GeV obtained from Monte Carlo calculations using 'isobar–pionization' type models (K_1 and P_2) with experimental data. The errors have the same significance as in figure 2. ⊹ Hadron energy 5–10 GeV, experiment; ⊹ hadron energy 20–40 GeV, experiment.
$6{\cdot}7 \times 10^4 < N_e < 1{\cdot}8 \times 10^6$;
$R \leqslant 20$ m.

Let us consider the model C_1. The general assumptions and the functional relations for some of the parameters are as follows:

C(i) the interaction cross sections for hadron–air nucleus collisions are independent of the hadron energy. The interaction mean free paths for different hadrons are taken as $\lambda_{\text{nucleon}} = 80$ g cm^{-2}; $\lambda_{\text{kaon}} = 120$ g cm^{-2} and $\lambda_{\text{pion}} = 120$ g cm^{-2}.

C(ii) the interactions of nucleons are characterized by an inelasticity parameter η whose average value has been assumed to be 0·4. Thus, on the average, the colliding nucleon loses only 40% of its energy in an interaction. In an individual interaction, however, η can have a value within $\pm 0{\cdot}2$ from its average value, that is, $\eta = 0{\cdot}4 \pm 0{\cdot}2$.

Table 1. Salient features of interaction models used in the calculations

Model type	Model name	Fireball multiplicity	Mean nucleon inelasticity	Nucleon fraction f_N N/(π+K+N)	Source particle
Fireball, Cocconi *et al.* (1962)	C_1	$E^{1/4}$	0·4	0·01	nucleon
Fireball, Cocconi *et al.* (1962)	C_2	$E^{1/4}$	0·4	0·01	nuclei (A = 50)
Fireball, Cocconi *et al.* (1962)	C_3	$E^{1/4}$	0·4	ln E	nucleon
Fireball, Cocconi *et al.* (1962)	C_4	$E^{1/4}$	0·4	$0{\cdot}14\,(500/E+1)^{-1}$	nucleon
Fireball, Cocconi *et al.* (1962)	C_5	$E^{1/4}$	0·2	$0{\cdot}14\,(500/E+1)^{-1}$	nucleon
Fireball, Cocconi *et al.* (1962)	C_6	$E^{1/4}$	0·4	$0{\cdot}14\,(500/E+1)^{-1}$	nuclei (mixed)
Fireball, Wayland *et al.* (1967)	W_1	$E^{1/4}$	0·4	$0{\cdot}14\,(500/E+1)^{-1}$	nucleon
Fireball, Wayland *et al.* (1967)	W_2	ln E	0·4	$0{\cdot}14\,(500/E+1)^{-1}$	nucleon
Isobar, Pal and Peters (1964)	P_1	$E^{1/2}$	$\simeq$ 0·5	0·01	nucleon
Isobar, Pal and Peters (1964)	P_2	$E^{1/2}$	$\simeq$ 0·5	$0{\cdot}14\,(500/E+1)^{-1}$	nucleon
Isobar, Koshiba (1969)	K_1	$E^{1/4}$	$\simeq$ 0·5	$0{\cdot}14\,(500/E+1)^{-1}$	nucleon

The pion and kaon interactions have been assumed to be completely inelastic and thus the original pion or kaon is unidentifiable among the particles emerging from the interaction region.

C(iii) The mean multiplicity $\bar{n}$ in a hadron interaction is related to the energy E (in GeV) of the colliding hadron by the quarter power relation as $\bar{n} = 2{\cdot}7\,E^{1/4}$. The fluctuations around this mean value, in individual interactions, are assumed to follow the nearly Gaussian distribution of the type $n \exp(-n^2/\alpha^2)$, where n is the multiplicity in the particular interaction and α is related to the mean multiplicity. This type of distribution has been shown (Bozoki *et al.* 1969) to fit the experimental data at accelerator energies.

C(iv) Since all the interactions are considered in the centre of mass system, the longitudinal momenta p_{1*} and transverse momenta p_t for the created particles have been assumed to follow the distributions

$$W_1^c(p_{1*}) \sim \exp(-ap_{1*})\,dp_{1*} \qquad W_t^c(p_t) \sim p_t^{3/2}\exp(-bp_t)\,dp_t.$$

The average transverse momenta ($= 5/2\,b$) have been assumed to have values of 0·40, 0·49 and 0·59 GeV/c for pions, kaons and nucleons respectively. The average transverse momenta have also been assumed to be independent of the energy of the colliding hadron. The constant a in the expression for W_1^c is determined by the conservation laws in individual interactions.

C(v) The recoil nucleon in nucleon–nucleon interactions has been assumed to have the same characteristics as the forward going surviving nucleon, that is, values of p_{1*} and p_t are the same except for the negative sign for p_{1*}.

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_{1*} 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

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

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

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

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

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

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 $2{\cdot}5\,^{+1\cdot5}_{-0\cdot5}$ 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 = 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

$$(T_0)_{\mathrm{nucleon}} = 0{\cdot}140\ \mathrm{GeV} \qquad (T_0)_{\mathrm{kaon}} = 0{\cdot}115\ \mathrm{GeV}$$

$$(T_0)_{\mathrm{pion}} = 0{\cdot}140\ \mathrm{GeV}.$$

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, $3·3 \pm 0·8$ and $2·5\,^{+1·5}_{-0·5}$. 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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