TIME STRUCTURE OF THE HADRONIC COMPONENT OF EXTENSIVE AIR SHOWERS

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Abstract

A detailed study of the time structure of hadrons of energy > 5 GeV in extensive air showers has been carried out at Ootacamund ($8 \cdot 00$ gm/cm^2) using a total absorption spectrometer at the centre of the T.I.F.R. air shower array. A comparison of the experimental results with theoretical calculations shows that the experimentally observed spectra can be explained only on the basis of a rather large production ($\sim 15\%$) of nucleon-antinucleon pairs among the secondaries of high energy interactions. Also it has been shown that an isobar-*cum*-pionisation type of model is preferred to a pure pionisation model in ultra high energy interactions. A small fraction of hadrons ($\sim 0 \cdot 5\%$) of energy > 20 GeV are found to arrive considerably delayed (> 25 ns) with respect to the shower front. While these are indicative of the presence of heavy mass particles (M ~ 10 GeV/c^2) among the hadrons in air showers it is concluded experiments of a more direct nature are essential for establishing the production of heavy mass particles.

In this paper all the details regarding the experimental set up, the procedures for classification and analysis of data and the methods adopted for the evaluation of the errors in the measurement of energy and time delay are presented and the main conclusions from the experimental results summarised. Details of calculations of the time structure functions on the basis of different models of high energy interactions and a critical discussion of the comparison of the experimental results with theoretical predictions are presented elsewhere.

1. Introduction

Experimental studies on extensive air showers have been confined mostly to the determination of the energy spectra and lateral distributions of the electrons, muons and hadrons at the observational levels of mountain altitude and sea-level. Very little information exists on the time structure or the relative delays between these components. Though the propagation time of an extensive air shower through the atmosphere is of the order of a few tens of microseconds, an overwhelmingly large fraction of particles in the regions not far from the shower core are contained in a narrow disc of thickness of about 1–2 metres with the consequence that the relative delays between the particles are only of the order of a few nanoseconds. This was established in 1953 by Bassi *et al.*[1] who exploited the narrowness of the shower disc for the purpose of determining the arrival direction of air showers by measuring the relative delays between the particles separated by few tens of metres along the shower front. Bassi *et al.*,[1] also showed that the penetrating particles in air showers are delayed by about 10 nanoseconds with respect to the shower front. Recently, the arrival time of muons in air shower has been studied by Blake *et al.*[2] to obtain the approximate production height of muons.

It is obvious that the hadronic component of air showers consisting of pions, kaons and nucleons being more massive than the electrons and muons should trail behind the shower front. The time lag of these particles depends on their characteristics like the mass, the energy, the production height and the zig-zag nature of their path in the atmosphere due to the transverse momenta acquired by them in the interaction processes. However, no investigation on the time structure of hadrons was carried out till 1965 when suddenly there was a spurt of interest in looking for delayed particles in air showers as evidence for the production of heavy mass particles, like the quarks, which had been postulated by Gellmann[3] and Zweig[4] on the basis of higher symmetry schemes of elementary particles. Several experiments[5] have been carried out since 1965 in search of these delayed particles in air showers. The experiment of Chatterjee *et al.*[6] carried out with the T.I.F.R. air shower array at Ootacamund in 1965 which also was motivated by similar considerations, showed that a detailed and comprehensive study of the time structure of hadrons would be highly rewarding not only from the point of view of the search for heavy mass particles, but also from the point of view of unravelling the extent of nucleon-antinucleon production in high energy interactions. It was realised that for this purpose it was necessary to improve the time resolution in the measurement of delay and also record a sufficiently large number of showers to enable detailed classification in terms of the various shower parameters and hadron energies. In this paper we report in detail the experimental aspects of the improved version of the 1965 experiment, also carried out at Ootacamund (altitude of 800 g cm^{-2}) and present briefly the main results on the characteristics of high energy interactions deduced from the time structure study. More detailed and comprehensive discussions on the experimental results have been presented elsewhere.[7–10]

2. EXPERIMENTAL ARRANGEMENT

The experimental set up consists of an air shower array and a hadron detector. The array shown in Fig. 1, has 20 density detectors, which are plastic scintillators of 5 cm thickness, spread around the hadron detector. The farthest detectors are located at about 40 m from the hadron detector. Each plastic scintillator is viewed by a 5″ photo-multiplier (DUMONT 6364) from a distance of about 60 cm. The pulse height data from these detectors are punched on paper tape in a logarithmic mode. The array also has five fast detectors, CH0, CH1, CH2, CH3 and CH4, for the measurement of the arrival direction of the shower. These detectors consists of 0·5 m² liquid scintillator (25 cm thick column of Toluene mixed with paraterphenyl and POPOP) and a 2″ photomultiplier (RCA 6810 A or Philips 56 AVP) with its face dipping slightly into the liquid. The relative times between the pulses from these detectors are measured for every recorded shower using a chronotron system.

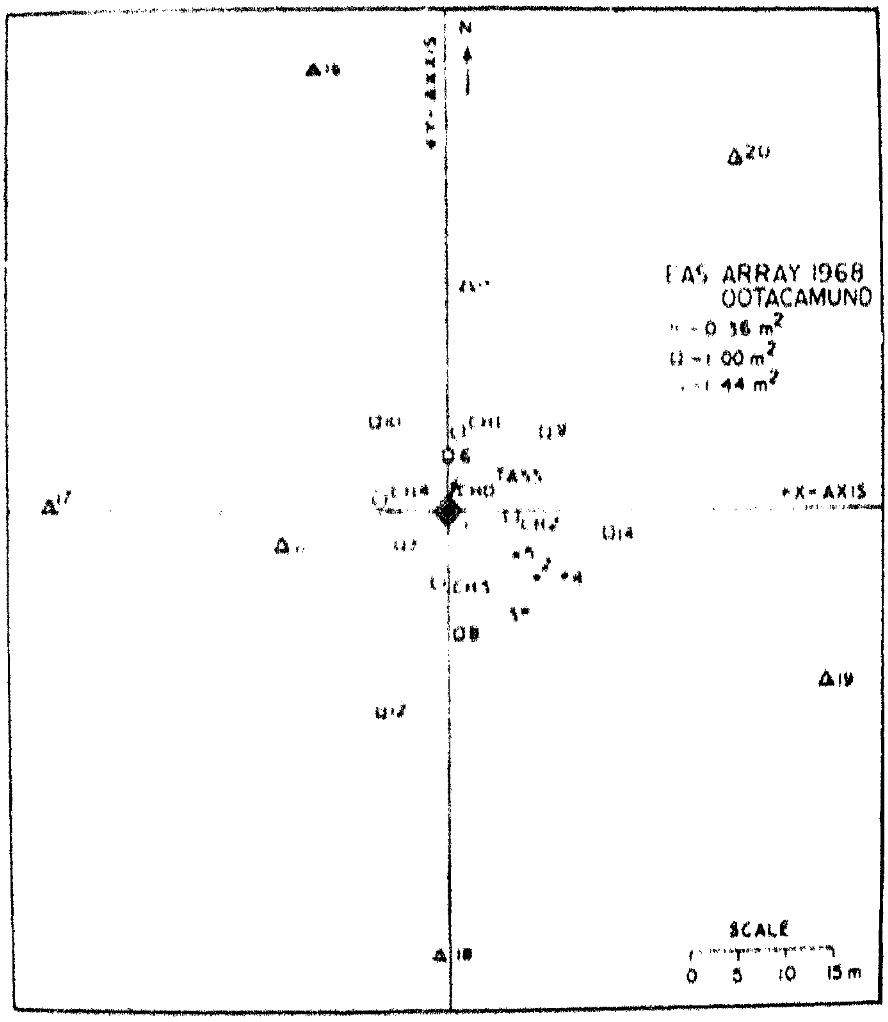
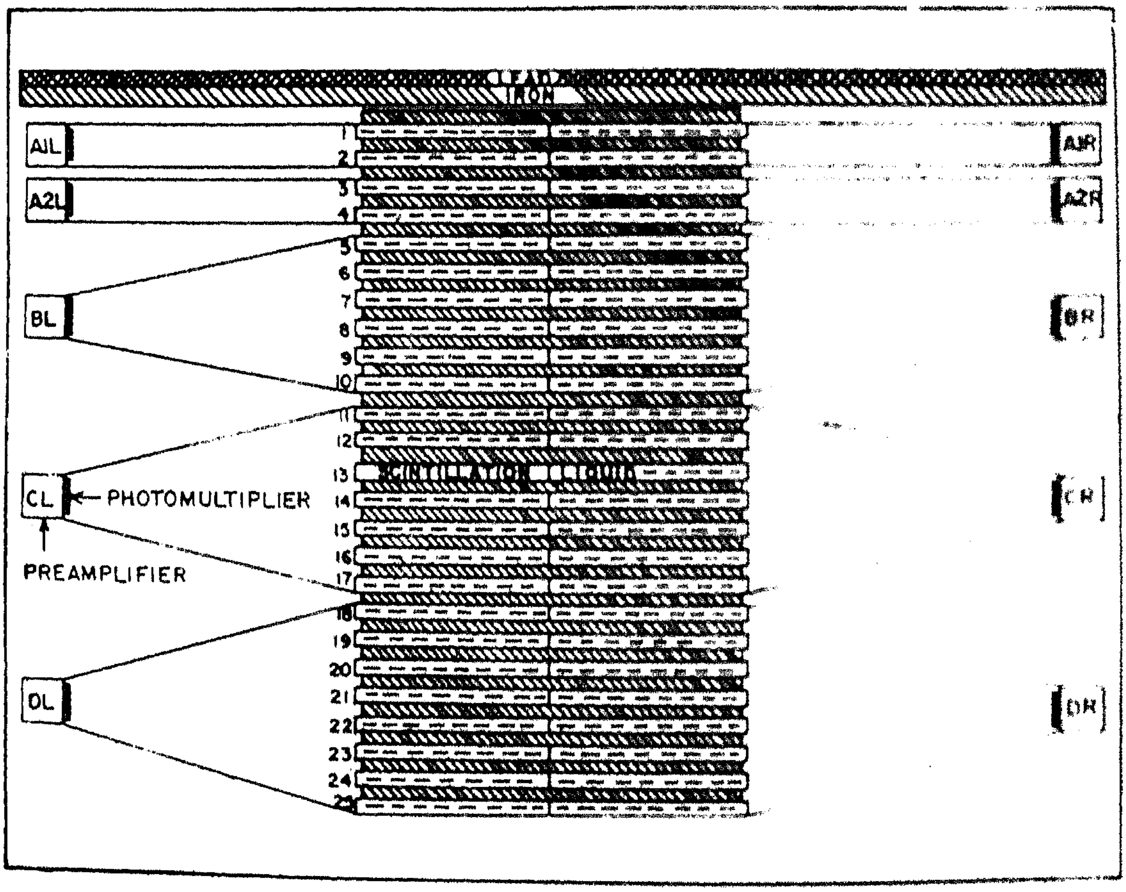


FIG. 1 Experimental Arrangement.

The hadron detector is a total absorption scintillation spectrometer (TASS) and has been described in detail by Ramana Murthy *et al.*[11]. The essential features of the TASS are shown in Fig. 2. It consists of 25 layers of iron, each 3·75 cm thick (30 gm/cm²) and area 120 × 120 cm², placed vertically over each other with a gap of about 4 cm between adjacent layers. In every gap between the iron plates and also below the lowermost plate, there are two liquid scintillation tanks. The tanks, each of area 114 × 64 cm² have a stepwise structure that ensures uniformity of light response. They are provided with glass windows on the front side for viewing. The scintillation liquid is Shellsol A, with paraterphenyl (3·5 gm/litre) and the wavelength shifter POPOP (5 mgm/litre) dissolved in it. The fifty tanks are viewed by a system of 10 photomultipliers and the mode of grouping of these tanks for being viewed by these 10 photomultipliers is shown in Fig. 2. The TASS is shielded on the non-viewing sides by a wall of 2·5 cm lead and 5 cm iron. There is also a shielding on the top of TASS consisting of 3·8 cm lead and 4·5 cm iron. The shielding on the top extends on the viewing sides upto



A CROSS-SECTIONAL VIEW OF TASS WITH PHOTOMULTIPLIERS

FIG. 2. A cross-sectional view of the Total Absorption Scintillation Spectrometer (TASS).

a metre from the edge of the TASS and is thus effective for the absorption of low energy particles with angles less than 30° with respect to the vertical. The pulse height data from the 10 photomultipliers are also recorded on paper tape in a logarithmic mode. Apart from the 10 photomultipliers shown in Fig. 2, there are 4 more fast photomultipliers (2″ diameter, Philips 56 AVP) which view the channels CL, DL, CR and DR respectively. These are mounted adjacent to the 5″, DuMont 6364 photomultipliers. The pulses from these four fast photomultipliers are used exclusively for timing the delay of the hadrons responsible for the ionisation in these channels. For this purpose the delay of the pulse that is obtained by mixing the outputs of the four channels CL, DL, CR and DR is measured relative to the pulse from the fast detector CHO situated on the top of the TASS which has no shielding and which is triggered mostly by shower electrons.

3. MEASUREMENT OF HADRON ENERGY WITH TASS

The principle of the TASS for the measurement of the energy of the hadrons, the calibration procedures, the errors of measurement, etc., have been discussed in detail in the paper of Ramana Murthy *et al.*[11] and also in the thesis of Tonwar.[7] The relevant essentials may be summarised as follows. The hadron in passing through the layers of iron and liquid scintillators suffers nuclear collisions producing secondary hadrons which for lower primary energies ($\lesssim$ 100 GeV) consist mainly of charged and neutral pions. The charged pions either interact and give rise to more pions or get absorbed in the instrument due to ionisation losses. Due to the condensed nature of the absorber, the decay probability for these charged pions within the absorber is relatively small. The neutral pions decay into gamma-rays which develop into electromagnetic cascades. The low energy electrons get absorbed due to ionisation losses. Some part of the energy of the incident hadron also goes into nuclear disintegrations. The disintegration products, mostly nucleons and light nuclei, are absorbed within a small amount of absorber due to their high rate of energy loss by ionisation. Thus practically all the energy of the incident hardon is converted into energy of ionisation in the TASS. The ionisation is sampled after every 3·75 cm of iron by the intervening liquid scintillators. The total energy of ionisation so sampled by the liquid scintillators is proportional to the total ionisation in the instrument which is just the total energy of the incident hadron. The calibration of the instrument consists in relating the observed pulse height in the scintillators to the ionisation energy loss due to relativistic muons traversing through the TASS in the near vertical direction.

4. ERRORS IN THE MEASUREMENT OF HADRON ENERGY

The errors in the measurement of hadron energy with the TASS are of the following two types:

(i) those due to calibration procedure and the logarithmic mode used for recording of pulse heights;

(ii) those due to the finite size, the striated non-homogeneous structure and the finite number of sampling scintillators in TASS and also due to the lack of information on the point of entry of the hadron into the TASS.

As already mentioned the calibration of the scintillators is carried out by triggering the TASS during part of the run for single cosmic ray muons going through it. Since the photomultipliers are nearly a metre away from the front face of the spectrometer, the light collection efficiency, though uniform, is rather poor and the pulse height distribution due to single particles has an FWHM of about 20%. In the operation of the TASS for adrons however, since the minimum energy considered is about 5 GeV which corresponds to the passage of about 10 relativistic muons, the light output is considerably more and the errors are much less.

In order to cover a wide range of energy the logarithmic system of recording the pulse heights has been used. In this system the pulse from the scintillator photomultiplier is shaped to an exponential form with a decay time of about 10 μs and the width of the pulse corresponding to a preset amplitude is measured. This width is proportional to the logarithm of the pulse amplitude. If a second pulse, even a small one, arrives in the time interval 10–40 μs, and overrides the exponential tail of the main pulse, then the pulse width is stretched leading to an over-estimation of the pulse amplitude. The second pulse could be due to a delayed low energy particle associated with the shower itself or it could be due to a chance coincidence of cosmic ray muons. It has been possible, however, to determine experimentally the exact amount of over-estimation that occurs *on the average* and also the frequency of occurrence of considerably large over-estimation. During the runs, for a short time two of the ten channels of TASS were connected simultaneously to the logarithmic mode of recording and to a system recording the pulse height in a linear mode. This provided the cross-calibration between the two modes for these two channels. Similar calibrations were obtained for all the ten channels by rotation. The comparison of the pulse heights recorded with the two systems showed that, *on the average*, the logarithmic system over-estimated the pulse height by about 20%. In about 3% of the cases the over-estimation was by a factor of 2 or more but only in less than 0·2% of the cases the over-estimation was by a factor of more than 4.

The second type of error which arises mostly due to the limitations imposed by the design of TASS cannot be estimated directly without the help of a high energy accelerator. For the range of energy of interest here, *viz.*, 5–50 GeV, the finite amount of matter of TASS of 750 g cm^{-2} does not lead to any significat error since this amount of matter is more than adequate to absorb all the energy of the hadron. Even for hadrons entering the TASS from the sides, 80–90% of their energy is absorbed in the TASS so long as the hadrons enter it above or close to the C channel. The fraction of the hadron energy which is inefficiently sampled by the TASS is the energy going into the disintegration of iron nuclei. Since the amount of matter in the form of iron is about 15 times that in the form of scintillation liquid, majority of the interactions for a low energy, say 20 GeV hadron, take place in the iron without there being corresponding interactions in the scintillator. This follows from the fact that a 20 GeV hadron cascade in the TASS has only about 10 hadron interactions in it and thus the chance of even one interaction taking place in the scintillation liquid is less than unity. Further, even for interactions that take place in the liquid, the 'grey' particles (~ 100 MeV) resulting from disintegrations escape to the nearest iron layer, losing only a small amount of energy in the liquid. Only the 'black' particles (~ 20 MeV) *i.e.*, the evaporation protons, the α-particles and the heavier nuclei, lose most of their energy in the liquid itself. The organic scintillators have a very low light yield for high rate of energy loss and therefore the energy loss due to the heavy fragments is not sampled proportionally by the scintillators, and thus the measured energy is an under-estimate. The correction factor can, in principle, be obtained directly by calibrating the TASS using an accelarator beam giving out particles in the tens of BeV range. Since no such accelerator is available in India, as an alternative Monte Carlo calcul.tions[7,12] of cascades, both hadronic and electromagnetic, were simulated for the TASS assembly using a computer. The parameters characterising the hadron interactions in the energy rangeof interest, *i.e.*, 10–100 GeV used in the calculations are only broadly known. However, it has been seen that the results of the calculations are insensitive to finer changes in these parameters and thus the conclusions derived from these calculations about the accuracy in energy measurement using TASS do not suffer from any serious uncertainty. In these calculations the heavily ionising particles resulting from nuclear disintegrations have been taken into account through plausible assumptions based on available experimental data. The calculations show that the ionisation energies sampled in the various sections, A, B, C and D of TASS when converted to primary energy is about 60% of the actual energy of the incident hadron, and thus on the average the energy that goes *unsampled* because of the reasons discussed above is about 40% of the total energy. Thus the measured energy should be multiplied by a factor of 1·6 to correct for the unsampled energy losses. The error in this factor, as seen from the distribution of the calculated energy around the average is about 30%. Since the logarithmic mode of pulse height measurement gives an over-estimate of the energy by a factor of 1·2 as discussed above, the true energy of the hadron can be obtained from the measured energy by multiplying it by a factor of 1·6/1·2 $\sim$ 1·3. Since the uncertainties in these compensating factors are large, the measured energy was not multiplied by this factor of 1·3 and has been taken as such to represent the true energy of the hadron.

Yet another factor which also gives rise to a systematic under estimate in the energy determination in the average picture is the following. For reasons of better shielding and protection against the contamination from the soft component as much as possible, only the botton two sections C and D, were used in the computation of the energy of the hadron. These two channels together offer about 450 g cm^{-2} of iron and 15 sampling scintillators which are quite adequate for the development and absorption of cascades in the 5–40 GeV energy range and for their efficient sampling as indicated by the results of the Monte Carlo calculations. Since in the experiment hadrons in air showers having a zenith angle upto 30° were accepted, nearly 75% of the hadrons were incident at the TASS from the sides skipping the section A completely and part or whole of section B. For these hadrons the relation between the measured energy and the total energy can be taken to be the same as for the whole TASS, for reasons mentioned above. For the remaining 25% of hadrons which enter the TASS from the top, the calculations show that the C and D channels will measure only 0·35 of the actual energy of the hadron. However, it is to be noted that since the criteria for selection of events are based on the energy released in the C and D channels, many of the hadrons that enter from the top and interact very close to the top and lose a major part of their energy before arriving at the C channel, are likely to be rejected. Those that do get selected will naturally be of much higher energy and because of the steep differential energy spectrum ($\sim E^{-2}$) for the hadrons in air showers in the 10–50 GeV energy range, this contamination from the higher energy events will be small. Thus the measured energy can be still taken as within ~ 30% of the actual hadron energy.

It is clear from the above considerations that since no correction factor is applied to the measured energy, the energy of the hadron obtained finally is, *on the average*, a systematic under-estimate by about 30%. It is necessary to stress this particular point since some of the new experimental results that have been obtained in this investigation are only sensitive to the lower limit of energy and not to the exact energy. Since relatively large widths (factor of 2 or more) have been used for the energy bins while studying the arrival time spectra of hadrons, the under-estimate by ~ 30% is not of much consequence. As mentioned earlier the statistical accuracy of the energy obtained is about ± 30%. The possibility of an over-estimation of energy in a few individual cases due to either large error in the logarithmic mode or due to exceptionally large energy release in the scintillator liquid is discussed later in relation to large delay-large energy events which are rather rare and do not affect the average picture.

5. MEASUREMENT OF ARRIVAL TIME

The pulses from the four timing TASS photomultipliers (56 AVP) are mixed together, amplified, discriminated and shaped to give a single triangular pulse of about 20 ns width at the base. This pulse is timed relative to the pulse from the fast shower detector CHO by a chronotron system schematically shown in Fig. 3. The meeting point of the two pulses on the "sorter cable" (consisting of 14 pieces of BICC 3038 cable, each 60 cm long) determines the delay of the hadron pulse. The shift of the meeting point from one junction of the sorter cable to the next junction corresponds to a change of relative delay of 7 ns. Each junction on the sorter cable is connected to a biased amplifier followed by flip-flops, and the information from the 15 junctions is recorded on the paper tape in a 'yes-no' code. If the meeting point happens to be inbetween two junctions a 'yes' is recorded at both of them. For a hadron which is time-coincident with the shower electrons (no delay) the meeting point of the pulse occurs at a particular junction called the 'zero delay' unit. The 'zero delay' unit is fixed by an auxiliary experiment in which the delay between CHO and an additional shower detector placed adjacent to it is measured. The photomultiplier and the associated electronics for this detector which is a plastic scintillator ($0 \cdot 36\ \mathrm{m}^2$ in area, and 10 cm thick) is taken from each of the 4 timing channels of the TASS in succession. The 'zero delay' unit is adjusted to be same for all the four

TASS channels by adjusting the length of the intermediate cable for each channel. It may be mentioned that since both the systems, CHO as well as the second scintillator are subject to errors due to rise time of pulses, jitter in the photomultiplier, etc., the zero delay point has a distribution

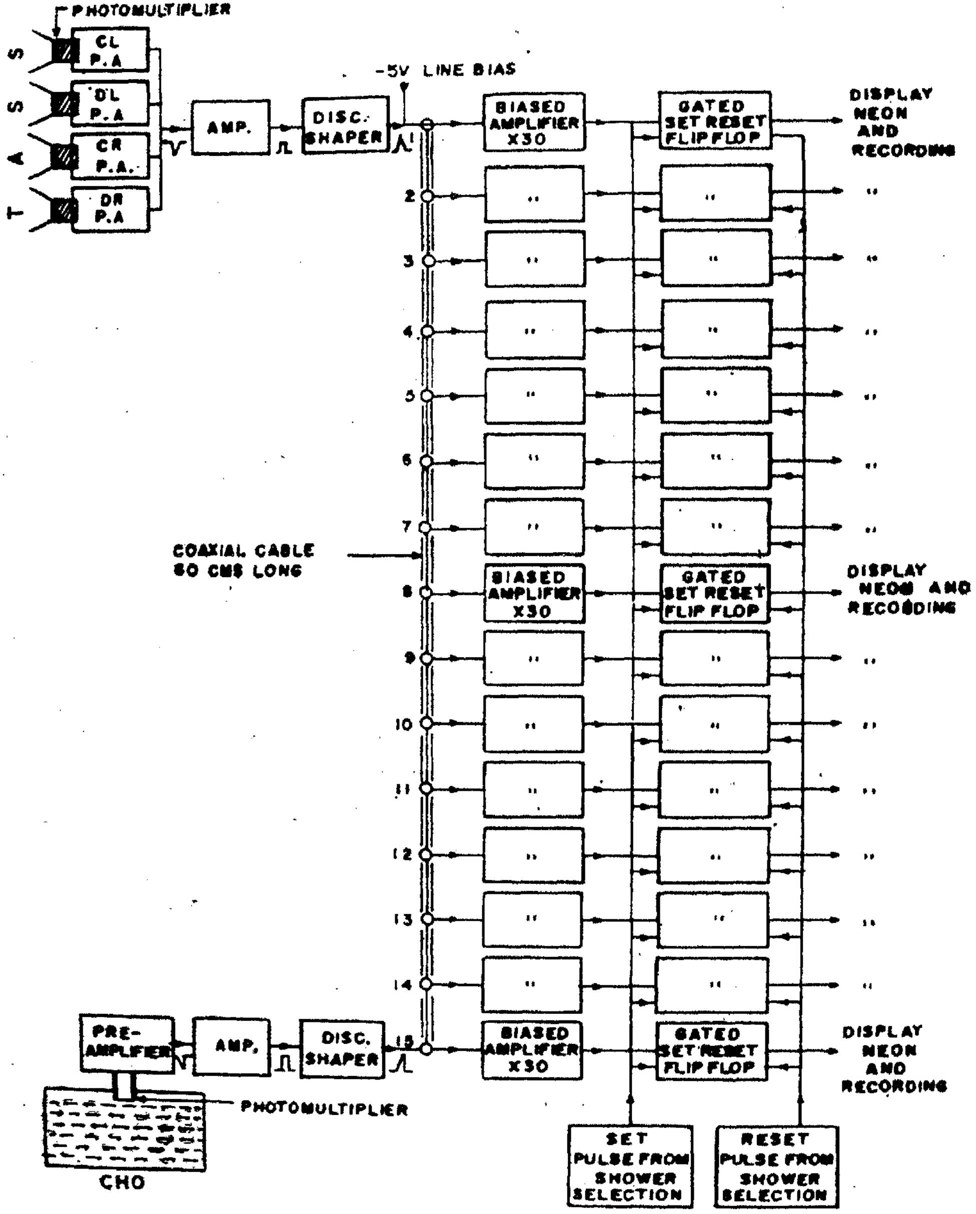


FIG. 3. Schematic diagram of the chronotron system for measurement of arrival time of the hadron signal from TASS relative to the singal from the shower detector CHO.

which is approximately Gaussian with a half-width of 0·5–0·8 unit. This distribution is sown in Fig. 4 for the four TASS timing systems when these were triggered by the shower particles. It has been found that the averages of these distributions are independent of the number of particles traversing the detectors though the distributions tend to be broader for decreasing particle density. Regular checks are carried out to ensure that the average values do not drift due to changes in the photomultiplier characteristics or in the electronics. Thus this average junction number provides the reference point for the measurement of arrival time of hadrons in air showers. The measurement of the delay of hadrons involves the errors due to (i) the finite rise time of the CHO pulse and jitter in the CHO photomultiplier, and (ii) similar causes in the TASS timing system. For obtaining the estimates of errors arising due to these two sources separately, the following procedure is

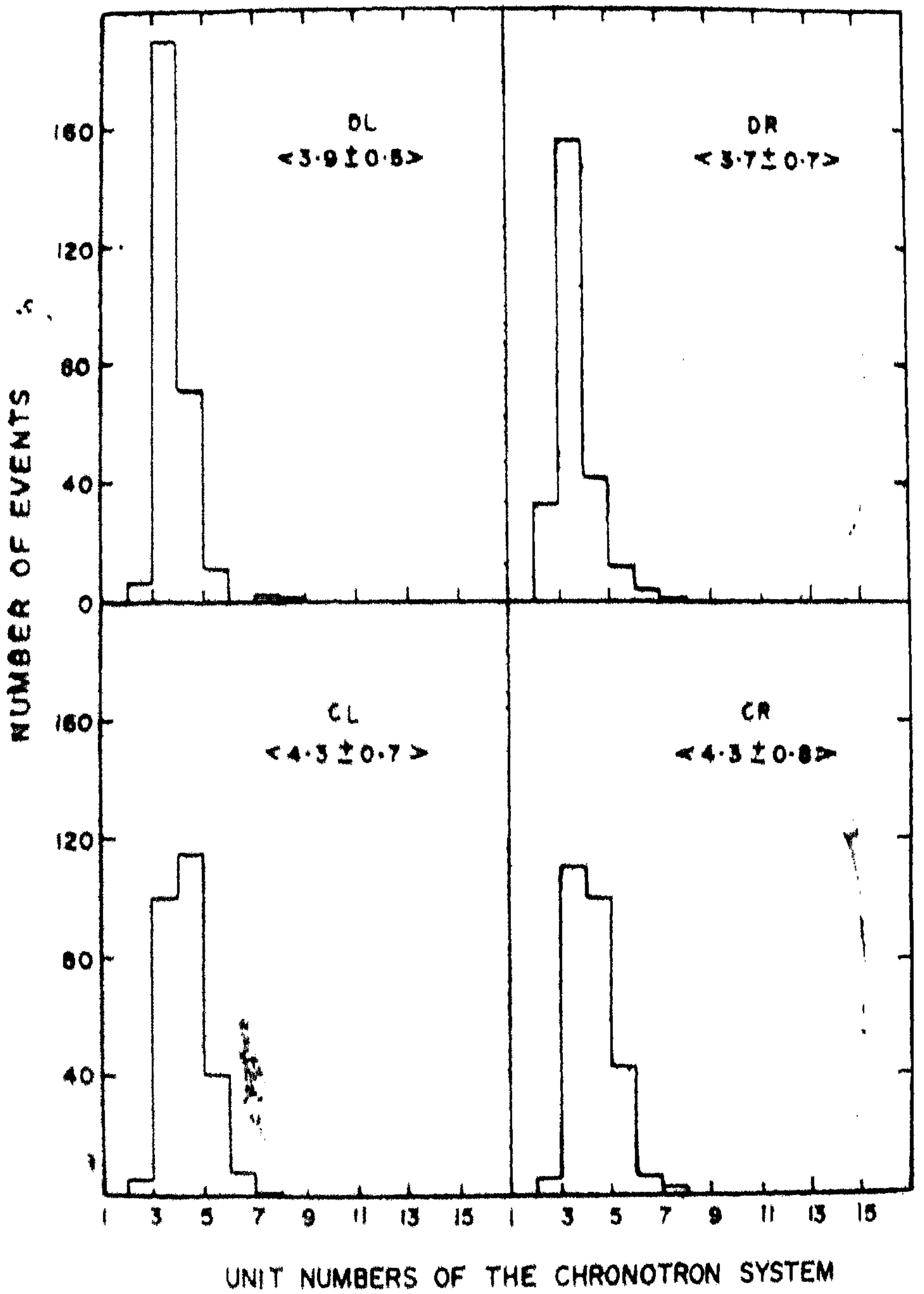


FIG. 4. Histograms for the measured time between the four TASS timing detectors, when arranged to detect mostly shower particles (electrons) and the shower detector CHO, expressed in units of the sorter cable of the chronotron system.

followed. The CHO photomultiplier system and one of the four TASS timing systems are made to view a single plastic scintillator and the relative time between them is studied as a function of the number of particles traversing the scintillator. The number of particles is measured by a system similar to the one used for measurement of the particle density in the air shower array. The distribution of these relative times are shown in Fig. 5 for four groups of particle densities. It is clear that the distribution tends to become narrow as the number of particles traversing the scintillator increases. Assuming that the distributions are approximately Gaussian, the half-width (one standard deviation σ_E) values have been calculated and

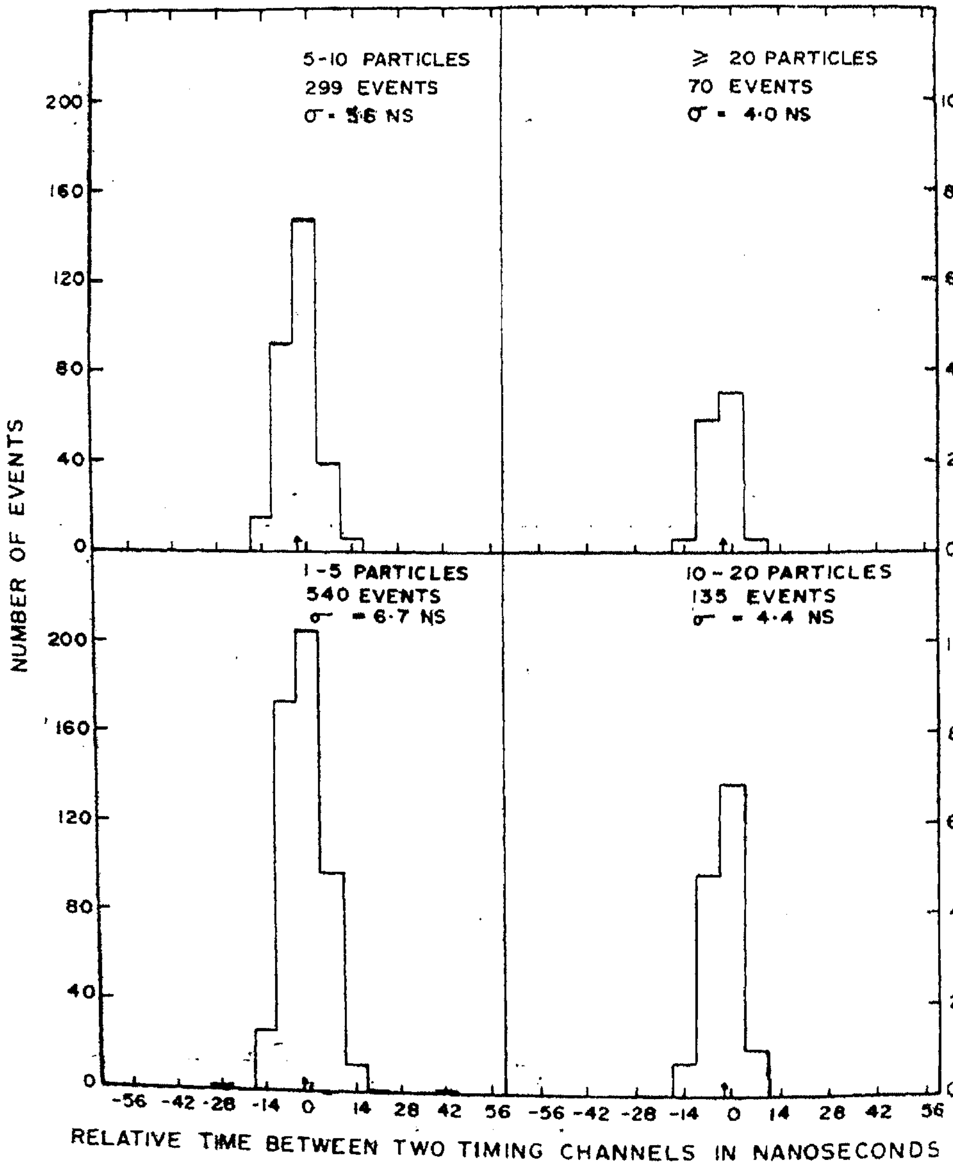


FIG. 5. Histograms for the relative time between two timing detectors viewing the same scintillator for different number of shower particles traversing the scintillator.

are shown in the figure. Since the two timing systems used here are identical in all details, it can be assumed that each distribution in Fig. 5 is composed of two distributions, each of half-width $\sigma_E/\sqrt{2}$. Thus the timing error in a CHO type of system can be represented by a Gaussian with half-width σ_S $(=\sigma_E/\sqrt{2})$. It needs to be mentioned that since the actual CHO detector is a liquid scintillator, 25 cm deep, and the photomultiplier has better optical contact, the σ_E values are expected to be somewhat smaller for the same particle density than the values given in Fig. 5 obtained using a plastic scintillator.

The estimate of the errors in the TASS timing channel is also obtained in a similar way. Two timing photomultiplier systems are made to view the same channel of TASS (CL) along with the usual system for pulse height measurement. The relative time between the two timing systems has a distribution and the width of this distribution is related to the energy release in the TASS channel. The distributions for four groups of energy release are shown in Fig. 6. The energy release is given in terms of equivalent number of relativistic muons. The situation here is similar to that in the case of CHO, except for the fact that distributions here are relatively broader. It has been seen experimentally that all the four TASS timing systems have similar distributions with similar values of the widths. Thus, using arguments as given above for the timing errors in CHO, it can be concluded that the errors in measured time of TASS channels are of a Gaussian nature and have a half-width σ_H which is $\sigma_T/\sqrt{2}$. The values of σ_T are given in Fig. 6 for different amount of energy releases in the TASS channels.

Thus the error in the measured arrival time for a hadron in a particular shower is a Gaussian with half-width σ, given by $(\sigma_S{}^2+\sigma_H{}^2)^{\frac{1}{2}}$, *i.e.*, $[(\sigma_E{}^2+\sigma_T{}^2)/2]^{\frac{1}{2}}$ provided the energy release for this hadron is confined to a single channel of TASS. However, if the energy release is comparable in both channels then σ is given by $[\sigma_E{}^2+(\sigma_T/\sqrt{2})^2/2]^{\frac{1}{2}}$. Thus it is possible to calculate the timing errors for hadrons of particular energy associated with showers which give particular value of density in CHO. However, in practice such divisions are not made, since a particular hadron energy can be associated with widely different density values in CHO and also the energy release in the TASS channels can be distributed in many different ways, for the same incident hadron energy. Therefore, it was decided to take the value of the width corresponding to a certain energy of hadron associated with a shower which contributed a certain number of particles in the CHO detector, as typical of the magnitude of the error in all the measurements. The hadron energy chosen is 5 GeV and the number of particles in CHO is 5 and for this case the width comes out to be 7 ns. It is obvious that for higher hadron energies the timing errors are smaller than the Gaussian distribution of half-width of 7 ns. It may be mentioned that the unit of measurement in the major part of the experiment is also 7 ns. Since the zero delay point has been fixed around the 5th junction the range of time measurement becomes − 28 ns to + 70 ns. However, by shifting the zero delay point to lower values, this delay can be extended to positive delay region at the expense of the negative region. This was done during part of the experiment to study the region 10 ns to 100 ns. During another part of the run, the unit of measurement was changed by increasing the

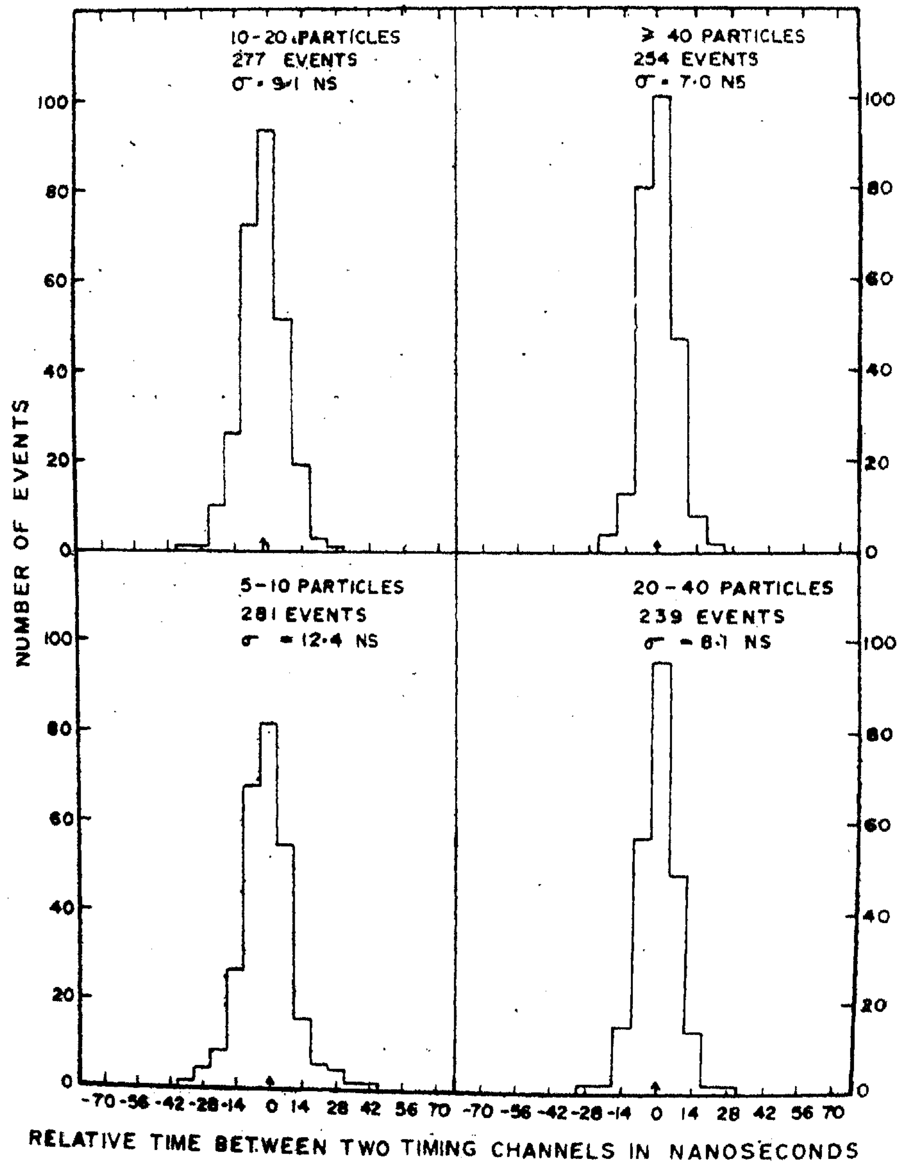


FIG. 6. Histograms for the relative time between two timing detectors viewing the same TASS channels CL for different amount of ionisation in this channel. The ionisation is expressed in terms of the passage of an equivalent number of relativistic singly charged particles (muons).

lengths of the 'sorter' cables to 17 ns thus extending the measured range to about 200 ns on the positive delay side.

6. DATA COLLECTION AND ANALYSIS

The experimental data was collected during two operational spells, the first one covering the period March to August 1968 and the second from April to July 1969. Various criteria of shower selection were used and these can be classified broadly into two types: In the first type no demand was made on the hadron arrival time while in the second type only those events were selected in which the detected hadron arrived delayed by more than ~ 10 ns relative to shower front. The first selection yields the unbiased time spectra and the second gives the spectra in the large delay region. The latter has been converted into unbiased spectra using the data from the first selection and the relative collection times for the two runs. The other requirements on the shower selection common to both the runs were: (i) at least one particle must pass through each of the four shower timing detectors, (ii) the particle density above CHO should exceed $5/m^2$ and (iii) the ionisation in the TASS timing channels should exceed that corresponding to the passage of ~ 5 relativistic muons. In part of the run the third condition was waived. In an effective operation time of about 1280 hours, nearly 65,000 showers were collected. These showers have been analysed for various shower parameters using the computer and following the procedure briefly discussed below.

The time differences in the arrival of the shower front at the four fast detectors of the air shower array are used for calculating the arrival direction of the shower. It is estimated that the error in the zenith angle obtained by this method is less than 5° for showers in the size range 10^5–10^6 particles. This error holds for zenith angles upto about 50°.

The estimation of the shower core position, lateral structure of shower particles and the shower size from the density data is carried out by a χ^2 minimisation method and is similar to that discussed in detail by Scherb.[13] The lateral distribution function has been taken to be of the form

$$\Lambda\,(N_e, \alpha, \gamma) = \frac{N_e}{2\pi\, r_0^2\, \Gamma(2-\alpha)} \left(\frac{r}{r_0}\right)^{-\alpha} e^{-r/r_0}$$

where $\triangle$ is the density at a distance r from shower axis in a shower of size N_e. α is the structure parameter which has been treated as a variable. γ_0 is the scattering length (107 metres) and Γ is the gamma function. It has been shown by Chatterjee *et al.*[14] that this relation fits the lateral distributions of shower particles very well for showers in the size range 10^4–10^7 and in the distance range of 5–50 metres. The errors in the shower parameters have been estimated by analysing by the same minimisation procedure a few hundred artificially generated showers. After taking into account the statistical as well as the probable systematic errors in the measured dencities, it is estimated[7] that the core distance is accurate to ± 4 metres for showers in the size range 10^5–10^6, the lateral structure parameter α is accurate to ± 0·3 and the estimated shower size is within ± 40% of the original value. The errors are, in general, less for higher sizes and steeper showers (higher α values).

Out of the 65,000 showers collected during the run the computer analysed only 51,000 showers which satisfied various criteria imposed during the minimisation procedures. Out of the showers analysed 10,550 satisfied the following conditions, which are deemed necessary for proper analysis of the hadron time structure: (i) size of the shower to lie between the values $6 \cdot 7 \times 10^4$–$1 \cdot 8 \times 10^6$, (ii) the zenith angle of the shower to be less than 30°, (iii) the lateral structure parameter α to have values in the range 0·4 – 1·9, (iv) the distance of the detected hadron from the shower axis to be less than 40 metres and (v) the energy release in either of the hadron timing channel pairs (CL, DL), or (CR, DR) of TASS to exceed 5 GeV.

These 10,550 showers have been classified into various groups according to size, core distance and values of the parameter α, as follows: Three size groups: (i) $6 \cdot 7 \times 10^4 - 2 \times 10^5$, (ii) $2 \times 10^5 - 6 \times 10^5$ and (iii) $6 \times 10^5 - 1 \cdot 8 \times 10^6$; three core distance groups: (i) 0–10 m, (ii) 10–20 m, and (iii) 20–40 m; four α-value groups: 0·4–0·9, 0·9–1·4 and 1·4–1·9. Finally for each of these sub-groups the hadron energy has been classified into four groups which are (i) 5–10 GeV, (ii) 10–20 GeV, (iii) 20–40 GeV and (iv) $\geq$ 40 GeV. Thus there are altogether 108 groups into which all the analysed data has been classified. These groupings allow a systematic study of the arrival time spectra for hadrons of various energies as a function of different shower parameters.

7. EXPERIMENTAL RESULTS

Typical arrival time spectra for hadrons of different energy in showers of specific characteristics is shower in Fig. 7. The hadrons which seem to arrive earlier than the shower front can all be accounted for by the Gaussian tail of the time distribution. It is possbile absorb all the negative delay events and the positive delay events which flow into the neighbouring delay channels because of the Gaussian distribution into the zero delay point which then becomes free from timing errors. This has been done in the presentation of all further data. The hadron time spectra for different energies have been studied in relation to the various shower parameters as follows.

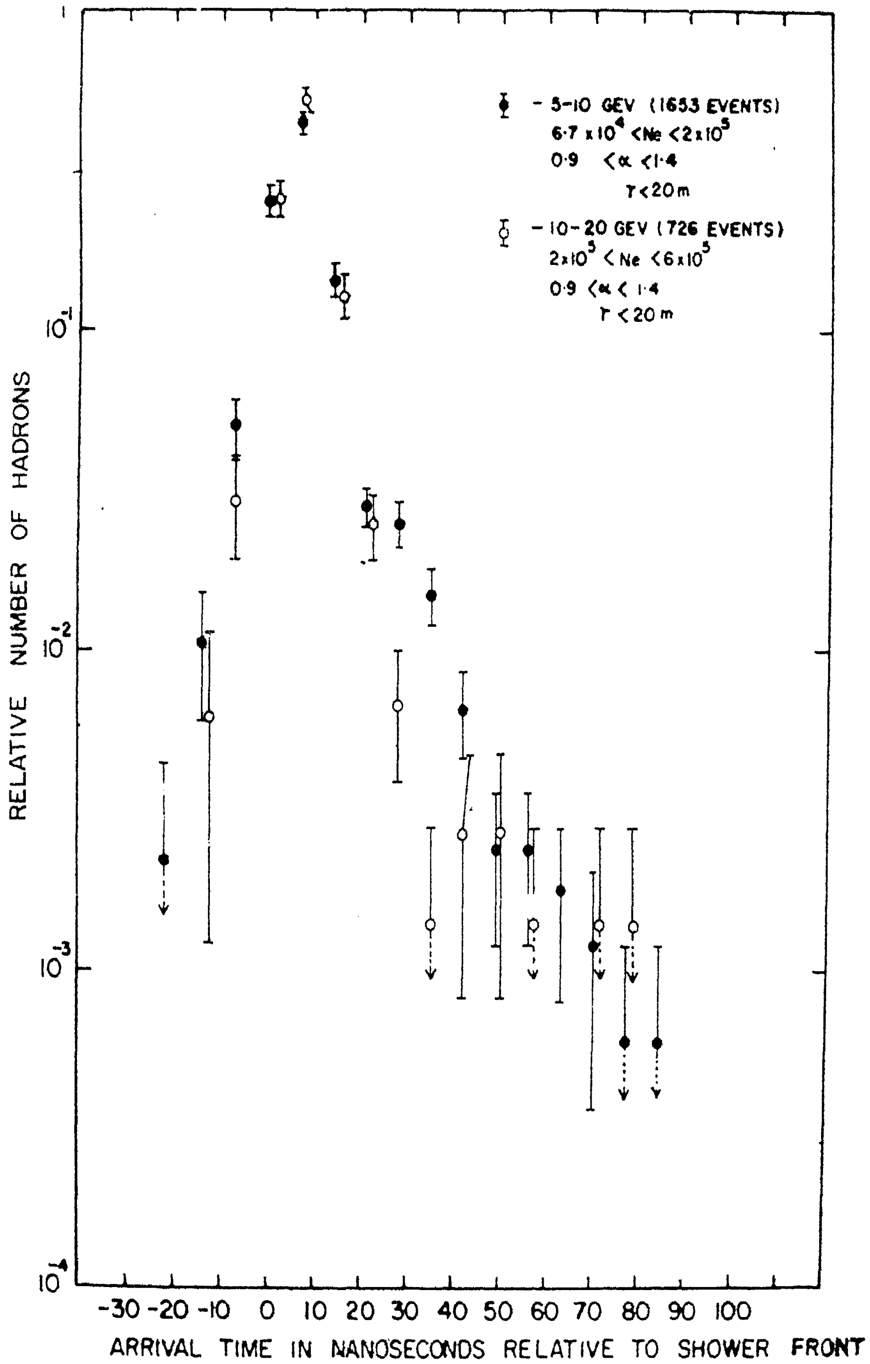


FIG. 7. Arrival time spectra for hadrons of two different energy groups in showers having different characteristics. N_e is the shower size, α is the electron lateral structure parameter (defined in Sec. 6) and r is the distance of the hadron from shower axis. The errors shown are statistical.

(*i*) *Hadronic time spectra as a function of the electron lateral structure.*— In Fig. 8 are shown the time spectra of hadrons of two energy groups in showers in the size range $6{\cdot}7 \times 10^4 - 2 \times 10^5$ for three different α groups.

The time scale is suitably shifted to accommodate the spectra of the two energy groups in the same figure. The errors shown on the points are statistical. As already pointed out, only hadrons contained within 20 m of the shower axis have been considered. It is evident that within statistical errors the spectra have little correlation, if any, with the electron lateral structure. A similar behaviour has been noticed for other size groups. It has also been seen that the time spectra of hadrons do not have any correlation with size of the showers having same α. Therefore, in order to improve the statis-

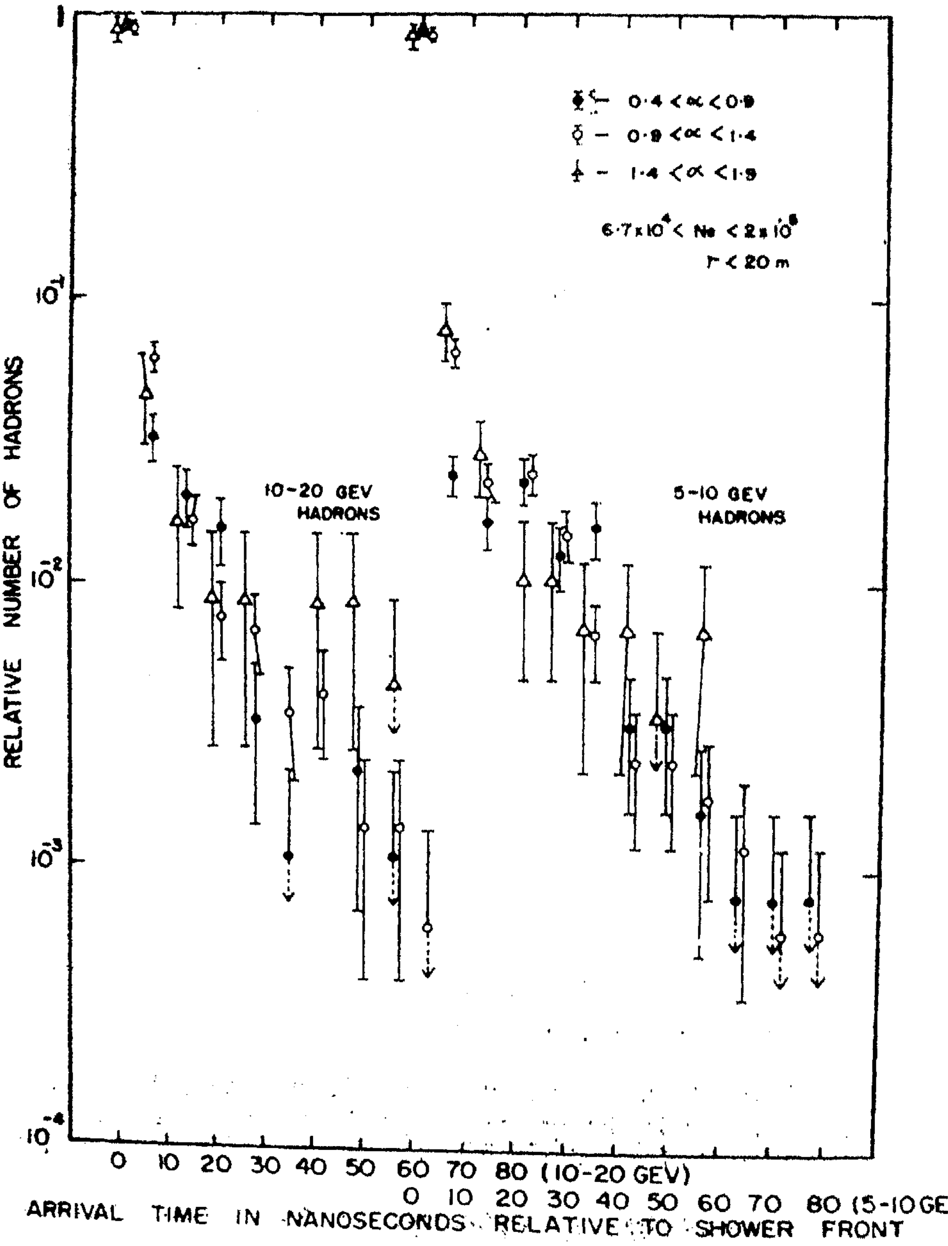


FIG. 8. Arrival time spectra for hadrons of two different energy groups in showers of size N_e for three different values of electron lateral structure parameter α. Only hadrons contained within distance r from shower axis have been considered.

tical accuracy, the data of all shower size groups have been combined and plotted in Fig. 9 for different α groups. It can be concluded from Fig. 9 that the time spectra of hadrons is insensitive to the electron lateral structure.

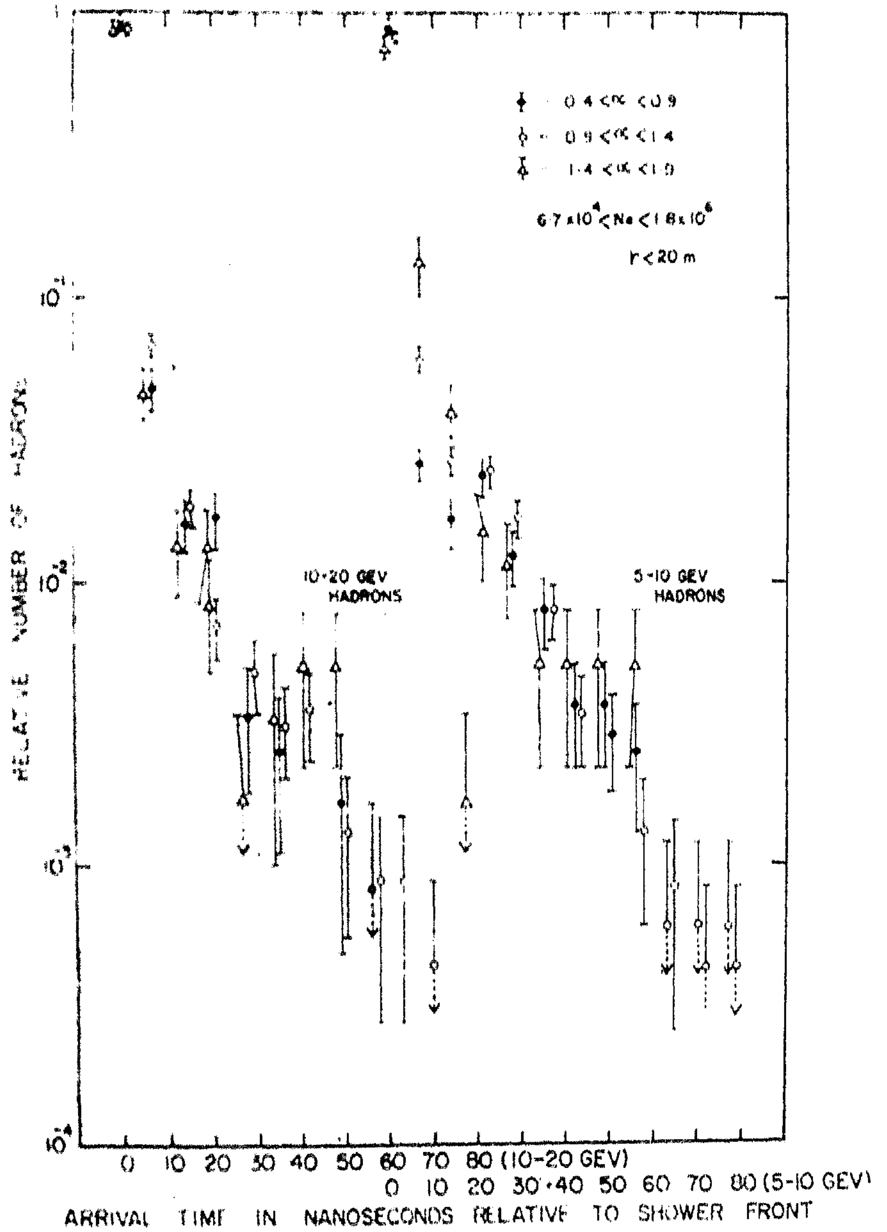


FIG. 9. Arrival time spectra for hadrons of two different energy groups in showers of size N_e for three different values of electron lateral structure parameter. Only hadrons contained within distance r from shower axis have been considered. The data presented here has been combined for all three size groups.

(*ii*) *Hadron time spectra as a function of the distance of the hadron from the shower axis.*—Combining the data for all values of the electron lateral structure parameter, α, the time spectra have been studied as a function of the distance r of the hadron from the shower axis. Since the time spectra for particular r group have been seen to have no dependence on shower size, in Fig. 10 are plotted the time spectra of 5–10 GeV and 10–20 GeV hadrons for different distance groups combining all shower sizes. There appears to be a tendency for this spectra to flatten at larger distances from the shower axis. However, the effect is only marginal for distances up to 20 m and is practically absent for the lower energy hadrons.

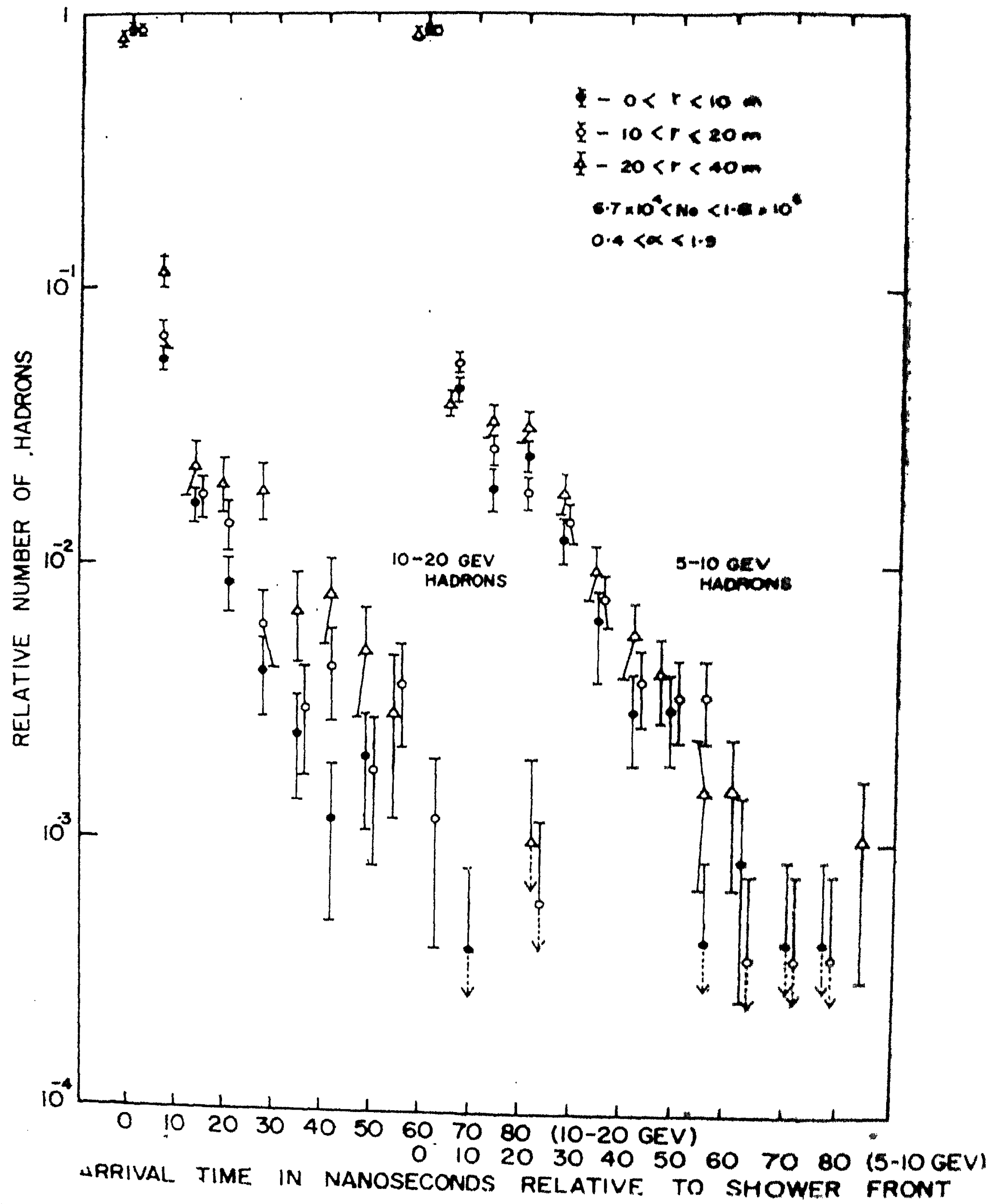


FIG. 10. Arrival time spectra for hadrons of two different energy groups in showers of size N_e and electron lateral structure parameter α for three different groups of the distance r of the hadron from shower axis.

(*iii*) *Hadron time spectra as a function of shower size.*—From (i) and (ii) above, it is obvious, that the hadron time spectra should be independent of shower size. The combined data in Figs. 11 and 12 for three different shower sizes and for four hadron energies confirms this expectation. It can therefore be concluded that for the study of time spectra as a function of hadron energy, it is possible to combine all the data irrespective of shower size, a-values (0·4–1·9) and core distances upto 20 m.

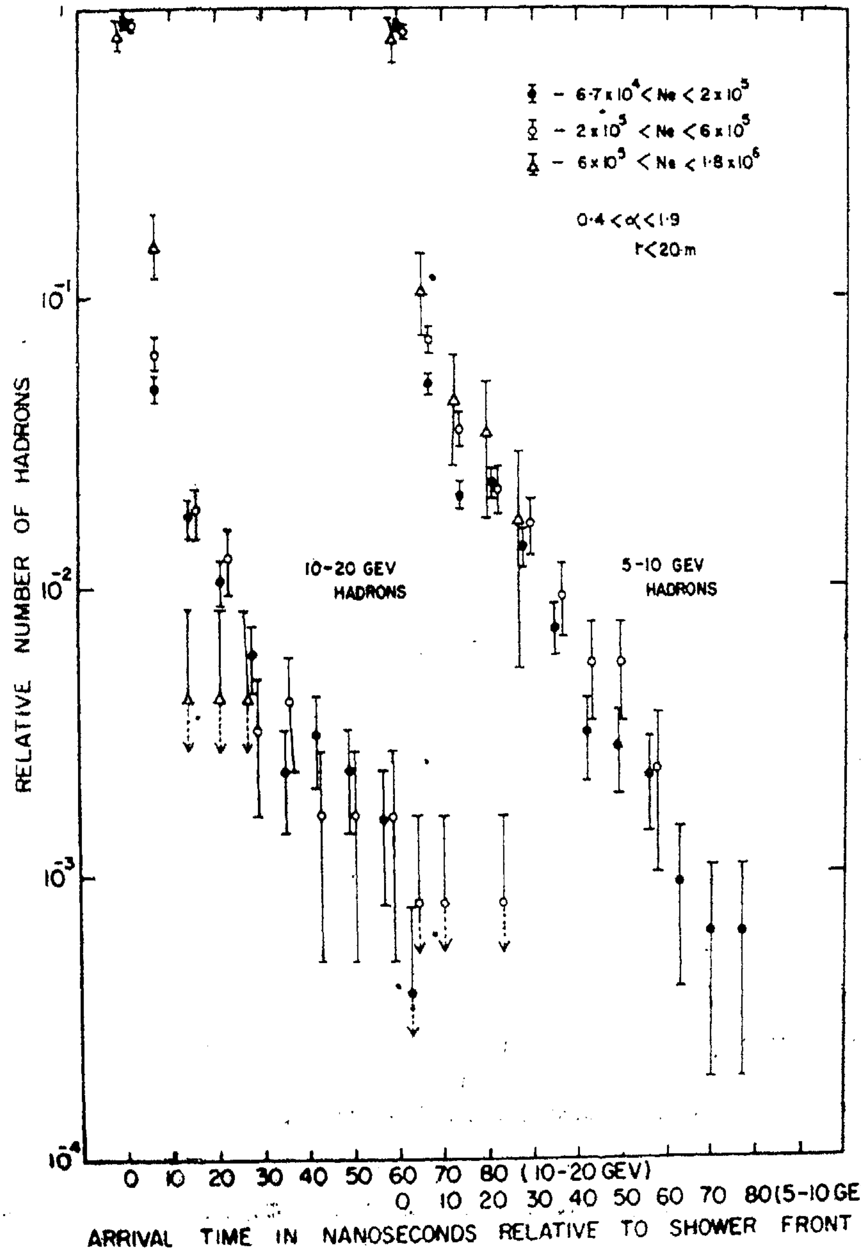


FIG. 11. Arrival time spectra for hadrons of two different energy groups in showers having lateral structure parameter a for three different shower size N_e groups. r is the distance of the hadron from shower axis.

(*iv*) *Hadron time spectra as a function of hadron energy.* In Fig. 13 are given the hadron time spectra for four energy groups combined for all shower sizes. It is seen that the time spectra become steeper as the hadron energy increases. It is also seen that there are a large number of events of high energy (> 20 GeV) which are considerably delayed (> 20 ns).

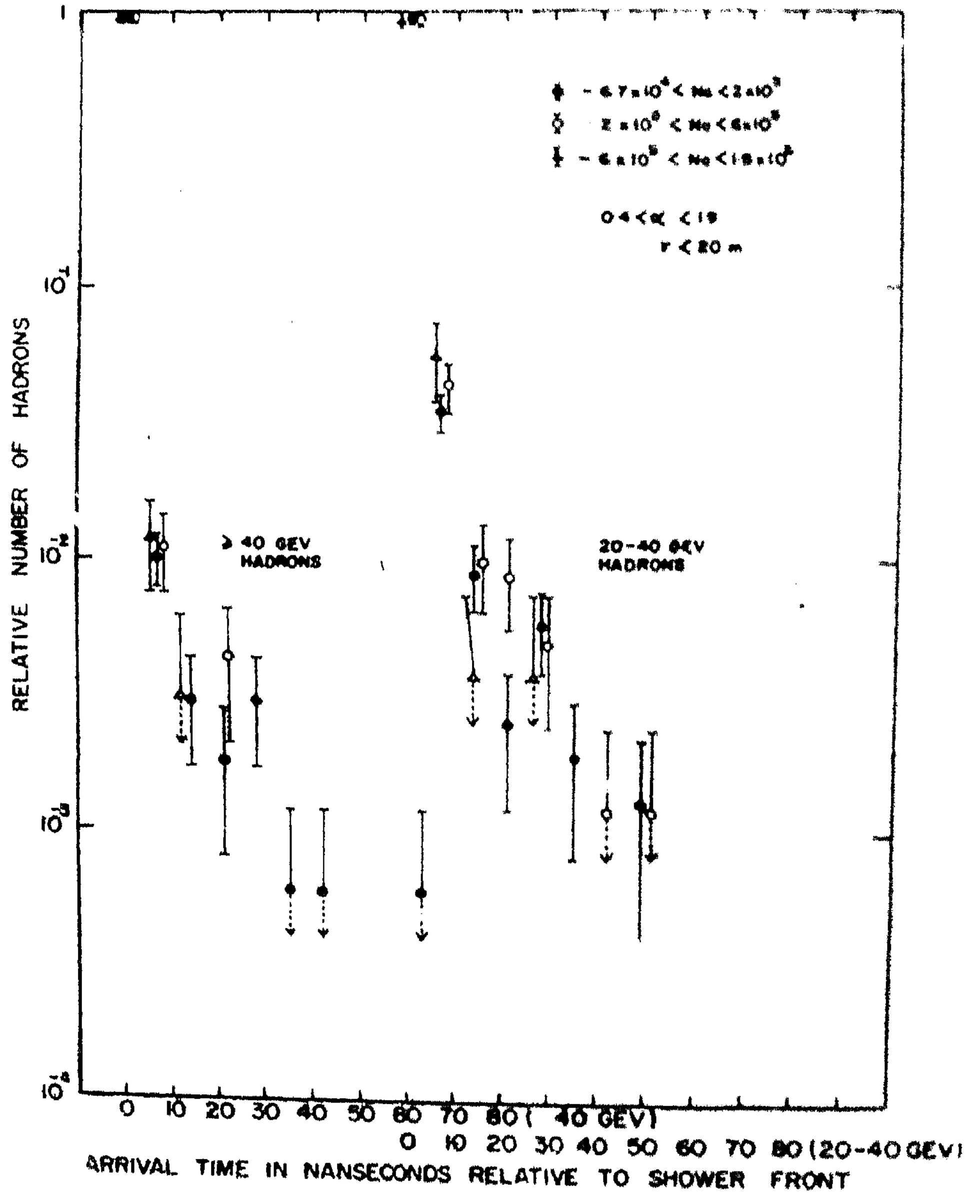


FIG. 12. Arrival time spectra for hadrons of two different energy groups in showers having lateral structure parameter a for three different shower size N_e groups. r is the distance of the hadron from shower axis.

(*v*) *Large delay hadrons.*—As mentioned earlier, in part of the shower run the range of time measurement was increased to about 200 ns to detect the hadrons which arrive delayed by more than 100 ns. In 320 hours of operation only 7 events were observed which were delayed by more than 100 ns but all these events had energies in the range 5–20 GeV.

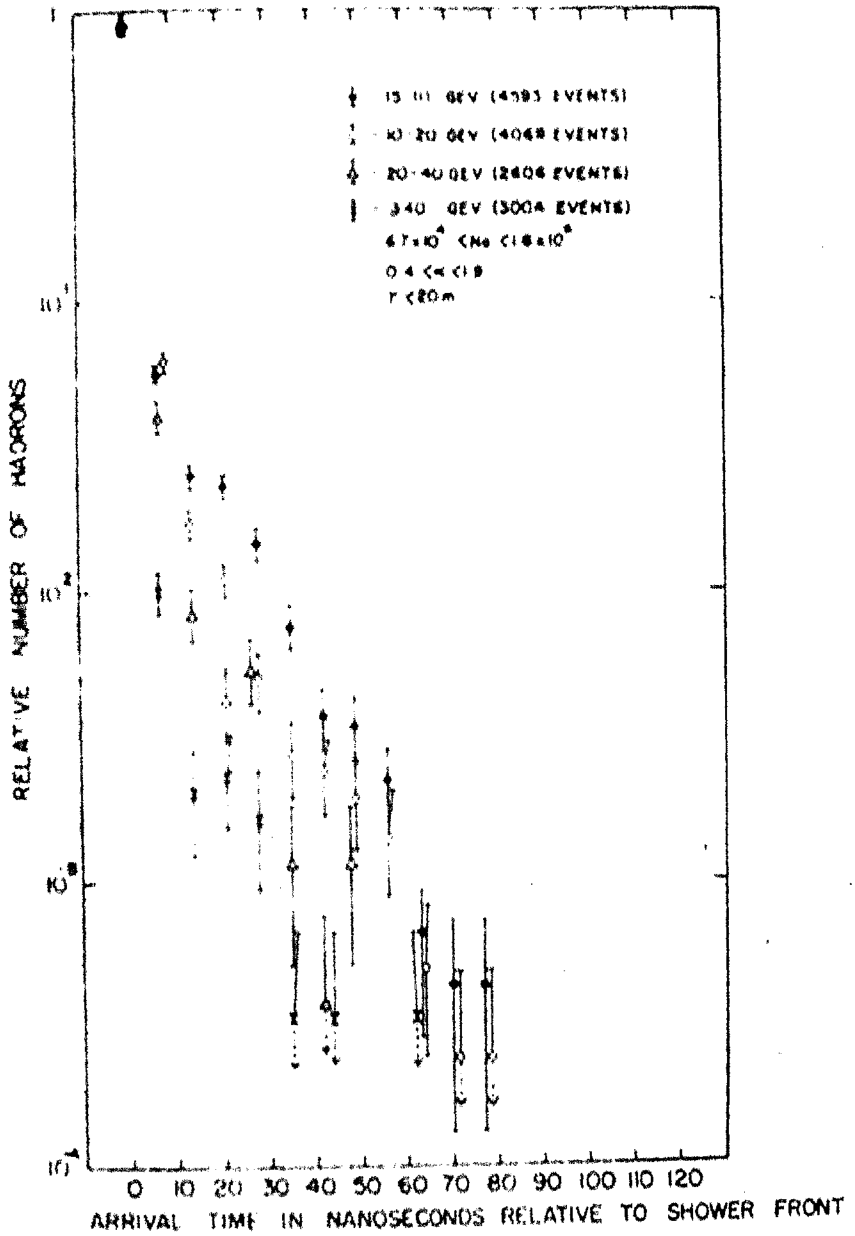


FIG. 13. Arrival time spectra for hadrons of four different energy groups which are contained within distance r of the axis of the showers characterised by size N_e and electron lateral structure parameter s.

8. SUMMARY AND CONCLUSIONS

The main results that have been obtained in the present investigation may be summarised as follows:

(*i*) The time structure of hadrons is not dependent on shower size or on the shape of the lateral distribution of electrons.

(*ii*) There is a weak dependence of the time structure on the distance of the hadron from the shower axis. The dependence is perceptible only at distances larger than 20 m. There is a tendency for the time spectrum to flatten for hadrons arriving at larger distances from the shower axis.

(*iii*) The time spectrum is highly dependent on the energy of the hadrons, and steepens as the energy increases.

(*iv*) There are considerable number of events which have comparatively high energy ($>$ 20 GeV) and large delay ($>$ 20 ns).

In order to understand the significance of these results and use them for deriving conclusions regarding the characteristics of high energy collisions, which is one of the objectives of the air shower investigations, it is necessary to obtain the theoretical time structure functions expected for hadrons of different energy. These have been obtained by performing detailed Monte Carlo calculations on the development and absorption of the nuclear and electromagnetic cascades in the atmosphere on the basis of some of the models of nuclear interactions that have been proposed. Details of these calculations and conclusions that can be drawn from a comparison with the present results have been presented elsewhere.[7-9] It has been shown[9] that the time structure of hadrons of energy 10–20 GeV definitely indicate that among the two distinct models that are currently in vogue on high energy collisions, *viz.*, the pure fireball type[15] and the Isobar-*cum*-pionisation type,[16] there is a definite preference for the latter. It has also been shown[8] that in order to understand the detailed shape of the time structure function observed experimentally, it is necessary to postulate the production of a large number of nucleon-antinucleon pairs in addition to pions and kaons in high energy collisions. The theoretical comparison shows that the extent of $N\bar{N}$ production has to be of the order of about 15% in collisions of energy $> 10^{12}$ eV compared to less than 1% at energies below 70 GeV, as revealed by accelarator experiments.[17] The present results on the abundant production of $N\bar{N}$ pairs confirm the earlier suggestion of Murthy *et al.*[18] that in order to explain the charged to neutral ratio of hadrons and some of the other characteristics of air showers it is necessary to increase considerably the production of $N\bar{N}$'s. Recently, Sivaprasad[19] has concluded, on the basis of studies of ultra high energy muons ($>$ 220 GeV) in air showers that if the composition of air shower primaries does not change significantly in the

10^{15}–10^{16} eV region, the results on the variation of the number of high energy muons with size necessarily require the production of a large number ($\sim 25\%$) of NN's among the hadrons produced at high energies. Combined with a gradual change in the primary composition, however, it seems possible to fit the muon results with about 20% of $N\bar{N}$ production.

It is clear from Fig. 12 that there are some events whose measured energies exceed 20 GeV and whose delay is more than 20 ns. These events are not expected in the normal picture of air shower development and the calculations show that the frequency of such delays for known hadrons of energy > 20 GeV in air showers is less than 10^{-4}. However, after taking into account the probable errors in the experimental data, it has been found that the frequency of such large delay events is $\sim 6 \times 10^{-3}$ of the normal events of energy > 20 GeV. These events, whose details have been discussed elsewhere,[10] also seem to have different interaction characteristics in TASS. The energy release for nearly 2/3 of the cases is confined to a single channel of TASS suggesting a longer interaction mean free path for the particles responsible for them. These events by virtue of the large delay and high energy offer themselves as strong candidates for heavy mass (~ 10 GeV/c^2) particles in air showers. It is to be emphasised that such an interpretation needs to be substantiated by further experiments incorporating visual detectors in addition to energy measuring and timing devices. These should be capable of operating in regions close to the core of air showers where the density of associated charged particles is very high.

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