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Search for massive interacting particles near the cores of extensive air showers of energies of about 2×10^{14}–10^{16} eV

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Abstract. An experiment carried out at mountain altitude to study the time structure of hadrons in extensive air showers has revealed the existence of a special class of delayed high energy interacting particles at distances less than 20 m from the axes of showers of energy greater than 2×10^{14} eV. These particles having energies more than 20 GeV and delays more than 20 ns relative to the air shower front, constitute about 0·5% of the hadrons of similar energy. Detailed calculations predict the frequency of events with such delay–energy characteristics to be less than 10^{-4} if they are due to known hadrons like nucleons and pions. The high energy large delay events however can be understood if there exist particles much heavier than nucleons (mass >10 GeV/c^2) which are produced in ultrahigh energy interactions. Under certain assumptions the flux of such massive interacting particles has been deduced from the experimental data as approximately 10^{-9} cm^{-2} s^{-1} sr^{-1}. It is shown that such a flux is not inconsistent with the upper limits given by earlier experiments. The present experiment does not give any information on the charge of these particles. Further experiments incorporating visual detectors and timing systems are needed to substantiate the interpretation of the events in terms of heavy mass particles.

1. Introduction

Ever since the theoretical speculation by Gell-Mann (1964) and Zweig (1964a, 1964b) about the possible existence of a triplet of particles with fractional charges which might be the basic constituents of all hadrons and the subsequent suggestions by Maki (1964), Bacry *et al* (1964), Gursey *et al* (1964) and many others about the possibility of these having integral charge instead of fractional charge, many experimental searches have been carried out for these particles using widely varying techniques. The negative results of the accelerator experiments (eg Antipov *et al* 1969a, 1969b) up to the highest available energies (70 GeV) suggest that if the fractionally charged particles exist and are produced in hadron interactions their mass must be greater than about 5 GeV/c^2. The heavy mass nature of these particles has been sought to be exploited in some of the experiments carried out to search for them in cosmic radiation. The experiments have looked for delayed energetic particles in extensive air showers since air showers are the product of numerous ultrahigh energy hadron interactions and the massive particles could be expected to be produced with reasonable frequency in these interactions. The massive particles, even if sufficiently relativistic, trail behind other air shower particles of similar energy and the time lag increases with particle mass m as m^2. Thus, for example, though a nucleon of 100 GeV energy is practically time-coincident with the air shower front composed mainly of highly relativistic electrons, a particle of mass 10 GeV/c^2 of similar energy will be delayed relative to the shower front by 16 ns for each kilometre of its path in the atmosphere. The various experiments (Damgard *et al* 1965a, 1965b, Chatterjee *et al* 1965, Jones *et al* 1967 and Bjornboe *et al* 1968) which searched for relativistic delayed particles in air showers at mountain altitude, sea level or underground have all given negative results. The only experiment which has given a positive flux for fractionally charged delayed interacting particles has been carried out by Dardo *et al* (1968, 1971) underground at a depth of 70 mwe. However, the flux reported by these authors is in disagreement with the results of other experiments like that of Bjornboe *et al* (1968) and Garmire *et al* (1968).

The present experiment is an improved version of the experiment of Chatterjee *et al* (1965) and seeks to detect massive interacting particles close to the cores of relatively large size air showers initiated by primaries of energies exceeding few times 10^{14} eV. The experiment was however mainly designed for a thorough study (Tonwar *et al* 1971a) of the time structure of the hadronic component in the 0–100 ns delay region relative to the air shower front in order to obtain an estimate of the composition (Tonwar *et al* 1971b) of the hadrons produced in high energy interactions in the atmosphere and to yield information on the characteristics of high energy interactions (Tonwar and Sreekantan 1971). The time spectra of interacting particles of energy greater than 20 GeV are of main interest in the search for massive particles since other known hadrons like pions, kaons and nucleons are practically time-coincident with the air shower front for such high energies. The experiment has been carried out at mountain altitude of 800 g cm^{-2} (Ootacamund) during 1968–9.

2. Experimental details

The experimental set-up consists essentially of an air shower array and a hadron detector. The TIFR air shower array (Tonwar *et al* 1971a) located at Ootacamund consists of 20 density detectors spread over an area of radius 40 m and four fast shower timing detectors situated at the corners of a square of side 10 m in the centre of the array. The array provides the data for determination of the shower size, the distance of the shower axis from the hadron detector, the arrival direction of the shower and other related shower parameters. The hadron detector is a total absorption scintillation spectrometer (TASS) discussed in detail by Ramana Murthy *et al* (1963) and consists of 750 g cm^{-2} of absorber (iron) in the form of 25 layers, each 30 g cm^{-2} thick, interspersed with liquid scintillation tanks, each filled with Shellsol A mixed with paraterphenyl and POPOP. The height of the liquid is 2 cm near the front glass window of the tank and increases in steps towards the rear to compensate for the absorption of light in transmission towards the front. The essential features of the TASS are shown in figure 1. Though the TASS has a total area of 120×120 cm^2, the arrangement for measurement of ionization in the scintillators as shown in figure 1 makes it possible to consider the TASS as composed of two independent units, each of area 120×60 cm^2. The TASS is provided with iron–lead shielding on the top and the nonviewing sides such that it is shielded on all sides completely against the low energy electron–photon component arriving at zenith angles of less than 30°. The various channels, A_1, A_2, B, C and D (figure 1) are calibrated individually in terms of the ionization energy deposited in the scintillator medium, by single relativistic muons traversing TASS in a near vertical direction. In order to avoid overestimation of the energy of the interacting particle due to the accompanying high energy electron–photon component of the air shower, the

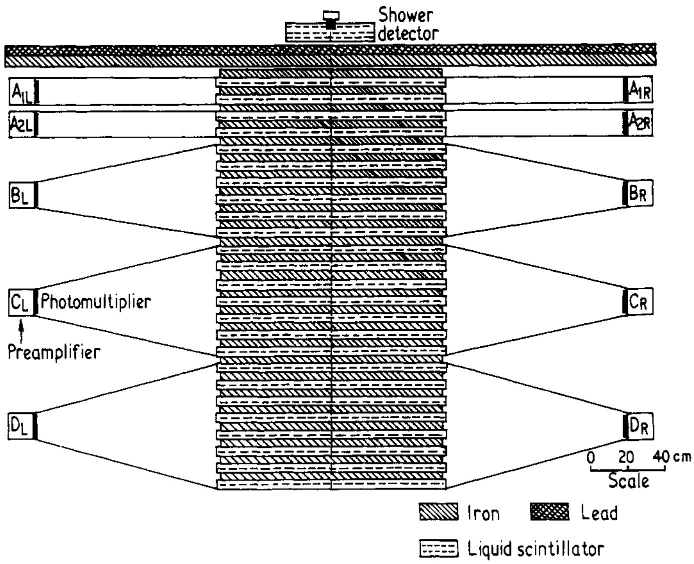

Figure 1. A cross sectional view of the total absorption scintillation spectrometer (TASS) and the shower detector.

energies released in the upper channels A_1, A_2 and B are not included for estimating the energy of the interacting particle. Only the energy released in the lower channels C and D is considered. Further, in any particular event, only the energy losses in one half section of the TASS, that is, either in the C_L–D_L channels or in the C_R–D_R channels, whichever higher, are attributed to the interacting particle. The delay of the particle defined as above is measured by timing the pulse obtained by mixing the pulses from the four channels C_L, D_L, C_R and D_R relative to the pulse from an unshielded detector ($75 \times 75 \times 25\,cm^3$ liquid scintillator) located at the top of the TASS. The timing system measures the time of only the earliest pulse from the mixed channel in case of multi-particle incidence of hadrons on the TASS in the same shower. However, except in the case of showers whose axes are close to the TASS, multiple incidence is known to be rare and to decrease rapidly as the distance from the shower axis increases. The delay has been measured by a chronotron system (Tonwar 1970) in units of 7 ns in a major part of the experiment, covering a delay range of -21 ns to $+84$ ns. For a shorter duration ($\simeq 30\%$) of the experiment, the unit was increased to 17 ns to extend delay measurements up to about 240 ns.

The possible errors in the shower parameters, energy loss of the interacting particle as measured by the TASS and the measured delays of these particles are discussed in the Appendix.

3. Experimental results

In an effective operating time of about 1280 h, about 65 000 showers were recorded using various selection criteria. All these showers were analysed on a computer for shower size, core location, arrival direction and other parameters. However, for the 'time structure' analysis the following restrictions were imposed on the shower parameters:

(i) Shower size N_e: $6{\cdot}7\times10^4 < N_e < 1{\cdot}8\times10^6$;
(ii) Distance r between the shower axis and the hadron detector less than 20 m;
(iii) Arrival angle θ of the shower relative to vertical less than 30°.

All those events which showed less than 5 GeV energy release in the lower two channels of either of the two sections of TASS were rejected. It may be mentioned that the term 'energy release' is used in the text for the energy obtained by multiplying the observed visible energy in the scintillator medium by the ratio of the amount of absorber in the form of iron to that in the form of scintillator. In order to obtain the true energy release due to the interacting particle it is necessary to take into account the unsampled energy loss. As discussed in the Appendix the true energy loss is about 1·3 times the measured loss as given by the visible ionization in the scintillator. Since this correction factor is not applied to the energy release as given here, the energy release represents always the lower limit of the energy of the interacting particle. From the data collected with 7 ns as the unit of time measurements, 14 270 events satisfied the conditions mentioned above. The corresponding number for the data with 17 ns timing unit is 5284. After folding the timing error distribution on the zero-delay points so as to absorb the negative delay parts of the observed time spectra, discussed in detail elsewhere (Tonwar *et al* 1971a), the distribution of the events according to energy release in the TASS and delay for the data using 7 ns timing unit are given in table 1. The corresponding distribution for events collected using 17 ns as the timing unit is given in table 2.

The arrival time spectra for hadrons of different energies based on the data given in table 1 are plotted in figure 2. The expected shapes of the spectra given by the four dimensional Monte Carlo simulation (Tonwar and Sreekantan 1971) of the hadron cascade of air showers in the atmosphere are also plotted in figure 2 for comparison. These calculations are based on the phenomenological model (isobar–pionization) of Pal and Peters (1964) and incorporate many known fluctuations in the various interaction parameters and also assume the increasing content of baryons among the produced particles with increasing energy. It may be emphasized that the Pal and Peters model gives relatively flatter spectra compared to many other models. It is seen from figure 2 that while the observed spectra for hadrons of energy lower than 20 GeV are reasonably well understood in terms of known processes, there are many more delayed events of energies greater than 20 GeV than expected. The detailed features of high

Table 1. Energy release–delay distribution for events collected with 7 ns as timing unit

Energy release (GeV) \ Delay (ns)	0	7	14	21	28	⩾35	⩾49
5–10	3958	264	114	105	67	85	33
10–20	3646	251	69	44	20	39	18
20–40	2445	105	22	11	14	7	3
>40	2953	30	6	7	5	3	1

Table 2. Energy release–delay distribution for events collected with 17 ns as timing unit

Energy release (GeV) \ Delay (ns)	0	17	34	51	68	⩾85
5–10	1519	67	17	3	1	6
10–20	1366	41	9	6	—	3
20–40	1005	14	3	2	—	2
>40	1211	3	3	1	2	—

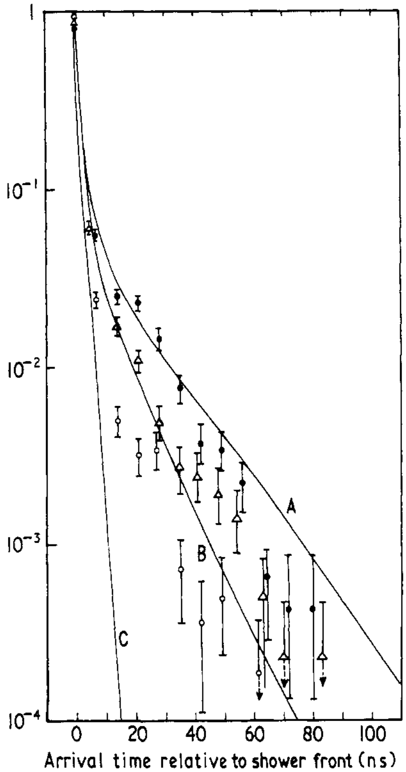

Figure 2. Comparison of the observed arrival time spectra of hadrons of different energies in air showers with the expected spectra obtained from Monte Carlo calculations. The errors on the experimental points are statistical. • 5–10 GeV; △ 10–20 GeV; ○ >20 GeV. The full curves are the Monte Carlo calculations for: A 5–10 GeV; B 10–20 GeV; C >20 GeV.

energy delayed events are presented in tables 3 and 4. A striking feature of these events is the faster absorption of the cascades in the TASS. It is seen that for nearly two thirds of the events the cascades produced by the particle responsible for these events are absorbed within a single channel of the TASS. It may be noted that the C_L or C_R channel offers

Table 3. Characteristics of high energy delayed events (events with energy release >20 GeV and delay >28 ns collected with 7 ns as timing unit)

Sr number	Identi-fication number	Shower parameters			Visible ionization in the TASS channels (MeV)						Energy release in C_L–D_L/C_R–D_R channels (GeV)	Time delay (ns)
					Left section			Right section				
		N_e	θ (deg)	r (m)	B_L	C_L	D_L	B_R	C_R	D_R		
1	01-1249	8×10^4	23	9	—	270	—	380	1750	430	33	28
2	03-1632	9×10^5	18	18	250	340	1430	330	290	870	26	28
3	18-0677	1×10^5	19	14	—	430	870	—	—	—	23	49
4	18-0752	7×10^4	29	3	480	5400	6450	—	—	—	178	63
5	26-0722	1×10^5	1	9	60	—	—	—	450	920	20	35
6	27-1665	3×10^5	18	9	250	160	1300	690	310	690	22	28
7	27-3107	2×10^5	1	12	1130	90	—	270	2150	380	38	28
8	27-3637	2×10^5	14	10	60	1230*	280*	60	40	—	23	28
9	53-0475	1×10^5	11	5	100	—	260	40	310	2460	42	28
10	01-1323	1×10^5	17	2	—	—	1560	150	220	180	23	35
11	04-1002	2×10^5	26	15	150	180	—	—	—	2070	31	28
12	12-0267	1×10^5	24	16	100	135*	5380*	—	—	—	82	28
13	18-0489	2×10^5	13	20	—	135	4070	150	160	—	63	28
14	26-0093	9×10^4	10	6	60	—	—	270	180	1710	28	28
15	26-0226	2×10^5	23	16	60	—	50	110	200	1710	28	49
16	26-0742	1×10^5	1	6	100	—	75	230	1370	230	24	28
17	27-0561	2×10^5	6	15	—	—	75	150	70	2020	31	28
18	27-0623	9×10^4	22	7	60	—	—	—	1430	130	24	28
19	27-0625	4×10^5	9	20	100	110	1510	130	90	230	24	42
20	27-0770	2×10^5	1	17	—	—	—	150	3400	—	51	28
21	27-0840	2×10^5	4	11	—	160	130	—	90	8500	129	28
22	27-0888	1×10^5	24	11	60	160	50	—	40	2870	43	42
23	27-2808	1×10^5	7	6	60	—	—	190	1280	380	25	49
24	27-3127	2×10^5	21	4	1570	1840	130	—	40	—	29	28
25	27-3649	5×10^5	25	16	80	—	50	150	1370	100	22	42
26	27-3664	2×10^5	17	7	630	135	720	170	90	3400	54	35
27	53-0615	2×10^5	20	1	800	160*	1230*	380	220	—	21	28
28	56-1667	1×10^5	9	19	115	90	1920	115	65	100	30	28
29	57-0328	8×10^4	25	3	190	—	2430	60	65	100	37	28

210 g cm^{-2} of iron to the cascade in the vertical direction and the D_L or D_R channel offers 240 g cm^{-2}. Qualitatively this feature is expected for an electron–photon cascade or a cascade produced by a hadron which later escapes subsequent interaction within the TASS. Another interesting feature for these high energy delayed events is the paucity of such events in showers of size lower than about 10^5.

4. Interpretation of high energy delayed events

It is seen from tables 1 and 2 that there are 42 events which are characterized by an energy release of more than 20 GeV in C–D channels of the TASS which are delayed relative to the air shower front by more than 28 ns. As mentioned earlier (figure 2) these characteristics are not expected for known hadrons in air showers. If the energy release exceeds 40 GeV, delays of more than 10 ns even are extremely unlikely. So the events

Table 4. Characteristics of high energy delayed events (events with energy release >20 GeV and delay >34 ns collected with 17 ns timing unit)

Sr number	Identi-fication number	Shower parameters			Visible ionization in the TASS channels (MeV)						Energy release in C_L–D_L/C_R–D_R channels (GeV)	Time delay (ns)
		N_e	θ (deg)	r (m)	Left section			Right section				
					B_L	C_L	D_L	B_R	C_R	D_R		
1	45-1292	1×10^6	10	16	190	2370	360	150	110	—	41	68
2	47-1531	1×10^6	6	19	—	—	100	210	420	1380	27	85
3	47-2432	4×10^5	9	14	—	—	130	130	1550	660	33	34
4	47-2876	8×10^5	10	11	290	450	2150	230	1010	690	39	34
5	45-0890	1×10^5	11	10	—	—	—	—	—	11500	173	34
6	46-0262	1×10^5	30	4	—	—	—	—	10980	200	168	51
7	47-0466	9×10^4	18	11	—	—	—	—	40	7270*	110	34
8	47-1008	1×10^5	3	6	—	160	200	190	1460	200	25	51
9	47-1102	2×10^5	22	12	130	1570	100	250	40	—	25	34
10	47-1144	1×10^5	12	9	—	—	3050	—	40	200	46	68
11	47-1486	1×10^5	11	11	—	—	—	150	110	1540	25	85
12	47-2104	1×10^5	21	8	—	160	240600	—	100	8140	3611	34
13	47-2465	5×10^5	30	19	—	90	1890	—	40	—	30	51

in table 1 which have energy release greater than 40 GeV but are delayed by only 21 ns should also be considered along with the other 42 events. Thus there are a total of 49 events recorded over an area of 1·4 m^2 in 1280 h of operation, which are contained within 20 m of axes of air showers of sizes in the range of $6{\cdot}7\times10^4$–$1{\cdot}8\times10^6$ particles, which fall into a special category (large delay high energy events).

Before considering the possible interpretations it is necessary to take out events which might have been included in this sample of 49 (enclosed in the broken line boxes in tables 1 and 2) due to errors in the measured parameters defining these events. The errors in the measured shower size, core distance and arrival direction of the shower, discussed in the Appendix, are too small to have any effect on the interpretation of these data. The errors in the measured time can be taken into account using the experimentally measured timing error distribution. Applying the error probabilities given in the Appendix, it is seen that only two or three of the events contained in the broken line box in table 1, can be accounted in terms of errors in delay measurements (smaller delay events). Similarly the errors in measured energy release in the TASS for these can be considered on the basis of the measured error distribution in the Appendix and again it can be easily seen that only three or four events in the broken line box in table 1, can be explained as being due to low energy particles whose energies have been wrongly overestimated. The possibility of overestimation of energy due to the incidence of two or more hadrons on the same section of the TASS in a particular event, because the integration time of energy measuring channels of the TASS is of the order of a few microseconds, can be ruled out in the case of high energy delayed events. This is because the timing system measures the arrival time of the earliest arriving hadron thus requiring that the other hadrons, if at all, have larger delays. The probability of two or more hadrons of, say, energy greater than 10 GeV (but less than 20 GeV) and delays greater than 28 ns arriving at the same location (within 0·7 m^2) in a shower of size about 10^5 particles is negligibly small because of the very small number ($\simeq 2$) of such hadrons per shower. Similar considerations apply to the events in table 2 and after taking into account all these errors and also studying individual events it seems clear that there are *at least* 36 events which are delayed by more than 21 ns and have released energy in excess of 20 GeV in the appropriate channel of the TASS. Since the total number of events of energies more than 20 GeV is 7858, these high energy delayed events constitute about 0·5 % of all events of energy more than 20 GeV. This number is almost two orders of magnitude higher than expected if only particles like pions, kaons and nucleons are assumed to be produced in high energy interactions.

The delay Δt of a particle of mass m (GeV/c^2) in travelling a distance d (km) relative to a light signal in the same direction is

$$\Delta t \simeq \frac{dm^2}{2E^2c} \simeq \frac{1600\, dm^2}{E^2} \text{(ns)}$$

where c is the velocity of light (in km s^{-1}) and E is the total energy of the particle (in GeV). If this particle interacts in the TASS and loses a fraction η of its energy in the TASS then

$$\Delta t \simeq \frac{1600\, dm^2\eta^2}{E_{\mathrm{m}}^2} \text{(ns)}$$

where E_{m} is the measured energy release. For a nucleon of energy 20 GeV interacting in the TASS, η is nearly unity since the nucleon loses all its energy due to multiple interactions in the thick body of absorber and thus

$$\Delta t \simeq 4d \text{ (ns)}.$$

Thus in order to explain a delay of 28 ns the nucleon is required to travel 7 km without interaction, which is rarely possible as shown by the detailed calculations mentioned earlier which take into account also the zigzag nature of the nucleon path in the atmosphere due to transverse momentum acquired in each interaction. These calculations have also shown that the increased path length expected for hadrons, if the transverse momenta acquired by the produced particles at higher energies are relatively higher (a few Gev/c) as suggested by many air shower experiments (eg Bakich *et al* 1970), does not lead to any significant increase in the relative number of high energy delayed hadrons arriving at distances less than 20 m from shower axis. The effect of higher transverse momentum is felt only at large distances from the shower axis. The large delays observed also cannot be accounted for in terms of heavier unstable (lifetime $< 10^{-8}$ s) particles since the particles are required to travel distances of the order of a few kilometres and do not have the advantage of high Lorentz factor. The possibility of production of α particles with high enough energy in high energy hadron interactions exists though the expected production cross section is very small. Since the interaction and consequently fragmentation probability for α particles in the atmosphere is relatively very high compared to nucleons, it is necessary to assume considerable α production in interactions occurring just one to two kilometres above the observational level. The hadron interactions at this level in showers of energies of about 3×10^{14} eV are mostly due to hadrons of energies less than about 1000 GeV. Thus if the high energy delayed events are sought to be interpreted as due to secondary α particles, it is necessary that about 5–10 % of interactions of energies 200–1000 GeV should produce at least one α particle. There is no experimental evidence as yet of such abundant production of secondary α particles of energies of a few tens of GeV, in thousands of interactions studied in nuclear emulsions and cloud chambers by many workers. The possibility of a fragment of primary nucleus, which initiated the air shower, surviving up to the observational level, can also be discounted for interpreting the high energy delayed events since these fragments have a very low probability of surviving in the atmosphere and of having the necessary energy and directional characteristics required. Thus it seems rather difficult to interpret the high energy delayed events within the framework of the present knowledge of the phenomenology of high energy interactions and the composition of the particles produced in these interactions.

The high energy delayed events find a natural explanation if relatively stable (lifetime $> 10^{-6}$ s) interacting particles with mass considerably higher than the nucleon mass are assumed to exist in nature and are produced occasionally in high energy interactions taking place during the development of the hadron cascade of an air shower. If the massive particles have interaction characteristics similar to those of nucleons, that is, interaction mean free path in iron approximately 120 g cm^{-2} and average inelasticity in an interaction about 0·5, then the observed energy–delay characteristics, say 20 GeV energy release and 28 ns delay, can be explained as due to a particle of mass of about 2–3 GeV/c^2. However, if the particles have longer interaction mean free paths as suggested by the distribution of energy in different TASS channels for the high energy delayed events (tables 3 and 4) and mostly escape another interaction in the TASS, η has to be considerably smaller than unity. This necessitates the assumption of a larger mass for the proposed particle than 2–3 GeV/c^2. This is also necessitated by the observation that there are events with delay greater than 30 ns and energy greater than 100 GeV.

Since three parameters η, m and d are involved in the energy–delay relation and the experiment provides only energy release and delay, it is not possible to determine uniquely the mass of the particle. Detailed calculations assuming some form of production mechanism for these massive particles and their interaction characteristics can, in principle, provide a better determination of mass if the calculated time spectra of the massive particle can be fitted to the observed events. However, the meagre statistics available do not encourage such an exercise and therefore up to the present only a guess, which is consistent with the observations, has been made. Most of the events can be understood as due to a particle of mass of the order of 10–20 GeV/c^2 which loses, on the average, 10–20% of its energy in the TASS and has an interaction mean free path of 300–400 g cm^{-2} of iron. The events of much larger energies, for instance more than 100 GeV, can be understood if in these events the particle has either interacted twice or lost 50–60% of its energy in a single collision. Assuming that such particles exist, the flux of these particles can be estimated in the following three ways.

(i) Since the 36 events have been collected by a detector of area 1·44 m^2 in a total of $3{\cdot}5 \times 10^4$ showers of size in the range $6{\cdot}7 \times 10^4$–$1{\cdot}8 \times 10^6$, the flux of the massive interacting particles in these showers can be given as 8×10^{-4} m^{-2} shower^{-1} assuming uniform distribution of these particles in the 0–20 m region around the axes of the showers.

(ii) Since the massive particles constitute nearly 0·5% of all hadrons of energy greater than 20 GeV and since a shower of size 10^5 (primary energy $\simeq 3 \times 10^{14}$ eV) contains about 150 hadrons of this threshold energy, 90 of which are contained within 20 m, it can be estimated that such a shower contains only one or two such massive particles at the observational level of 800 g cm^{-2}. This is deduced on the assumption that the lateral distribution of massive particles is similar to that of hadrons. It may be noted that the number of massive particles having energy lower than the threshold of 20 GeV set in the present analysis is not significant since the number of large delay (> 100 ns) events is very small. Only four events have been observed in the whole experiment which have released about 10 GeV energy in the TASS and are delayed by more than 100 ns. It is difficult to guess the number of high energy massive particles which have been missed in the present analysis due to the delay threshold of 21 ns. However, these uncertainties make all estimates of the flux of massive particles uncertain to within a factor of about two.

(iii) Since the detection of massive particles in the present experiment is restricted to within 20 m of axes of air showers and there is a tendency for the particle density to decrease with distance away from the shower axis, it is difficult to calculate the flux of massive particles in conventional units of particles $cm^{-2} s^{-1} sr^{-1}$. The flux in these units can be calculated only under the following assumptions: (*a*) the number of massive particles associated with showers of size less than $6{\cdot}7 \times 10^4$ is negligible, meaning thereby that there is a production threshold for these particles at about 10^{14} eV, and (*b*) these particles are always associated with air showers. The first assumption is supported by the experimental data as discussed in the last section and the second assumption specifies the production mechanism of the massive particles. After taking into account the selection biases in the experiment, it is deduced that the flux of the massive particles having the delay–energy characteristics as mentioned earlier is $8 \times 10^{-10} cm^{-2} s^{-1} sr^{-1}$. Correcting for the number of particles which might have released less than 20 GeV energy in the TASS or might have been delayed by less than 20 ns due to their high energies, it is estimated that the flux of massive interacting particles associated with showers initiated by primary cosmic rays of energy greater than 3×10^{14} eV is approximately $1\text{–}2 \times 10^{-9} cm^{-2} s^{-1} sr^{-1}$. It hardly needs to be mentioned that the flux will be higher near the axis of the shower and lower at far-off distances from the shower axis.

5. Discussion

Experiments to look for massive particles in air showers have been carried out by Damgard *et al* (1965a, 1965b), Chatterjee *et al* (1965), Jones *et al* (1967), Bjornboe *et al* (1968), Dardo *et al* (1968, 1971) and Picchi *et al* (1971). Except for the experiment of Dardo *et al* (1968, 1971) all other experiments have failed to detect these particles and have set upper limits on the flux of the massive particles of about a few times 10^{-10} particles $cm^{-2} s^{-1} sr^{-1}$. Therefore the results of the present experiment may appear to be in disagreement with the results of these experiments. However a detailed study of the requirements imposed on the characteristics of the massive particles reveals that there is no basic disagreement. Damgard *et al* (1965a, 1965b) restricted themselves to the observation of delayed signals from a detector placed below a huge absorber (900 g cm^{-2} iron). The minimum delay required was 100 ns relative to the air shower signal. Considering the paucity of events beyond 100 ns even in the present experiment, which has no such absorber and also the observation that cascades generated in the TASS by particles which are candidates for massive particles die down rather fast, it is not surprising that not many interesting events were seen by Damgard *et al.* Chatterjee *et al* (1965) observed 13 events in 23 days of operation which were delayed by more than 100 ns and which showed energy release of more than 7 GeV in the TASS. However due to possible experimental uncertainties regarding energy and time measurement, Chatterjee *et al* did not interpret their high energy delayed events in terms of massive particles. The data of that experiment have been analysed in detail recently (Tonwar 1970) and it has been found that the results support the present experiment.

The experiment of Jones *et al* (1967) is similar to the present experiment in many ways except for the absence of any detailed information on shower parameters. Jones *et al* have reported on the basis of data collected during 1542 h an upper limit on the flux of massive interacting particles of about 5×10^{-10} cm^{-2} s^{-1} sr^{-1}. However, from the observed energy distribution of particles delayed by more than 30 ns, given in their paper, it is seen that there are about 30 events whose energy release in the spectrometer exceeds 20 GeV. In these events the energy loss is confined to one or two channels of the spectrometer, which is a characteristic very similar to the one observed in the present experiment for the high energy delayed events. It is this characteristic of high energy delayed events which has led Jones *et al* to interpret them as due to low energy nucleons whose energy has been overestimated by the spectrometer. It needs to be mentioned that due to the small number of sampling probes in their spectrometer, the overestimation of energy due to heavily ionizing particles produced near or in the scintillator tends to be large. However, Monte Carlo calculations (Tonwar 1970) carried out for the TASS when repeated for their spectrometer, show that only about one third of the number of delayed events can be attributed to low energy nucleons. Thus it is suggested that many of the events observed by Jones *et al* can also be interpreted as due to massive interacting particles. It is interesting to note that the number of delayed high energy particles is similar in both the experiments, that of Jones *et al* and the present one, even though the minimum shower size demanded in the two experiments is different. Jones *et al* collected 3×10^5 showers in 1542 h compared to $3{\cdot}5 \times 10^4$ showers collected in the present experiment in 1280 h. This comparison supports the argument advanced in the previous section that the number of massive particles decreases rapidly for shower sizes lower than about 10^5 particles. This has an important consequence on the production cross section as well as on the production mechanism of these massive particles.

The experiments of Bjornboe *et al* (1968), Dardo *et al* (1968, 1971) and Picchi *et al* (1971) have all been carried out underground. Two experiments have been carried out by Bjornboe *et al* to search for massive particles, named 'plutons' by the authors, in air showers. In the first experiment the delay between the signals from a surface scintillator and a detector kept at a depth of 36 mwe underground was measured and evidence for peaks in the delay distribution extending from 20 to 500 ns was looked for. Since no enhancement was seen above the background level in any delay interval, an upper limit of the order of 3×10^{-10} particles cm^{-2} s^{-1} was deduced for the flux of massive particles. In the second experiment of Bjornboe *et al* the underground detector was kept at a depth of 16 mwe. But the detection of the massive particle required a delayed π–μ–e type of event in the detector system underground. In this experiment the upper limit to the flux was deduced as about 2×10^{-10} particles cm^{-2} s^{-1}. These upper limits are a factor of 3–5 lower than the flux obtained in the present experiment. However as pointed out by Bjornboe *et al* in their paper, their experiment is sensitive to massive particles only if the inelasticity of these particles in their interactions is rather small ($< 0{\cdot}05$). In the case of higher inelasticity the particle flux is expected to be strongly attenuated at the large depths of their experiment. The massive particles proposed to explain the high energy delayed events of the present experiment, on the other hand, should have higher inelasticity if they are to explain the observed delay–energy characteristics. Thus there does not seem to be any disagreement between the results of the experiments of Bjornboe *et al* and the present experiment. In another experiment underground at 70 mwe Dardo *et al* (1968, 1971) have reported on the observation of a positive flux of about $3\times10^{-8}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ of delayed particles having delays of 10–15 ns relative to other particles underground, presumably muons, which are part of an air shower. Also the delayed particles were found to give ionization in the detector corresponding to that expected from fractionally charged particles and interact in the absorber in between the detectors with a characteristic interaction mean free path of approximately $600\,\text{g cm}^{-2}$ of lead. The preliminary results of an improved experiment incorporating spark chambers being carried out at the same location (Picchi *et al* 1971) show essentially the same frequency of shower events. However, detailed analysis regarding pulse size and delay distributions are not yet available to conclude whether the results concerning fractionally charged particles agree or disagree with those of Dardo *et al.*

It should be mentioned here that the present experiment does not measure the charge of the massive interacting particles. However, it seems clear from a comparison of the flux observed in the present experiment ($\simeq10^{-9}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$) with the upper limits on the flux of fractionally charged particles in air showers ($\simeq10^{-10}$–10^{-11} $\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$) obtained by Hazen (1971) and Clark *et al* (1971) that these massive particles are not fractionally charged.

6. Conclusion

The study of time structure of interacting particles of energies greater than 20 GeV near the axes of air showers of energies greater than about 10^{14} eV has revealed that there are cases of large delay high energy particles whose observed frequency cannot be understood in terms of the behaviour of known hadrons in air showers within the framework of the present knowledge regarding high energy interactions, and development and propagation of showers in the atmosphere. These particles can however be interpreted in terms of as yet unknown massive interacting particles. The observed delay–energy characteristics for these particles are satisfactorily explained if these particles have masses in the range 10–20 GeV/c^2 and are characterized by an average inelasticity of about 0·2 and mean free path in iron of approximately 300–$400\,\text{g cm}^{-2}$. The experimental data are inadequate to fix any of these characteristics of the particles with better accuracy. The flux of these particles obtained after making some plausible assumptions about their production characteristics is about 1–$2\times10^{-9}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$. Also the number of such particles in a shower of size about 10^5 is estimated to be one or two particles per shower. It is shown that the present result on heavy mass particles is not contradicted by the results of most other experiments, which have given only upper limits to the flux. The particle charge is not distinguished by the present experiment but comparison of the flux given by the present experiment with the results of those which have looked for fractionally charged particles in air showers suggests that these massive particles are unlikely to have fractional charge. The interpretation of the large delay high energy events in terms of massive interacting particles is a very likely one, but by no means unique. In order to substantiate this interpretation, it is necessary to record the interaction itself in a visual detector like a multiplate cloud chamber or a spark chamber, and at the same time measure the delay of the interacting particle relative to the air shower front. An experiment on these lines is being set up at Ootacamund using a large multiplate cloud chamber.

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Appendix. Discussion of errors

A.1. Errors in shower parameters

The probable errors in the various shower parameters are obtained through artificial air shower analysis. These are discussed in detail elsewhere (Tonwar 1970). It has been estimated that the measured shower sizes are accurate to within $\pm 40\%$, the arrival direction has an accuracy of $\pm 5°$ and the distance between the hadron detector and the shower axis is accurate to within ± 4 m for an individual shower.

A.2. Errors in arrival time

The error in the measured arrival time results from the finite rise time in the electronics and jitter in the photomultiplier. These errors have been measured experimentally as discussed elsewhere (Tonwar *et al* 1971a) and it is shown that the measured time has a gaussian distribution around the true value. The width of the distribution depends on the pulse amplitude which itself is related linearly to the number of particles traversing the detector. The half width σ of the distribution $(\exp(-t^2/2\sigma^2))$ in the case of visible ionization in a given channel, say C_L, exceeding about 800 MeV is 6 ns. Thus for energy releases in a given channel exceeding about 15 GeV this value for σ can be used for estimating the number of events in which time could have been wrongly measured. However, since four channels of the TASS are mixed and the mixed pulse is timed, the timing error is expected to be considerably smaller. Using the value of 6 ns for σ it can be easily seen that the probabilities for the time of an event having energy release of more than 20 GeV in the TASS being overestimated by 7, 14 or 21 ns are $1{\cdot}2 \times 10^{-1}$, $9{\cdot}8 \times 10^{-3}$ and $2{\cdot}2 \times 10^{-4}$ respectively.

A.3. Errors in the measurement of energy release

The hadron energy is computed using the visible energy release in various sampling layers of the TASS and it is subject to errors of the following types.

(i) Errors due to the calibration and the logarithmic mode of recording the pulse height have been discussed in detail elsewhere (Tonwar *et al* 1971a) and it is concluded that while the error in the average pulse height attributed to a single muon going through the TASS vertically is $\pm 20\%$, the logarithmic mode of recording the pulse height leads to a systematic overestimate of the pulse height, *on the average*, by about 20%. This overestimate occurs due to occasional overriding of small pulses on the decaying tail of the main pulse. It is found that the overestimation factor has a value of more than two in about 3% of the events and more than four in less than $0{\cdot}2\%$ of the events. Thus these errors can be easily taken into account in the data statistically. It is interesting to note that few events in tables 3 and 4 are free from this error due to experimental conditions at the time of arrival of the particular events. The visible energies for these events are marked by an asterisk.

(ii) Errors due to finite size, the striated nonhomogeneous structure, the finite number of the sampling layers and the lack of information on the point of entry into the TASS for the incident interacting particles (these errors are again discussed in detail elsewhere, see Tonwar 1970) and the estimates of their magnitude have been made on the basis of detailed Monte Carlo simulations of hadron as well as electron–photon cascades, in the TASS. In the TASS due to the presence of a sampling layer after every 30 $g\,cm^{-2}$ of iron, the effect of fluctuations is not very significant. The calculations have assumed a realistic model for the nuclear disintegration process with the hadron interactions. It is seen that for hadrons entering the TASS from the top, the measured energy, given by the sampled ionization, is nearly 60% of the total energy of the hadron and the spread around this value is $\pm 30\%$. Unless the incident particle strikes the TASS very near the edge in an outward going direction, there is no energy loss, through sides or bottom for hadrons of energies less than about 100 GeV. Even for particles entering from the side nearer the C channels the energy absorption is quite efficient for hadrons of this energy. Considering the transition effect as measured by Crannel *et al* (1969), the zenith angle distribution of showers and the effective geometry of the TASS and taking into account the systematic overestimate of the energy discussed earlier, it is concluded for known hadrons the energy release measured by the C and D channels is nearly 70–80% of the primary hadron energy. The calculations also reveal that due to any rare fluctuations in the cascade development, say due to more energy going into slow particles produced in or near the scintillators, the measured energy release has a probability *smaller than* 0·5% of exceeding the primary hadron energy. On the contrary the measured energy release is much more often an underestimate for the hadron energy.

(iii) Errors due to the heavily ionizing particles have been mentioned above in estimating the errors in general; however it is necessary to discuss this aspect in some detail to estimate the errors in rather rare cases. If the cascade produced by an interacting particle in the TASS has N hadron interactions each contributing, say 800 MeV (Murzin 1967), to the nuclear disintegration process, then the number of slow particles, on the average, depositing their energy in the scintillator can be written as

$$N_{\text{slow}} = \tfrac{1}{15}N(n_g + n_{ng} + n_h + n_{nh})$$

the factor $\frac{1}{15}$ represents the ratio between uniformly spaced scintillator and iron media. n_g is the average number of grey particles produced per interaction, n_{ng} is the number of neutrons corresponding to grey particles. n_h and n_{nh} are the corresponding number of black particles and 'black' neutrons per interaction respectively. Now since the grey particles deposit energy in iron and scintillator in proportion of the matter traversed due to their higher energy (assumed to be, on the average, 165 MeV), then the excess visible energy deposited by the neutrons interacting in the scintillator and by the black particles can be taken as

$$E_{\text{slow}} = \frac{N}{15}n_g E_{ng} + \frac{N}{15}n_h E_h + \frac{N}{15}n_{nh}E_{nh}$$

where E_{ng}, E_h and E_{nh} are the energies lost in the form of visible radiation by a 'grey' neutron, a black particle and a 'black' neutron in the scintillator respectively. Assuming that the different interactions are statistically independent, the excess energy in the case of a four standard deviation fluctuation (probability $< 10^{-3}$) in the number of particles depositing their energy in the scintillator is

$$\Delta E_{\text{slow}} = 4\left(\frac{N}{15}\right)^{1/2}(E_{\text{ng}}n_{\text{ng}}^{1/2}+E_{\text{h}}n_{\text{h}}^{1/2}+E_{\text{nh}}n_{\text{nh}}^{1/2}).$$

Assuming rather high values for E_{ng}, E_{n} and E_{nh} of 50, 10 and 5 MeV respectively and taking $n_{\text{ng}} = 2$, $n_{\text{h}} = 5$ and $n_{\text{nh}} = 5$ one obtains for a hadron of energy about 20 GeV ($N \simeq 15$)

$$\Delta E_{\text{slow}} \simeq 400\ \text{MeV}$$

which would lead to an overestimate in the measured energy by 6 GeV. Since all other processes in the TASS lead to an underestimate of the energy, this 6 GeV is not sufficient to make the measured energy exceed the primary hadron energy. This crude estimate shows that as long as the primary energy of the interacting particle is about 20 GeV or higher, the measured energy is unlikely to exceed the primary energy. It is thus clear from this that the visible ionization observed for the high energy delayed events is too high to be accounted in terms of low energy particles and the energy of the interacting particles is most likely to be considerably higher than obtained from the measured energy release in the TASS.

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