S. Naranan, *et al.*
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Cloud Chamber Evidence for the Presence of Simultaneous High Energy Nuclear-Active Particles at Mountain Altitudes.

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Summary. — In an examination of twenty two thousand pictures of penetrating showers recorded with a multiplate cloud chamber, ($60 \text{ cm} \times 60 \text{ cm} \times 20 \text{ cm}$), in a time of operation of 5 310 hours, at an altitude of 2.2 km, thirtytwo cases have been obtained in each of which two or more simultaneous parallel high energy nuclear-electromagnetic cascades, (~ 100 GeV), are seen developing in the plates of the chamber. The visible energy of the individual cores has been determined by the track length method. It is found that in most of the cases the visible energies of the parallel cascades in a picture are of comparable magnitude. The separation between the cores ranges from 5 to 40 cm, and the corrected distribution looks flat. There is clear indication that about half of the events are associated with dense air showers. The « unassociated » events have been interpreted in terms of local nuclear interactions of particles of energy $\geqslant 450$ GeV in air up to a height of 140 meters above the apparatus. The « associated » events have been explained as being parts of air showers containing about 100 nuclear-active particles of energy $\geqslant 100$ GeV near the core.

1. – Introduction.

While scanning pictures of penetrating showers obtained with a multiplate cloud chamber operated at an altitude of 2.2 km, several cases were noticed of « simultaneous » parallel high energy cascades which had developed in the

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plates of the chamber. A detailed analysis of these photographs showed that the events, in many respects, were similar to the « structure bursts » recorded by Grigorov *et al.* (1), at an altitude of 3.2 km, with crossed layers of ionization chambers under lead. The main features that make these « double core » events observed in the cloud chamber important are:

1) the parallel cascades are due to interactions of high energy nuclear-interacting particles of *comparable* energies (~ 100 GeV);

2) the frequency of occurrence of events with a separation < 40 cm over an area of 0.11 m^2, which is the area of the chamber, is not negligibly small; and

3) about 50 per cent of the « double core » events are associated with dense air showers as shown by the cloud chamber photographs.

An attempt at even a semi-quantitative understanding of these features of the « double core » events has led us to the conclusions that:

a) in high energy interactions ($\geqslant 450$ GeV), most of the energy is carried away by few secondaries with a ratio of maximum to minimum energy less than 7 to 8 and

b) extensive air showers of energy $\geqslant 10^{15}$ eV at mountain altitudes contain a number of nuclear active particles of high energy (~ 100 GeV) of the order of 100.

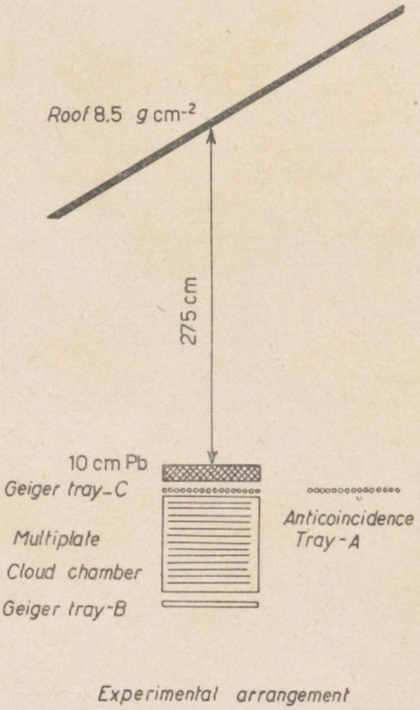

Fig. 1. – Experimental arrangement.

2. – Experimental arrangement.

The photographs were obtained with a multiplate cloud chamber of dimensions $(60 \times 60 \times 20)$ cm^3, operated for a period of 2 years a Ootacamund at an altitude of 2.2 km above sea level. The chamber was triggered with a penetrating shower selection system. The details of the experimental arrangement are given in Fig. 1. The chamber was fitted with thirteen 1.25 cm lead plates for part of the time, and with thirteen 1.9 cm brass plates for the rest of the time.

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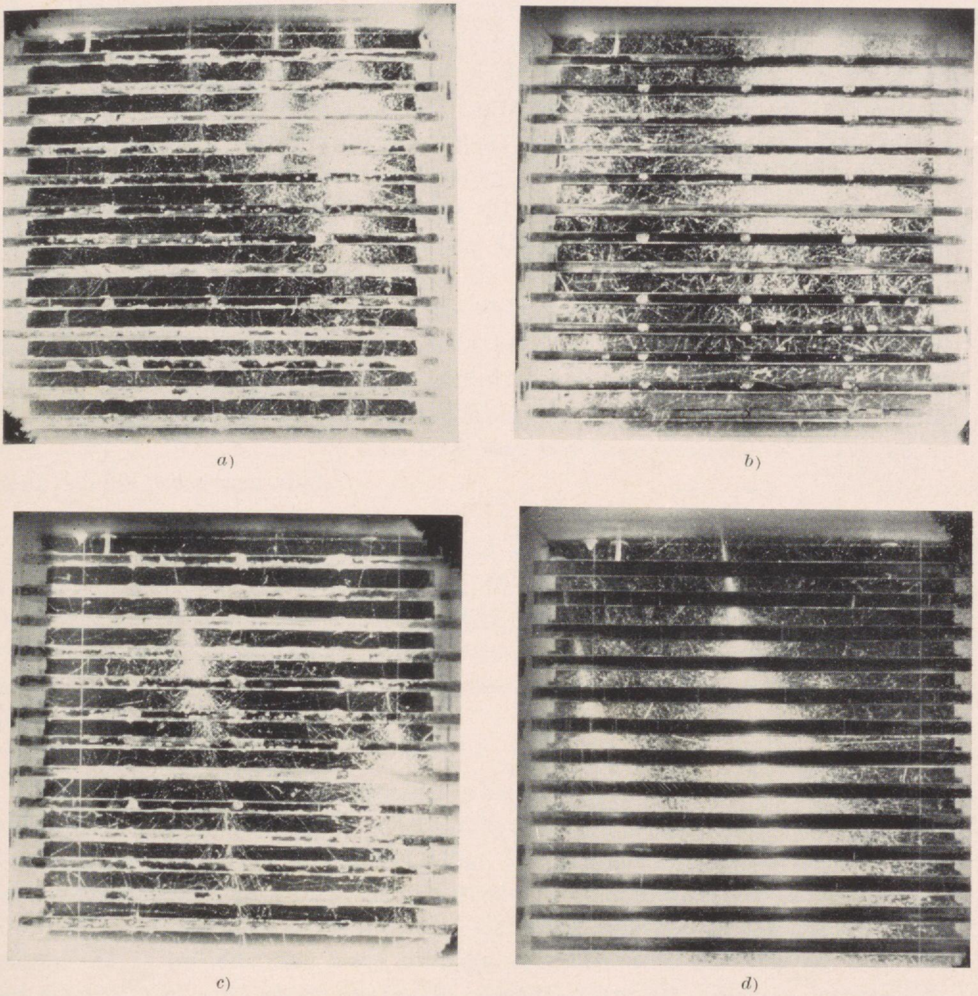
(1) N. L. Grigorov, V. Y. Shestoperov, V. A. Sobinyakov and A. V. Pogurskaya: *Žu. Èksp. Theor. Phys.*, **33**, 1099 (1957).



a) b) c) d)

Fig. 2. – *a*) Event No. OV 98. An event in which both the cores are in geometry and enter the chamber after being partly developed in the lead on the top. A third core of low energy can be seen on the left. Visible energy estimates: Left 26 GeV, Right 120 GeV. *b*) Event No. DM 32. An event in which both cores are in geometry and enter the chamber after being fairly well developed in the lead on top. Numerous electron tracks seen in the first few compartments, far from the cores, provide evidence for the association of the event with extensive air shower. Visible energy: Left 95 GeV, Right 55 GeV. *c*) Event No. TZ 143. An event in which both the nuclear-active particles interacted inside the chamber. Energy estimates: Left 21 GeV, Right 50 GeV. *d*) Event No. VI 100. A typical event in which the visible energies of the cores are very high. Visible energy estimates: Left 95 GeV, Right 185 GeV. (In this case the visible energies may be underestimated by as much as a factor 2. See text).

3. – Results.

3·1. *Frequency of events obtained.* – A total of 22 000 pictures of penetrating showers of energy $\geqslant 10$ GeV were obtained. Nuclear interactions of energy $\geqslant 200$ GeV were recorded with a frequency of about one a day. There were 32 cases in each of which two or more parallel high energy cascades were seen to have developed in the plates of the chamber; these are referred to hereafter as « double core » events (*). Cloud chamber photographs of four such typical events are shown in Fig. 2.

The total time of operation of the chamber was 5 310 h. For a period of 2 380 h, the chamber was operated in conjunction with an anticoincidence Geiger counter tray of area 0.3 m^2 placed at a distance of about a meter from the chamber. During this period 8 double core events were recorded. In the remaining 2 930 h, when the anti-tray was not in operation, as many as 24 such events were recorded.

3·2. *Lateral separation.* – The lateral separation of the cores varied from 5 cm to 40 cm, the mean value being 16 cm. The frequency distribution as a function of lateral separation looks flat, when corrected for the variation of the efficiency of detection with separation. Events with core separation less than 4 cm were discarded since in these cases the resolution into individual cores was difficult.

3·3. *Nature of the particles producing the cascade.* – Each event was examined stereoscopically to determine whether or not the axes of the cascades pass through the top 10 cm lead block (Fig. 1). All those cascades in which the axes were found to pass through 10 cm lead, were necessarily of nuclear origin, since in these cascades the number of electrons observed in the various compartments of the chamber were at wide variance with the number expected for remnants of pure electromagnetic cascades after 16 radiation lengths. In many of these cases, as also in most of the cases where the cores did not pass through the lead block, the emergence from the cores of heavily ionizing particles or penetrating particles provided direct evidence for the nuclear origin of the cascades.

3·4. *Energy estimates.* – The visible energies in the individual cores were estimated by the track-length method. The number of particles in each compartment was determined as follows: the *projected width* of complete saturation

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(*) There are a few events with more than two cores. However, we designate all the events as double core events.

was first measured and a track density of 10 per mm was attributed to this width. For the other less dense regions, appropriate track densities were estimated visually and multiplied by the corresponding widths. The number of particles obtained by this method is naturally a lower limit, since the central saturated region for which a flat density has been ascribed may have a gradient. With a view to judge the extent of uncertainty due to this gradient, we re-evaluated the number of tracks assuming that they were distributed laterally as $1/r$ up to distances at which the number of tracks was small. For this case, it is easy to show that the total number of tracks in the shower in the compartment is given approximately by $2.5w_i \cdot i$, where w_i is the width of the central region at the edge of which the projected ionization is i times the minimum ionization. This re-evaluation showed that, for cascades with a visible energy up 75 GeV, the correction needed was negligible compared to the uncertainties in the visual estimate, *i.e.* ± 25 per cent. In the case of very high energy cascades, (estimated visible energy $\geqslant$ 200 GeV), the estimated track length may be an underestimate by as much as a factor of two, and never more. However, we did not correct our visual estimates by the above method because it involves an assumption of a lateral distribution whose validity may be questioned.

To obtain the visible energies of the cascades, the track length was multiplied by 34 MeV per radiation length for lead plate pictures (*) and by 36 MeV per radiation length for brass plate pictures. Our energy estimates may be regarded as absolute lower limits and not likely to be in error in absolute values by more than a factor of two in the extreme cases. As we shall see later on, the conclusions drawn in this paper do not depend on the absolute values of energy so much as on the lower limits of the energy values. In the Table, we have listed the visible energies of the two cores for all the observed events.

There is no way of knowing whether a particular cascade had been initiated by a nucleon or a pion. So all the events were analyzed assuming the two possibilities. The energy of the particle was obtained by multiplying the visible

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(*) There is some confusion in the literature about the value to be used for lead. According to BENDER (²) it is 34 MeV per radiation length. HAZEN (³) gives a value of 25 MeV per radiation length, which may be said to be not in disagreement with Bender's. But HINOTANI *et al.* (⁴) and DANILOVA *et al.* (⁵) arrive at a figure of 25 MeV per cm of lead, which means a value of about only 15 MeV per radiation length. However, in these latter experiments, the primary energies were obtained from calculated shower curves which may be in error.

(²) P. A. BENDER: *Nuovo Cimento*, **2**, 980 (1955).

(³) W. E. HAZEN: *Phys. Rev.*, **99**, 911 (1955).

(⁴) K. HINOTANI, K. SUGA and Y. TANAKA: *Journ. Phys. Soc. Japan*, **9**, 883 (1954).

(⁵) T. V. DANILOVA, O. I. DOVZHENKO, S. I. NIKOLSKI and T. V. RAKABOLSKAYA: *Žu. Ėksp. Theor. Phys.*, **34**, 541 (1958).

TABLE. I. – *Visible energy estimates of cores.*

Event No.	Visible energy of cores in GeV		Remarks
	Higher	Lower	
UD 253	29	21	« Unassociated events »
XJ 40	84	41	
XS 64	58	21	
TS 81	33	31	
BB 128	90	55	
CL 35	63	49	
RP A	160	19	
YG 20	25	24	
BS 81	271	187	« Associated events »
BW 15	53	40	
CA 84	200	81	
WZ 96	36	13	
BN 53	68	56	
RQ 51	80	14	
TZ 143	50	21	
VI 100	185	95	
TG 94	40	21	
RZ 51	49	19	Both cores out of geometry.
DM 32	195	55	Events obtained with the anti-coincidence tray in operation.
OV 98	120	26	
OX 98	66	56	
SZ 288	39	21	
CT 81	36	14	Events which could arise from interactions in the roof.
IY 128	12	10	
IZ 174	36	12.5	
KB 18	40	9.5	
PW 51	28	9	
RC 127	10	10	
RD A	89	21	
SJ 144	25	10	
VD 74	9.2	5.3	
XV 18	6.6	5.7	

energy of the cascade by a factor of 4, when the particle producing the cascade was considered to be a nucleon, and by a factor of 2, when the particle was considered to be a pion. These factors were obtained on the assumption that the inelasticity is 0.5 in the collision of nucleons with lead or brass nuclei and 1 in the case of collisions of pions. The possible contribution to the visible energy from the π^0's produced by subsequent collisions of secondary charged pions was also taken into consideration, in arriving at these conversion factors.

3·5. *Classification of events.* – As shown in Fig. 1, there was a roof over the cloud chamber at a height of about 275 cm, with an equivalent thickness of 8.5 g cm^{-2}, and composed of only light elements. The cascades observed in the chamber were normally dense and broad and so the parallelism could be judged to an accuracy of only 2 to 3°. Therefore some of the cascades may in reality be slightly convergent and arise from the particles produced in high energy interactions in the roof. We have separated the possible « roof » events from those that have occurred outside from considerations of the estimated energy, the separation of the cores and *upper limits* to the transverse momenta, *i.e.* 1 GeV/c for pions and 3 GeV/c for nucleons. This classification is not sensitive to the nature of the particles producing the cores, whether they are pions or nucleons. It turns out that not more than 10 events can be attributed to secondaries arising from interactions in the roof. This category is mostly made up of the very low energy events (see Table).

Out of the remaining 22 events, 18 were obtained when the anti-tray was not in operation, and only 4 when the anti-tray was in operation. In order to avoid any bias due to the selection system, we shall, in what follows, consider only those events which were obtained when the anti-tray was not in operation. Out of the 18 events, 17 were such that at least one of the two cascades passed through the top lead block. There was only one case, in which neither of the cores passed through the top lead. We shall ignore this, since it does not satisfy the triggering requirement. Of the 17 events, in 9 cases the cloud chamber photographs showed association of the events with rather dense ($\geqslant 100$ particles m^{-2}) air showers. The air shower density is a conservative estimate in view of the presence of a 10.5 cm lead layer on top of the chamber. Hereafter, we shall refer to these events as « associated events ». In the remaining 8 events, either the association was weak (density $\leqslant 20$ particles m^{-2}) or there was no association at all. We shall call these as « unassociated events » for the purposes of discussion.

4. – Discussion.

4·1. « *Unassociated* » *double core events.* – As seen from the Table, the visible energies of individual cores of unassociated double core events vary from

19 GeV to 160 GeV. However, the ratio of the visible energies of simultaneous parallel cascades is in all cases less than 3, except in one instance in which the ratio is about 8. These cascades, as previously pointed out, cannot be pure electromagnetic cascades, and must arise as a result of the collision of nuclear interacting particles, like nucleons and pions, with lead or brass nuclei as the case may be. In order to release visible energies of more than 19 GeV, a nuclear-interacting particle must have an energy greater than 38 GeV if it is a pion and greater than 76 GeV if it is a nucleon, (see previous Section 3·4). These pions and nucleons may arise in collisions—hereafter referred to as *local interactions*—of higher energy primary particles with air nuclei in a layer of air above the chamber. The maximum separation of the cores, observable in this experiment, is about 40 cm; this naturally restricts the height at which the interaction could have occured in the air. We can, however, fix within broad limits, for each observed event, the potential range of heights in which the interaction could have taken place. For this we have used the estimated energies of the two cores and assumed values fo 270 MeV/c and 500 MeV/c (*) for the transverse momenta of pions and nucleons respectively. The broad limits defining the range of heights come from the limits $\big((4 \div 40)\ \text{cm}\big)$, for the observable separation of the cores. From this the mean height of interaction was obtained as 140 metres and the amount of matter for interaction $\sim 14\ \text{g cm}^{-2}$. The question arises whether the observed number of unassociated double core events can be quantitatively explained in terms of interactions in this $14\ \text{g cm}^{-2}$ of air; for this we need to know the efficiency for the detection of double core events and the flux of high energy particles at the level of observation. The efficiency depends on the separation between the cores and the probabilities of interaction in the lead block and in the plates of the chamber. The separation varies from 4 to 40 cm and the mean value is 16 cm. But as already pointed out, the frequency distribution of events as a function of lateral separation is flat and so the true mean separation of the double cores may be much larger than 16 cm. However, an upper limit to the efficiency of detection is obtained by considering the mean separation as 16 cm. Nuclear interactions taking place in the top few cm of the lead block will not be detected since the cascades produced will die down before reaching the chamber. We have considered therefore only 5 cm of lead immediately above the chamber as the effective producing layer, in addition

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(*) The potential height at which interactions could have occured depends sensitively on the *lower limits* to the transverse momenta assumed. For the purposes of the present estimate, we have assumed that the distribution of transverse momenta for pions is flat between 200 MeV/c and 500 MeV/c which gives a weighted mean value of 270 MeV/c. For nucleons we have used an effective mean value of about twice the transverse momentum for pions, which we think is reasonable in the absence of more exact information on the transverse momenta for nucleons.

to the plates inside the chamber. For interactions in the plates, the survival probability through the top lead block has to be taken into account, for those cascades for which the axes pass through the top lead. From all such considerations we arrive at an upper limit of 0.06 for the overall efficiency for the detection of double core events in the chamber. This efficiency means that if 100 pairs of nuclear interacting particles arrive with a mean separation of ~ 16 cm, with one of the nuclear interacting particles in the solid angle defined by the chamber, then 6 cases of double events will be observed in the chamber. Actually 8 cases have been observed, in a time of operation of 2 380 hours, over an area of $0.11\ \text{m}^2$, within a solid angle of 0.5 sr. This means there must have been at least 128 pairs of nuclear-interacting particles incident during this time. From this we can deduce the flux of particles that should have passed through the $14\ \text{g}\ \text{cm}^{-2}$ of air and produced nuclear interactions which gave rise to these 128 pairs. This flux comes out to be $1.4\cdot 10^{-3}\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$. This value corresponds to the flux of nuclear-active particles of energy $\geqslant 450$ GeV, at our height of observation, as deduced from the frequency of single interactions in the cloud chamber during the same operating period and as also deduced from the observations—at a higher altitude—of ČUDAKOV *et al.* ([6]) corrected suitably for the altitude difference. It was noted that about 15 per cent of the single nuclear interacting particles at these energies were associated with dense air showers. So, only 85 per cent of the flux was taken into account when making the comparison with the flux of particles responsible for the unassociated double core events.

If we now try to understand the double core events in terms of the interactions of particles of energy $\geqslant 450$ GeV we immediately come to the conclusion that this is possible only if in a majority of the collisions the primary energy is carried away by a few secondary particles (including the follow-through nucleon). Only then can we get particles of comparable energy (within a factor of 7) and of such high energy. This conclusion is valid whether the cores are assumed to be produced both by pions only, or one by a nucleon and the other by a pion. If one of the cores is due to the follow-through nucleon then the inelasticity in the primary interaction has necessarily to be $> 12\%$. It is unlikely that in the majority of cases both the cores are produced by nucleons, since this involves the production of nucleon and antinucleon pairs in local collisions, for which the primary energy has to be much higher and for which the flux would be too small. The possibility of closely spaced comparable energy nucleons coming from the fragmentation of heavy primaries, particularly α-particles, can also be ruled out purely from flux considerations. The conclusion drawn by us regarding the nature of inter-

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([6]) A. E. ČUDAKOV, N. A. DOBROTIN, N. L. GRIGOROV, G. N. VERNOV and G. T. ZACEPIN: *Suppl. Nuovo Cimento*, **2**, 737 (1958).

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actions of particles of energy $\geqslant 450$ GeV, *i.e.* that the energy must be carried away by a few secondaries in a majority of the collisions, finds support in the recent results on the analysis of high energy jets with nuclear emulsions (7).

4·2. *Associated double core events.* – The nine associated double core events cannot arise from *local interactions* (see Section **4**·1) of unassociated high energy nuclear interacting particles, since the observed density of the associated air showers cannot be developed in a few grams of air. As pointed out before, the flux of single nuclear-interacting particles associated with air showers is only 15 per cent of the total flux. So, not more than one or two events can arise from the *local interactions* of associated nuclear-active particles. The associated double core events must then essentially be due to the nuclear-interacting particles in the cores of air showers. We know that the particles responsible for the observed cores have energies of ~ 100 GeV. Purely from considerations of transverse momentum, nuclear-interacting particles of about this energy will be spread out in a circular area with a radius of ~ 3 metres around the core. This being the case, the probability of two nuclear active particles arriving with a separation less than 40 cm is quite small, unless the number of nuclear active particles of this energy is very high. This number may be estimated as follows:

Let A denote the area over which nuclear-active particles, with energy required to produce the observed cascades, are spread out in air showers. We shall assume that the density is uniform over this area; for the present calculations and magnitudes considered, this assumption is not greatly in error. Let σ be the area of detection of the chamber. If F is the number of air showers incident over the area in the period of operation, the number of single core events in the chamber is given by

$$S = F\varepsilon_S \exp\left[-\frac{\sigma n}{A}\right]\frac{\sigma n}{A}\,,$$

where ε_S is the efficiency of detection of single core events and n is the number of nuclear-active particles in the air showers. The number of double core events (as defined previously by us) in the chamber will be given by

$$D = F\varepsilon_D\left\{1 - \exp\left[-\frac{\sigma n}{A}\right]\left(1 + \frac{\sigma n}{A}\right)\right\},$$

where ε_D is the efficiency for detecting double core events. Since we know the values of S, D, ε_S, ε_D and σ we can deduce the value of (n/A), the density

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(7) C. F. Powell « *Nuclear Processes at super-high energies* », Mimeographed report, Kiev Conference on High Energy Physics (1959).

of nuclear-active particles necessary to account for the observed ratio of single core events to double core events. We get

$$n/A = 3.6^{+1.0}_{-1.25} \quad \text{particles/m}^2 \; .$$

From this, to get at the total number of nuclear-active particles contained in the showers, we have to fix A. If we assume that the high energy nuclear active particles are mostly pions, with an energy $\geqslant 100$ GeV—necessary to produce the observed cores—they will be spread over a circular area of radius ~ 3 metres for an assumed transverse momentum of 400 MeV/c. If the nuclear active particles are nucleons, their mean energy has to be 200 GeV and if we assume a transverse momentum of 1 GeV/c, they have to be distributed over an area of radius ~ 3.5 m. The value of A can therefore be taken as ~ 30 m² Then n will be $70 \div 140$.

This calculation is based on the average behaviour of air showers, *i.e.* that on the average the particles are spread over a circular area of certain radius and the showers contain a definite number of nuclear active particles n. However, there may be wide fluctuations in the nature of collisions, in the transverse momenta acquired by the particles and in the number of nuclear-interacting particles produced; it is also possible that there are close correlations at production between pairs of particles. Some of the double core events might as well be the result of such wide fluctuations. However, we find that the ratio of the number of double core events to the number of single core events, (after correcting for detection efficiencies) is as high as 0.4. This gives us confidence that the application of an average picture may not be wrong.

From the frequency of observed events we may say that showers containing about 100 high energy nuclear-active particles at a mountain altitude of 2.2 km, correspond to primary energies of $\geqslant 10^{15}$ eV at the top of the atmosphere. Unfortunately, there are no experimental results at mountain altitude which tell us the number of nuclear-active particles of high energy (~ 100 GeV), in air showers. The experiments of ABROSIMOV *et al.* (⁸) at sea level, show that showers of size $3 \cdot 10^5 < N < 2 \cdot 10^6$ contain as many as 55 nuclear-active particles of energy above 100 GeV within a radius of 6 metres from the core.

As pointed out in the introduction, GRIGOROV *et al.* (¹) have observed the so-called « structure bursts » which are similar to our double-core events. However, the energies of the events observed by them are higher, as also the altitude of observation. They have interpreted their events in terms of purely local interactions of nuclear-active particles of energy $(10^{12} \div 10^{13})$ eV. The ob-

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(⁸) A. T. ABROSIMOV, V. A. DMITRIEV, G. V. KULIKOV, E. I. MASSALSKY, K. I. SOLOVYOV and G. B. KHRISHTIANSEN: *Žu. Èksp. Theor. Phys.*, **36**, 751 (1959).

served association with dense air showers is attributed to the development of cascades which arise from the decays of π^0-mesons produced in the same local high energy interactions. In our case, all the events cannot be attributed to local interactions only since, as already emphasized, the observed densities of associated air showers cannot be developed in a few grams of air and the flux of high energy single nuclear-active particles associated with dense air showers is much too small to account for the associated double core events.

Regarding the nature of local interactions, the conclusions of GRIGOROV *et al.* are similar to ours, *i.e.* that in high energy collisions in air the primary energy is carried away by a few secondary particles.

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We have great pleasure in thanking His Excellency BISHNURAM MEDHI, the Governor of Madras, for putting at our disposal laboratory space at Raj Bhavan, Ootacamund. We are thankful to Professor M. G. K. MENON for his interest in this investigation and for helpful discussions. The cloud chamber photographs used in this investigation were obtained in connection with an experiment on *S*-particles, and we are indebted to Mr. A. B. SAHIAR who initiated the project on *S*-particles in the Institute. We wish to express our thanks to Mr. SIDDESWAR LAL for his valuable help during the course of the experiment and the analysis. Our thanks are also due to Messrs. A. R. APTE and K. F. DINSHAW for their help in running the chamber.

RIASSUNTO (*)

Esaminando 22 000 fotografie di un uno sciame penetrante ottenute con una camera a nebbia con molte lastre (60 cm × 60 cm × 20 cm), in 5 313 ore di funzionamento, ad una altitudine di 2 200 m, si sono riscontrati 32 casi in ciascuno dei quali si vedono svilupparsi nelle piastre della camera una o più cascate nucleari-elettromagnetiche parallele simultanee di alta energia ($\sim$100 GeV). L'energia visibile dei singoli cores è stata determinata col metodo della lunghezza della traccia. Si trova che nella maggioranza dei casi le energie delle cascate parallele visibili nella stessa fotografia sono di grandezza paragonabile. La separazione fra i cores va da 5 a 40 cm, e la distribuzione corretta appare piana. Vi sono chiare indicazioni che circa la metà degli eventi sono associati a sciami densi dell'aria. Gli eventi « non-associati » sono stati interpretati in termini di interazioni nucleari locali di particelle di energia $\geqslant$450 GeV in aria sino ad un'altezza di 140 m al di sopra dell'apparecchio. Gli eventi « associati » sono stati interpretati come facenti parte di sciami dell'aria contenenti circa 100 particelle nucleari attive di energia $\geqslant$100 GeV vicino al core.

(*) *Traduzione a cura della Redazione.*

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Triggered Spark Counter Arrays of Large Area (Square meters) for Experiments on Very High Energy Cosmic Ray Particles.

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Summary. — The constructional and operational features of triggered spark counters of large area are described. These counters are being used, in conjunction with nuclear emulsions, in current experiments in this laboratory on high energy nuclear interacting particles which arrive simultaneously over large areas, sometimes associated and at other times unassociated with air showers. For these experiments the spark counters and emulsions are being used in arrays covering an area of a few square meters.

1. – Introduction.

Experiments are in progress in this laboratory to study in detail the frequency, multiplicity, energy distribution and lateral separation of high energy nuclear interacting particles associated and unassociated with extensive air showers. The frequency of these events is so low that it is necessary to have large detecting areas, of the order of several square meters, in order to record a sufficient number of events in a reasonable time of operation. Because of this requirement of a large area it is not practicable to use multiplate cloud chambers for a comprehensive investigation. In looking for an ideal detector that can give information on all the aspects mentioned above and which can be built economically to cover large areas, it was realized that this could be achieved with a suitable combination of spark counters and photographic

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(*) Now at Columbia University, U.S.A.

emulsions (*). For this it would be necessary to construct large area spark counters in which a visible spark would be produced at the position at which a beam of extremely collimated charged particles passed through it. The set-up that was envisaged was the following. The nuclear interacting particles would interact in an absorber and produce a narrow jet of charged and neutral pions; the γ-rays resulting from the decay of the neutral pions would, on passing through a lead converter below, give rise to a collimated beam of electrons; the beam of electrons and mesons then passes through a thin horizontal layer of nuclear emulsions followed by a spark counter immediately below. If the spark counter produces a visible spark at the position at which the beam of particles passed through it, then the co-ordinates of the beam in the emulsions would be known; the number of electrons in the beam can be counted in the emulsion and the approximate size of the interaction determined; a system of two spark counters one below the other, would enable a determination of the direction of the jet and would also fix the co-ordinates in the emulsion more accurately; the occurrence of simultaneous parallel sparks would reveal the presence of multiple nuclear active particles; the system could be put in association with an extensive air shower (EAS) array and the size and core position of the associated shower determined; if the core of the EAS passed through the area of the spark counters, then a very precise location of the position of the core would be possible; it is obvious that this system would work only at very high energies where the particles would be produced with the necessary collimation. These very attractive features prompted a detailed experimental investigation on large area spark counters.

In the first instance a spark counter comprising a metal plate on one side and a set of parallel wires on the other was constructed with a sensitive area 50 cm × 27 cm and was operated with a continuous (D.C.) voltage. This counter had an excellent response to α-particles but there were two serious disadvantages. Firstly, there were quite a number of spurious spark breakdowns and secondly, the ozone produced as a result of the large corona discharge attacked all parts of the spark counter. To get over these disadvantages, an attempt was made to operate this type of counter on pulsed voltages. A polonium α-source was deposited on the plate of the spark counter and a mica window proportional counter fixed opposite to this source. The voltage was pulsed on the spark counter whenever on α-particle entered the proportional counter after passing through the gap of the spark counter. It was

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(*) This system is, in principle, similar to the one reported by GRIGOROV *et al.* (¹) who have used photographic emulsions in conjunction with ionisation chambers for the investigation of high energy interactions.

(¹) S. I. BRIKKER, N. L. GRIGOROV, M. A. KONDRATEVA, A. V. PODGURSKAJA, A. I. SAVELEVA, V. A. SOBINJAKOV and V. Y. SESTOPEROV: *Suppl. Nuovo Cimento*, **2**, 733 (1958).

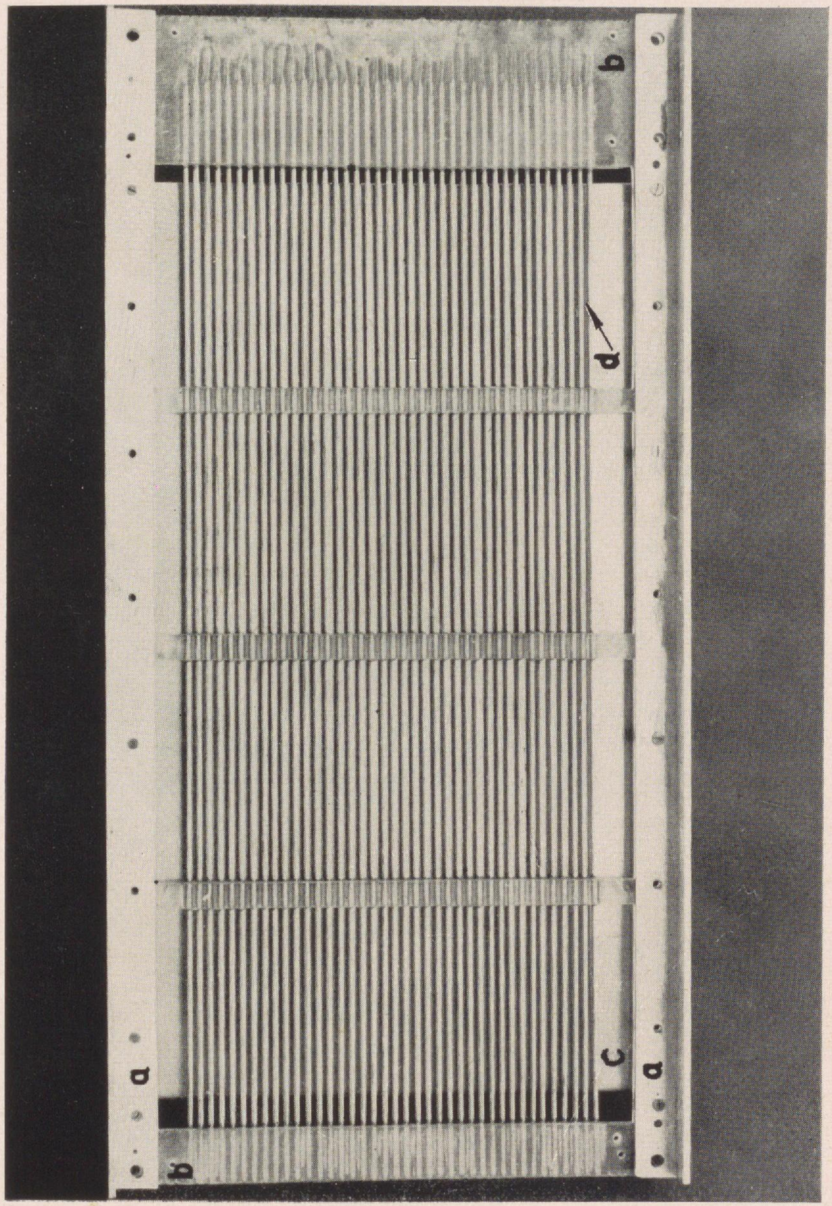

PLATE I. – Photograph of a completely assembled spark counter: *a*) aluminium angles to keep the plastic frame straight; *b*) plastic frame 60 cm × 30 cm; *c*) stainless steel plate 50 cm × 30 cm × 3 mm; *d*) brass welding rods 58 cm long, 3 mm diameter.

found that with pulsed voltages the spark counter did not respond to α-particles. All possible parameters like spacing, wire diameter and clearing field, as also the amplitude, duration and rise time of the pulsed voltage etc., were tried but the response was still negative.

After considerable experimentation a design was evolved which met with all the requirements stated above and which was found most suitable from the point of view of construction and operation and also from the point of view of convenience in photographing the sparks. In this paper, are given the details regarding the constructional and operational features of such spark counters developed in this laboratory.

References to earlier work on spark counters are listed below (2).

2. – Constructional features.

Specially chosen cylindrical brass welding rods of good surface and linearity, each 60 cm long and 3 mm in diameter, are placed parallel to each other on a plastic frame 60 cm × 30 cm with a spacing of 3 mm between the rods; the rods are permanently stuck to the frame with araldite. Aluminium angles are fixed to the frame to keep it straight. A highly polished stainless steel plate of thickness 3 mm and of size 50 cm × 30 cm is treated with dilute hydrochloric acid to remove surface contamination and then washed and dried. This plate is fixed to the frame by means of 2 BA screws and nuts, with a spacing of about 3 mm between the rods and the plate; the spacing can be varied by changing the washers. A transparent plastic sheet is fixed over the frame to prevent dust from settling down in the gap of the spark counter. All the rods are connected together by wires. A photograph of the spark counter is given in Plate I.

3. – Operational features.

3·1. *Pulsing.* – The stainless steel plate is connected to earth and a negative voltage pulse whose amplitude could be varied from 2 to 5 kV, is applied to the rods whenever required. The rise time of the pulse is kept less than

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(2) W. Y. Chang and S. Rosenblum: *Phys. Rev.*, **67**, 22 (1945); A. Ryts: *Helv. Phys. Acta*, **22**, 1 (1949); R. D. Connor: *Proc. Phys. Soc.*, B **64**, 30 (1951); N. K. Saha and Narendra Nath: *Nucleonics*, **15**, 94 (June, 1957); M. J. Swetnick and N. G. Anton: *Nucleonics*, **15**, 93 (June, 1957); R. W. Pidd and L. Madansky: *Phys. Rev.*, **75**, 1175 (1949); J. W. Keuffel: *Rev. Sci. Instr.*, **20**, 202 (1949); E. Robinson: A **66**, 73 (1953); F. Bella and C. Franzinetti· *Nuovo Cimento*, *Proc. Phys. Soc.*, **10**, 1461 (1953); T. E. Cranshaw and J. F. de Beer: *Nuovo Cimento*, **5**, 1107 (1957).

0.05 μs to have a high efficiency of response, and the decay time kept of the order of one microsecond to minimize spurious breakdowns. The pulsing is done using a thyratron circuit similar to the one described by CRANSHAW and DE BEER (²). A low clearing field (~ 20 V) is maintained continuously between the rods and the plate for removing old ions; this helps in reducing spurious breakdowns. The counter is operated in complete darkness to minimize breakdowns due to photoelectric effects.

With a higher voltage of (10 ÷ 14) kV, obtained from a pulse-transformer, it is found that the same spark counter can be operated with a spacing ~ 6 mm, which is almost double the previous value of 3 mm. It is of importance to operate the spark counter with a larger spacing, since the requirement of uniformity of spacing is then less stringent. This makes it possible to build individual spark counters of very large area about half to one square meter.

3'2. *Photography.* – The chief advantage of this type of spark counter over parallel plate spark counters is the convenience and simplicity in the photography of the sparks. In parallel plate spark counters, the spark has to be necessarily photographed through the gap; for this the alignment of the cameras has to be very accurate, and also a very large depth of focus is involved. The latter requirement can be met by using pinhole apertures, but for this the intensity of the spark has to be very great. It is not desirable to increase the intensity of the spark, since the surface will be damaged and spurious breakdowns will be greater. For these reasons spark photography in parallel plate

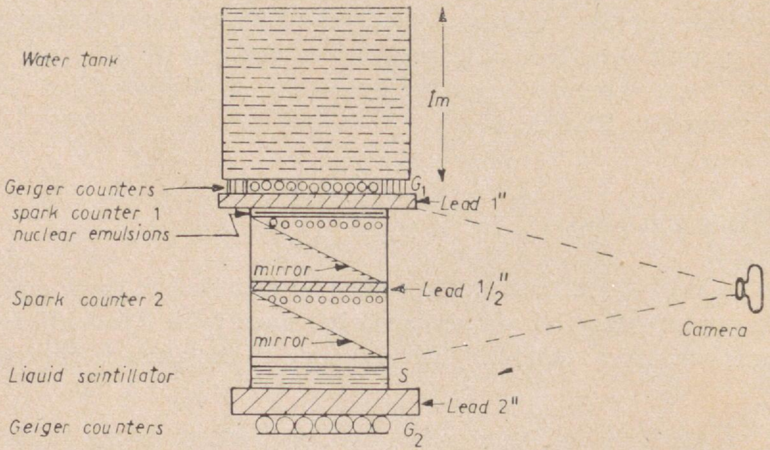

Fig. 1. – Experimental arrangement to test the feasibility of employing nuclear emulsions in conjunction with double spark counter array for the study of high energy jets. The coincidence $G_1\,S\,G_2$ selects nuclear interactions produced mostly in the water tank. The lead plates above the spark counter are meant for the rapid development of the cascades. The direction and co-ordinates of the jets are given by the position of the sparks in the two spark counters.

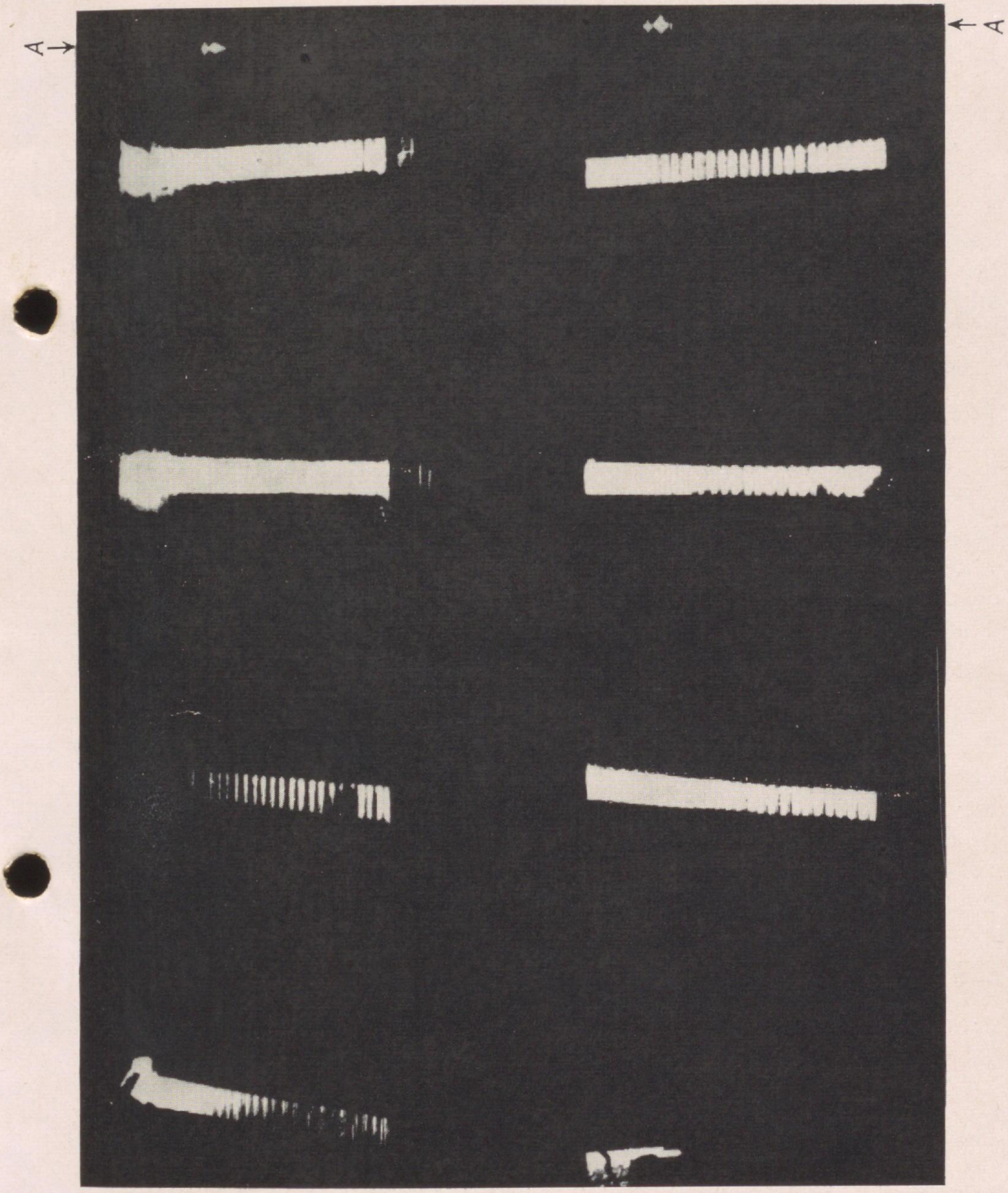

Plate II. – Photograph of a typical double spark event. The sparks have occurred (shown AA) in the right extreme compartment in both the counters. The bright strips seen in the photograph correspond to the portions of brass rods below the ribs of the plastic frame illuminated for a short time, immediately after photographing the sparks but before advancing the film. This serves as a convenient reference frame for locating sparks.

counters of large area poses very difficult technical problems. Moreover, to get the spatial co-ordinates accurately, stereoscopic photographs have to be taken, or else the sparks have to be photographed from two perpendicular directions. In the present spark counters the photography is done with just one camera and in a very simple way using a system of mirrors suitably inclined, as shown in Fig. 1.

The sparks can be located to an accuracy of (3 mm × 3 mm) which is sufficient for the experiments envisated. A typical photograph of a spark is shown in Plate II.

This type of photography using mirrors imposes one limitation, namely, if two spark counters are used one below the other, then the spacing between them cannot be reduced below a limit. However, this is not a serious disadvantage since a certain minimum spacing between the spark counters is essential for an accurate determination of the direction of the jet and also for establishing the parallelism of the jets when there are multiple nuclear interacting particles incident.

3.3. *Efficiency*.

i) Response to singly charged particles at minimum ionization: To determine the operational characteristics for minimum ionizing singly charged particles, the spark counter was placed between two geiger counters registering the passage of cosmic ray particles. The voltage on the spark counter was pulsed whenever there was a coincidence between the Geiger counters. It was observed that sparking took place almost always (99%) in the region covered by the Geiger counter telescope and very rarely (1%) outside. The percentage of spurious breakdowns as obtained from this observation and by random triggering was less than 1%, at normal operating voltages. The efficiency of the spark counter, defined as the ratio of the number of spark breakdowns to the number of double coincidences, was determined as a function of the applied voltage, the clearing field voltage and the delay in the application of the pulse. The results are shown in Figs. 2 and 3 for a particular spark counter. It was found that by careful adjustment of spacing and applied vol-

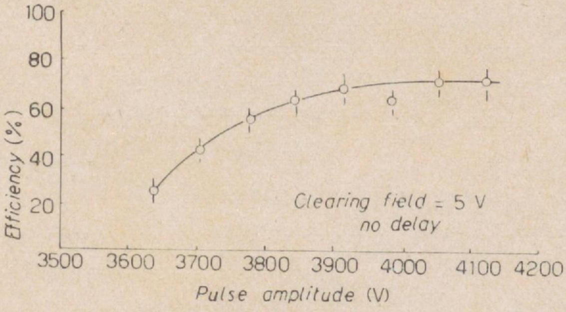

Fig. 2. – Variation of the efficiency of the spark counter for single cosmic ray charged particles, as a function of the pulsed voltage.

tage the efficiency for single particles can be pushed up to almost 90%. The counter was found to be equally sensitive whether the particles passed through the rods or in the gaps between the rods.

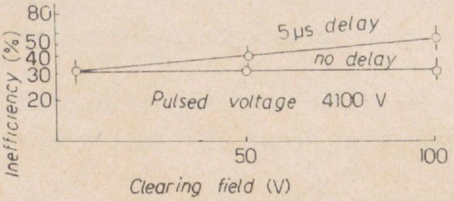

Fig. 3. – Inefficiency as a function of clearing field, and delay in the application of the pulsed voltage.

ii) Response to α-particles: With the same counter, when the operating voltage was adjusted for an efficiency of about 5% for singly charged minimum ionizing particles, the efficiency of response to α-particles was almost 100%. This was checked by depositing a thin film of a polonium α-source on the plate and pulsing the voltage by a proportional counter as before (see Section **1**). This experiment shows that by a suitable adjustment of the efficiency, it is possible to make the spark counter respond preferentially to collimated jets that to some extent simulate α-particles in ionization.

4. – Operation with other particle detectors.

To determine the optimum conditions of operation of the spark counter for the detection and location of high energy jets produced by cosmic ray particles, the spark counter was operated in conjunction with a multiplate cloud chamber and with nuclear emulsions. The experiments were carried out at Ootcamund (2.2 km above mean sea level).

4·1. *Operation with the multiplate cloud chamber.* – The spark counter was mounted above the multiplate cloud chamber. Above the spark counter was kept a lead block of 10 cm thickness in which nuclear interactions were produced and which also served as a medium in which the nuclear and electromagnetic cascades developed. The spark counter was set to operate at an efficiency of $\sim 0.2\%$ for singly charged minimum ionizing particles. The cloud chamber and the spark counter were triggered for penetrating showers, with a scintillator-geiger counter selection system; since the selection system was not very rigorous, it responded to penetrating showers and air showers. The cloud chamber photographs provided visual evidence regarding the type of events which actuated sparks in the spark counter. It was found that the spark counter responded to high energy penetrating showers as expected; it was also found to respond sometimes to air showers. The response to air showers could not be explained in terms of the efficiency for single particles, since the

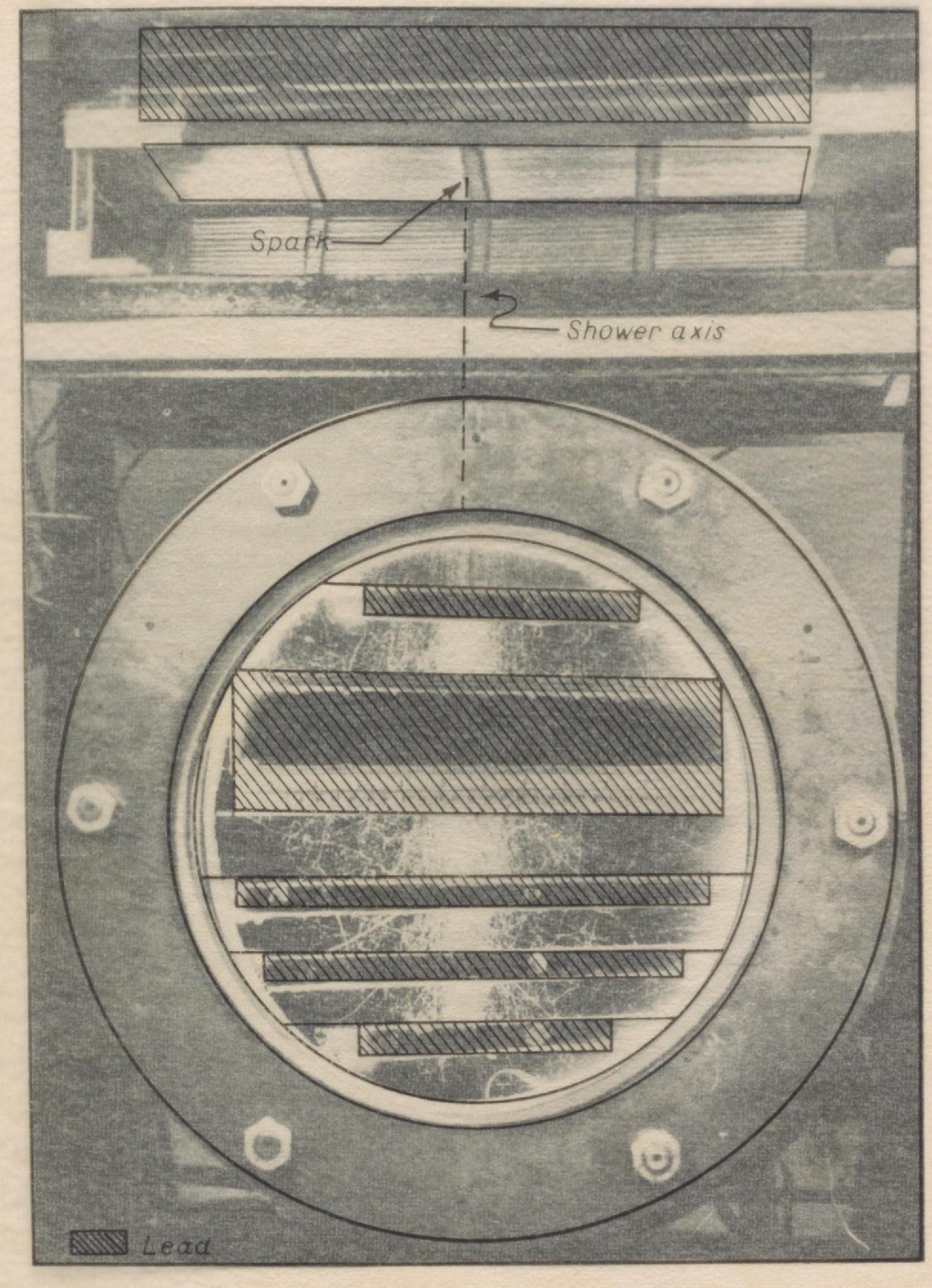

PLATE III. Cloud chamber photograph of a high energy penetrating shower produced in the lead block above the chamber and developing further in the lead plates inside. A spark was seen in the spark counter in the region through which the axis of the shower passed the spark counter (see the superposed illustration).

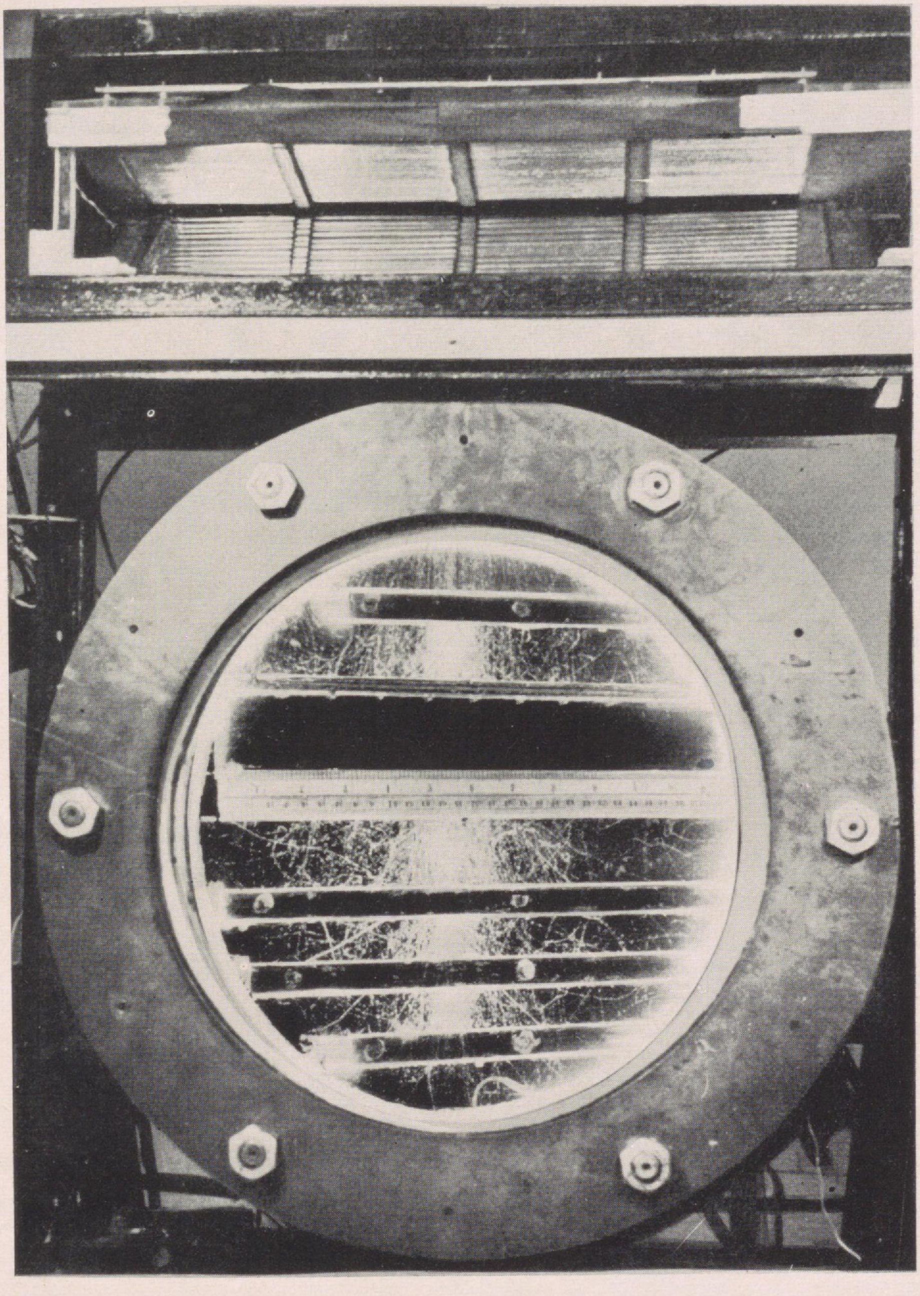

PLATE III. – Cloud chamber photograph of a high energy penetrating shower produced in the lead block above the chamber and developing further in the lead plates inside. A spark was seen in the spark counter in the region through which the axis of the shower passed the spark counter (see the superposed illustration).

number of such particles passing through the spark counter was small, as seen in the corresponding cloud chamber photographs. The response is due most probably to heavily ionizing fragments and collimated showers of the type commonly seen emerging from the plates in multiplate cloud chambers. To ensure that the spark counter responds only to high energy penetrating showers, and to reduce considerably its response to air showers in which the high energy nuclear active particles do not pass through the spark counter area, a system of two spark counters one below the other can be employed. Correlated sparks in the two spark counters can only be due to high energy penetrating showers. The double spark counter system also has the additional advantage of giving the direction of the jet and of establishing parallelism in the case of simultaneous jets.

4·2. *Operation with nuclear emulsions.* – A system of two spark counters was operated at Ootacamund, in conjunction with a penetrating shower selection system as shown in Fig. 1. A layer of Ilford G-5 200 μm thick nuclear emulsions was placed above the top spark counter. The spark counter voltage was pulsed whenever there was a coincidence of the type $G_1\,S\,G_2$. The scintillator was biased such that the $G_1\,S\,G_2$ coincidence rate was about 2/hr. These coincidences are mostly due to penetrating showers with energies $\geqslant$ 20 GeV. Air showers in which the nuclear active particles do not pass directly through the array will not be admitted by this triggering system. The results are given in the following Table I.

TABLE I.

Time of operation (h)	Pulsed voltage (V)	Efficiency of spark counter for single particles		Number of triggers	Sparks		
		Top spark counter	Bottom spark counter		In top counter only	In bottom counter only	In both counters
28	4070	4.7%	8.5%	41	10	6	4
42	3850	4.1%	4.0%	69	12	5	10
42	3740	0.5%	1.5%	70	7	3	5

It follows from the table that when the efficiency of each spark counter is adjusted to about 5% for singly charged minimum ionizing particles, the efficiency of the system for penetrating showers, *i.e.* that one or both spark counters are triggered, is more than 50%. As already mentioned, the triggering rate of 2/hr corresponds to penetrating showers of energy about 20 GeV, and at this energy the collimation of the particles is poor and the number of electrons produced by the development of γ-rays is also small. An efficiency of 100% cannot therefore be expected. The double sparks, which correspond to very high energy penetrating showers constitute about 10% of the number of triggering pulses. If the latter are due to showers of energy $\geqslant 20$ GeV, as previously stated, the double sparks should be attributed to showers of energy $\geqslant 100$ GeV. In all cases where double sparks were recorded a search was made in the emulsions at the places (5 mm × 5 mm) indicated by the spark counters and in the direction defined by the line joining the sparks, for multiple parallel tracks due to the collimated nuclear electro-magnetic cascades. In some cases, $(5 \div 15)$ tracks confined within a radius of ~ 50 μm were observed. One can expect 5 tracks confined within a circle of 50 μm under about 5 radiation lengths of lead when the energy of the γ-rays is more than 50 GeV. Such γ-rays will in general arise from nuclear interactions involving energies of about 10^{12} eV. It is difficult to detect in the emulsions events in which the number of tracks is < 5 in a circle of radius 50 μm. Thus the lower limit to the energy of the nuclear interacting particles that can be detected with the combined system of spark counters and nuclear emulsions is about 10^{12} eV. Because of this, in all recorded cases of double sparks the corresponding events have not been detected in the emulsions. Nuclear emulsions of 50 μm thickness would reduce the cost considerably if they could be used. On trials, however, they were found to be unsuitable; because of their small thickness it was difficult to observe the tracks and establish definitely their parallelism. It should be feasible to use a thickness < 200 μm, possibly ~ 100 μm. It may also be emphasized that only those squares of emulsions need be taken out for examination through which jets have passed as indicated by the double sparks.

An important experimental observation is that even though all the rods were connected together electrically, simultaneous multiple sparks were recorded, sometimes quite close to each other (few cm). Therefore, it is not necessary to use many pulsing circuits.

5. – Conclusions.

It is feasible to construct triggered spark counters with areas of the order of half to one square meter, which respond preferentially to high energy jets (> a few hundred GeV) produced by cosmic ray particles. Double spark counter systems can be used to give the position and direction of high energy jets and will be particularly useful in the study of simultaneous high energy nuclear interacting particles (3 4) associated and unassociated with air showers.

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(3) N. L. Grigorov, V. Y. Shestoperov, V. A. Sobinyakov and A. V. Podgurskaya: *Žurn. Èksp. Teor. Fiz.*, **33**, 1099 (1957).

(4) S. Naranan, R. Raghavan, P. V. Ramanamurty, B. V. Sreekantan and A. Subramanian: *Nuovo Cimento*, **16**, 401 (1960).

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Nuclear emulsions can be used in conjunction with such double spark counter system to obtain estimates of the energies of the nuclear interacting particles. Areas of the order of several square meters can be covered with an array of such large area spark counters and nuclear emulsions.

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RIASSUNTO (*)

Si descrivono le caratteristiche costruttive di contatori a scintillazione di grande superficie. Questi contatori vengono usati, in unione con emulsioni nucleari, per esperimenti correnti in questo laboratorio su particelle ad alta energia da interazioni che arrivano simultaneamente su larghe aree, alcune volte in associazione con sciami dell'aria ed altre volte senza associazione con questi ultimi. Per questi esperimenti i contatori a scintillazione e le emulsioni sono usati in disposizioni che coprono un'area di alcuni metri quadrati.

(*) *Traduzione a cura della Redazione.*

N. B. MISTRY, *et al.*
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