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Evidence for the production of new particles in cosmic ray experiments deep underground

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Abstract. In the cosmic ray experiments deep underground in the Kolar Gold Mines, a special class of events has been observed, at present 6 in number, characterised by several, (in general 3), charged particles arising from a vertex, either in air or in the thin material of the detectors, with large opening angles; the vertex is at a distance of around 70–100 cms from the rock wall. The most plausible interpretation of these events is that they are due to the decay of new, massive and long-lived particles produced in neutrino collisions inside rock, or through hitherto unknown processes.

Keywords. New particles; underground experiments; muon neutrinos.

1. Introduction

The natural muon-neutrino (ν_μ, $\bar{\nu}_\mu$) beam arising through the decays of pions, kaons and muons in the atmosphere has been used over the past decade, (Achar *et al* 1965, Reines *et al* 1965), to study weak interaction phenomena at high energies with detectors operated deep underground. The essential basis of these experiments has been that atmospheric muons at these great depths are characterised by a steep angular distribution, *i.e.* they arrive mostly at small zenith angles; whereas the penetrating tracks at large zenith angles can be attributed to muons arising from neutrino interactions in the surrounding rock. Useful information has been obtained through these studies, (Krishnaswamy *et al* 1971), on the intensity of neutrino-induced muons deep underground, which can be compared with the expectations based on the calculated intensity and energy spectrum of atmospheric neutrinos, and the cross-sections for their interaction with rock nuclei as a function of energy based on various theoretical assumptions, including the existence of the hypothetical W-boson; from these observations a lower limit of 3 GeV could be set for the mass of W-boson.

In these experiments, at great depths underground in the Kolar Gold Mines, employing scintillators, visual detectors and absorbers as telescopes and as magnet spectrographs, it was noticed (Krishnaswamy *et al* 1971) that, in a good

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fraction, ($\sim 40\%$), of the events, there were multiple tracks due to muons or hadrons. This fraction is much too large in comparison to what one expects for normal inelastic processes such as,

$$\nu_\mu (\bar{\nu}_\mu) + \text{target} \rightarrow \text{target} + \mu^- (\mu^+) + \text{hadrons},$$

in which muons and hadrons are generated in interaction with the rock surrounding the detectors and leak out to be recorded in the detectors. For such events, the available target thickness is limited to a few interaction lengths for hadrons, in contrast to muon events which can arise at any depth inside rock depending on the range of the muon. Thus the fraction of multiple track events is expected to be rather small. Krishnaswamy *et al* (1971) had stated: " We have observed a comparatively high frequency of multiple-track neutrino-induced events ... An intriguing feature of the multi-track events is that their points of origin lie very close to the detector.... Events 4 and 43, with two and three penetrating particles respectively originated inside the rock at a depth between about 0 and 4 m. The other three events, numbers 29, 48 and 74, had their points of origin very close to the detector system, lying close to the rock surface, or in the structural elements of the detector or even in the air or in the detector elements themselves. We believe that this aspect may be quite significant ". With the statistics then available, it was not possible to derive any further conclusions regarding the nature of these events.

Further events that we have seen in our current experiments lead us to the conclusion that these, and the earlier events of Krishnaswamy *et al* (1971), constitute new phenomena involving multi-track events whose vertices (estimated from the track geometry) lie in air or very thin material. From a critical evaluation of the data, it would appear that the most natural explanation is that these events are due to the decay of new, massive and long-lived particles produced in neutrino interaction inside the rock or through hitherto unknown processes. In this paper, we give an account of these events and our reasons for reaching this conclusion. Throughout this paper, unless otherwise indicated, by neutrino we imply (ν_μ, $\bar{\nu}_\mu$).

2. Experimental details

These events have been observed in two experimental configurations: (i) in the neutrino experiments conducted by the Bombay-Osaka-Durham collaboration at the depth of 7600 feet (equivalent to 7000 hg/cm^2) in the Kolar Gold Mines, between 1965–69, with telescopes and magnet spectrographs; (Achar *et al* 1965, Krishnaswamy *et al* 1971); and (ii) in the muon experiments now in progress at the depth of 3655 feet (equivalent to 3375 hg/cm^2) in the same mines with a magnet spectrograph of area 8 m^2.

In these experiments the detectors were made up of plastic scintillator walls, with absorbers in-between, to signal the passage of penetrating charged particles; and the trajectories were rendered visible through neon flash tube arrays.

We now discuss the 6 multi-track events (including the 3 earlier reported by Krishnaswamy *et al* 1971), observed in these two experimental configurations.

2.1 *Events* 1, 2 *and* 3 (*Krishnaswamy* et al 1971)

They were recorded during the period 1965–69 in the neutrino experiment conducted at the depth of 7000 hg/cm^2 underground. The detectors were telescopes, comprising of three vertical layers of neon flash tubes, separated by two walls of lead absorbers, each of thickness 1″, and outer walls of plastic scintillator to provide the trigger; the vertical elements were each of area $2\,\mathrm{m} \times 3\,\mathrm{m}$. Each scintillator wall was made up of 6 units, each of area 1 m^2. A four-fold coincidence between pulses from a pair of photomultipliers viewing a 1 m^2 area of one scintillator wall and a similar pair on the other wall provided the basic trigger for the neon flash tube array. In this arrangement, the zenith angles of tracks (projected on a plane normal to the scintillator wall), could be measured to an accuracy better than 1°. At these large depths, there is negligible background from atmospheric muons for zenith angles $> 45°$; and thus all such large angle events were classified as products of neutrino interaction.

In event No. 1, there are 3 tracks ' A ', ' B ' and ' C ', as shown schematically in figure 1. Track ' B ' is due to a penetrating particle, since there is no evidence of a shower or detectable scattering along the trajectory. This could be a muon or a hadron. Tracks ' A ' and ' C ' are at angles of 60° and 48° with respect to ' B ' grazing the edge of the detectors; and the minimum energy loss of the concerned particle inside the detector would have to be about 30 MeV. Particle ' C ' probably went out of geometry producing a knock-on electron from the lead wall, evidence for which can be seen in the middle layer of neon flash tubes. Tracks ' A ' and ' C ' could have been caused by muons, hadrons or electrons. The three tracks when projected backwards meet at a point ' P ', as shown in figure 1 which is at a minimum distance of 57 cm from the rock wall, and is most probably in air, and with a lower probability, could have been in the thin structure materials of the telescope. From a detailed reconstruction of the event it appears very unlikely that the vertex lies within the rock; though this possibility cannot be ruled out if phenomena characteristic of electrons, such as scattering, had occurred.

In event No. 2, shown in figure 2, there are again three tracks ' A ', ' B ', and ' C '. Tracks ' A ' and ' B ' are due to muons or hadrons, since there is no evidence for cascade production or scattering along the trajectory through lead absorbers. Track ' C ' passes through two scintillator blocks and a long distance in a neon flash tube layer; and in addition, has associated with it a short track due to a low energy knock-on electron. The minimum energy loss of this particle ' C ' inside the detector would have to be about 60 MeV. The track could have been caused by a muon, hadron or electron. When extrapolated, the three tracks meet at a point ' P ' just outside the scintillator. The vertex is most probably in air; but again we cannot completely rule out the possibility that it is located in the thin (2 mm) aluminium housing or at the edge of the scintillator. The minimum distance of the vertex from the rock wall is 130 cm.

In event No. 3, shown in figure 3, there are only two tracks due to penetrating particles ' A ' and ' B '; in the traversal through the lead absorbers there is no indication of scattering or interaction. These tracks are therefore either due to muons or hadrons. When extrapolated, they meet at a point ' P ' in air at a distance of 63 cm from rock wall. (*Note*: The angles of tracks 'A' and 'B' as given in the paper of Krishnaswamy *et al* (1971) are incorrect; the correct values are those shown in table 1 of this paper).

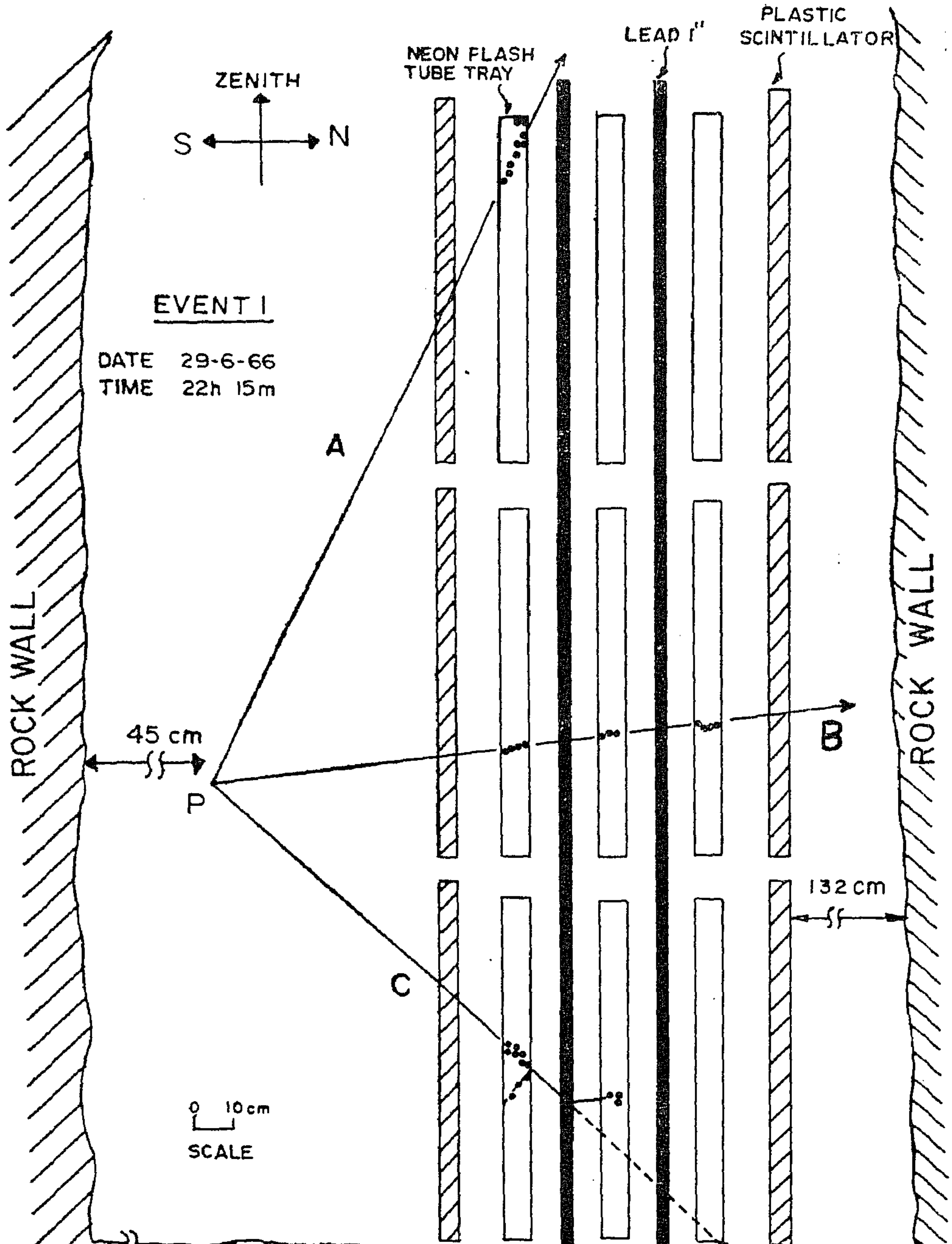

Figure 1. A sketch of event 1 recorded at the depth of 7000 hg/cm^2 in telescope 1; the black dots represent the neon flash tubes that were activated along the trajectories of the charged particles A, B and C. The meeting point of these tracks is most probably in air.

2.2 *Event* 4

This was recorded in the magnet spectrograph experiment at the depth of 3375 hg/cm^2. The detector consists of a magnetised wall of thickness 40 cm, area 2 m × 4 m and excited to a field of 14·5 Kilogauss. There are two walls of plastic scintillators, of the same area, on either side of the magnet, which provide the trigger for the neon flash tube array. With these visual detectors, the projected angles of tracks seen in at least two sets of NFT trays can be measured to an

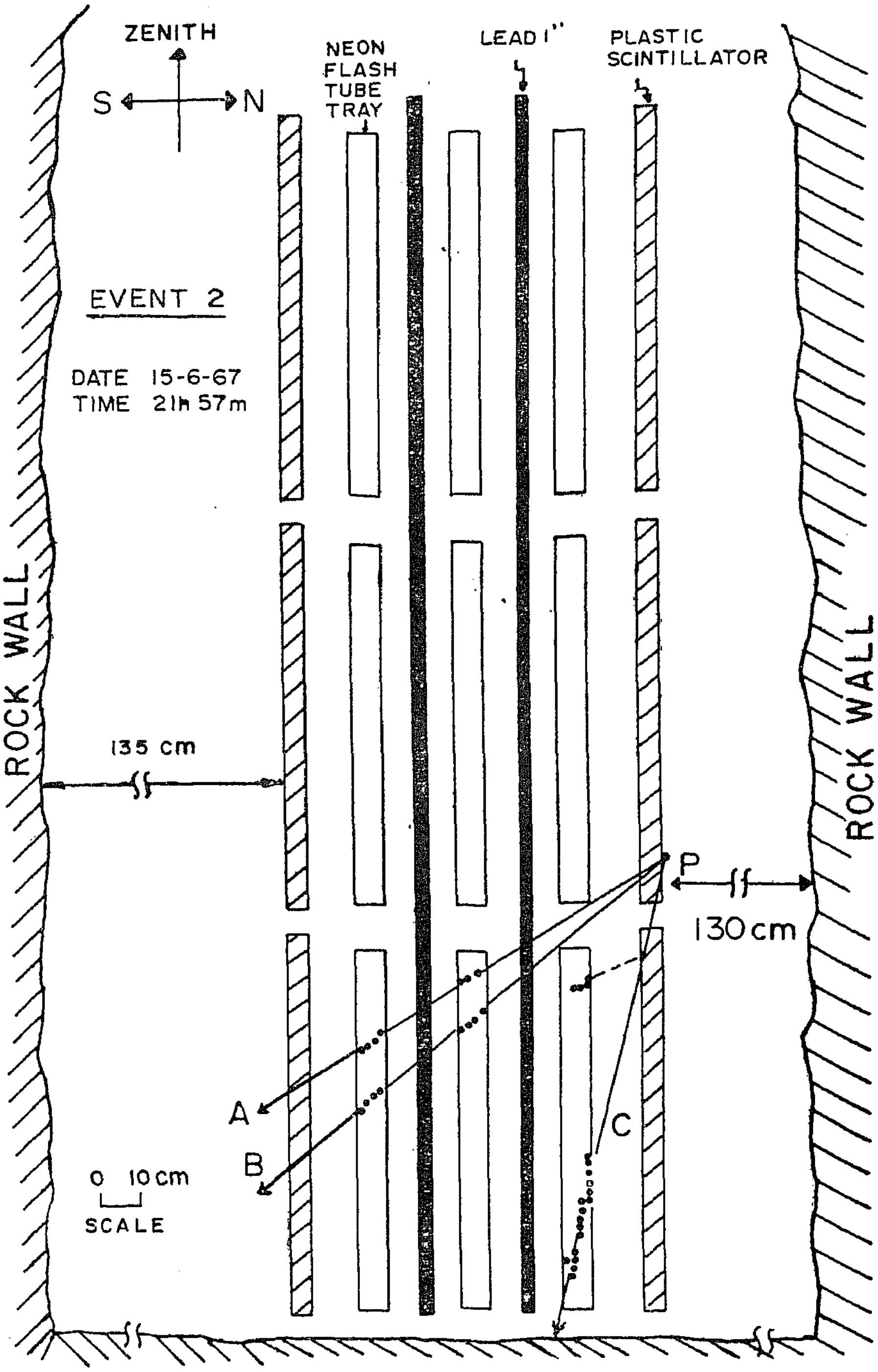

Figure 2. A sketch of event 2 recorded at the depth of 7000 hg/cm^2 in telescope 1; there are 3 tracks due to charged particles with the vertex ' P ' just outside the scintillator wall.

accuracy of 1°. A sketch of the event is shown in figure 4. There are three tracks ' A ', ' B ' and ' C ' due to charged particles, which when extrapolated meet at a point ' P ' in air, at a minimum distance of 55 cm from the rock. Since the tracks are known only in terms of projections on a vertical plane, the point ' P ' could be anywhere on a line of about 2 m in length parallel to the rock wall. There is no material in the vicinity of this line, (up to $\sim$ 30 cms), and ' P ' is clearly in air. Track ' B ' passed through a minimum of 40 cm of iron corresponding to at least $2\frac{1}{2}$ interaction lengths for hadrons without any trace of interaction;

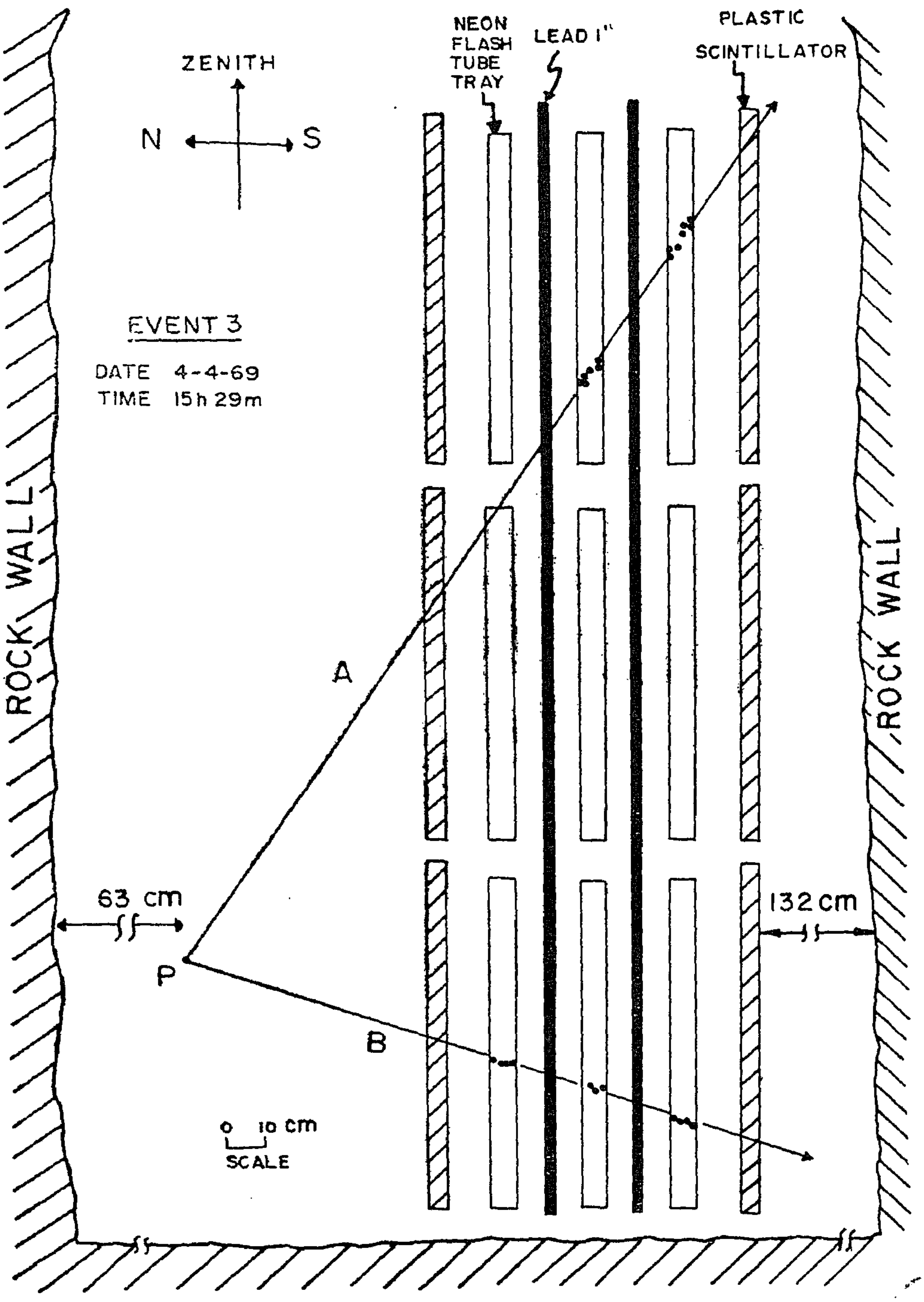

Figure 3. A sketch of event 3 recorded at the depth of 7000 kg/cm^2 in telescope 2; there are 2 penetrating particles A and B arising from a point in air.

and it is thus most probably due to a muon. It is not possible to reach any conclusion about the nature of the particles that caused the tracks 'A' and 'C' as they had gone out of the geometry of the detector. These two tracks could have been caused either by muons, hadrons or electrons. From the disposition of the tracks it is clear that they arose from a point in air, probably through the decay of a particle travelling upwards; at such angles there is essentially no background due to atmospheric muons. The opening angles of the tracks arising from the decay at 'P' are very large as can be seen in the figure. There was no magnetic field at the time this event was recorded.

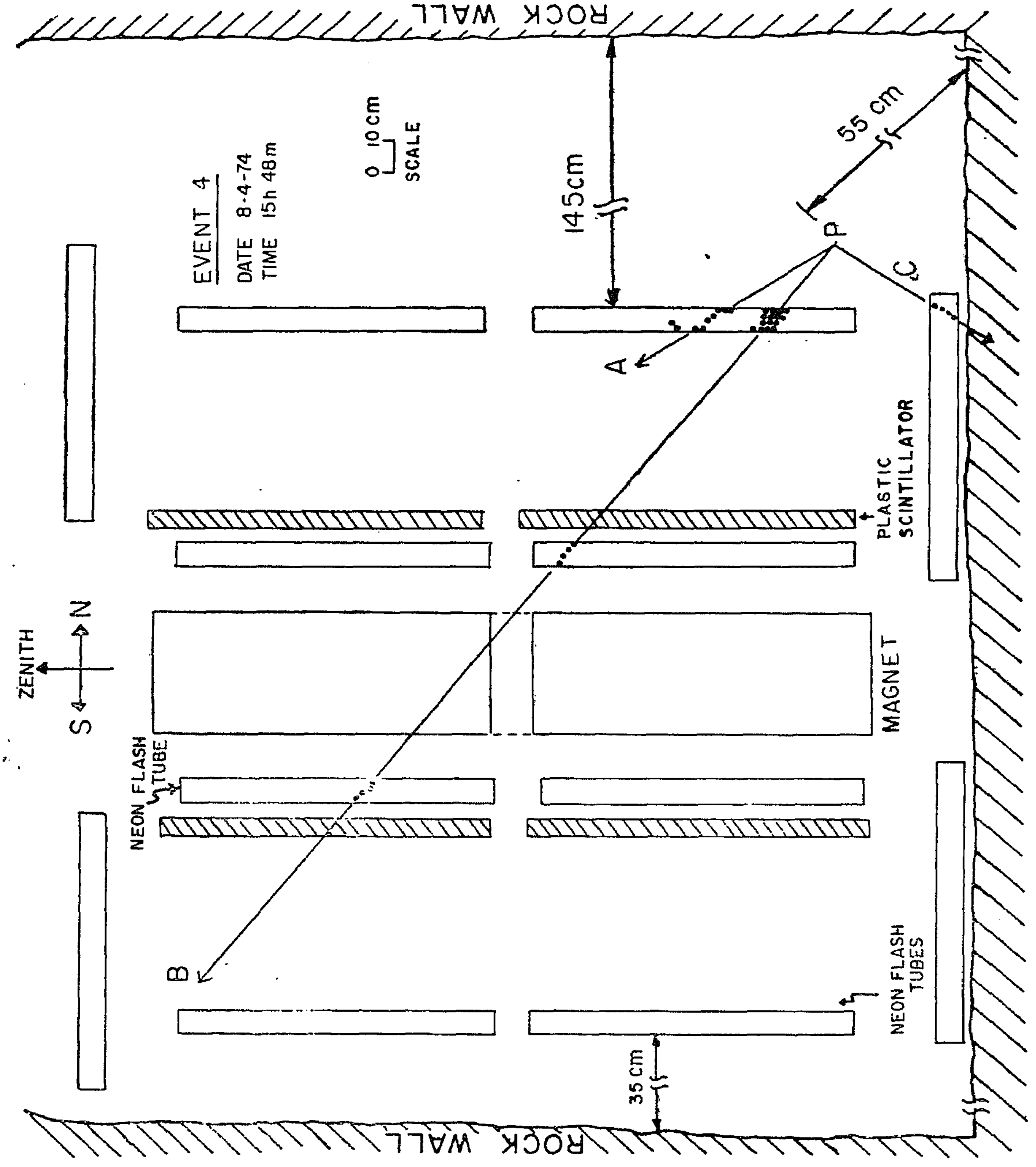

Figure 4. A sketch of event 4 recorded at the depth of 3375 hg/cm^2 in a magnet spectrograph. There was no magnetic field at the time this event was observed. The three particles A, B and C appear to arrive from a point 'P' which is definitely in air.

Table 1. A detailed description of the multiple tracks seen in events 1–5

Event No.	No. of tracks	Projected Distance of 'P' from rock (Detector)	Projected zenith angles of tracks	Characteristics of penetration (minimum amount of material traversed)	Nature of particles
1	3	57±5 cm (Tel. 1)	*a.* 25° upwards *b.* 96° *c.* 48°	22·5 g/cm^2* 5 cm of Pb 13 g/cm^2*	e, μ or hadron μ or hadron e, μ or hadron
2	3	130±10 cm (Tel. 1)	*a.* 56·50° *b.* 51° *c.* 12·5°	6·1 cm of Pb 6·5 cm of Pb 32·5 g/cm^2*	μ or hadron μ or hadron e, μ or hadron
3	2	63±5 cm (Tel. II)	*a.* 35° upwards *b.* 72°	9·3 cm of Pb 5·2 cm of Pb	μ or hadron μ or hadron
4	3	55±5 cm (Mag. Spec.)	*a.* 35° upwards *b.* 52° upwards *c.* 35°	6 g/cm^2* 40 cm of iron 6·5 g/cm^2*	e, μ or hadron μ e, μ or hadron
5**	3 + 1 (primary)	260±15 cm (Mag. Spec.)	*a.* 20° upwards *b.* 75° upwards *c.* 37° *d.* 81° upwards	58 cm of iron 21 cm of iron 33 cm of iron . .	μ (> 1 GeV) μ (probably) μ (probably) New particle (probably)

* Amount of material (plastic scintillators, aluminium plates, glass, etc.) traversed by the particle inside the detector assembly. The minimum energy loss of these particles would be about 2 MeV/(g. cm^{-2}) of material traversed, if they are relativistic.

** The event is not "in air", but occurred in the iron wall (figure 5).

The relevant details of these four events are summarised in table 1; and we can see that these events are characterised by the following features: (1) high probability that the vertex lies in air or in thin material at an average distance of about 70 cm from the rock wall; (2) 2–3 charged particles in general arising from this vertex; (3) large opening angles between the tracks; and (4) there are one or more penetrating particles which with high probability are muons but could also with less likelihood be hadrons.

2.3 *Event* 5

This event, recorded at the depth of 3375 hg/cm^2, has characteristics similar to those mentioned above except feature number (1); the origin in this case is not in air but in the 40 cm thick magnet at a distance of about 260 cm from the rock wall. A sketch of this event is shown in figure 5, and relevant experimental details are given in table 1. There are four tracks 'A', 'B', 'C' and 'D', with large angles between them, and apparently meeting at point 'P' inside the magnet. Since the four concerned charged particles traversed the magnet, with the field

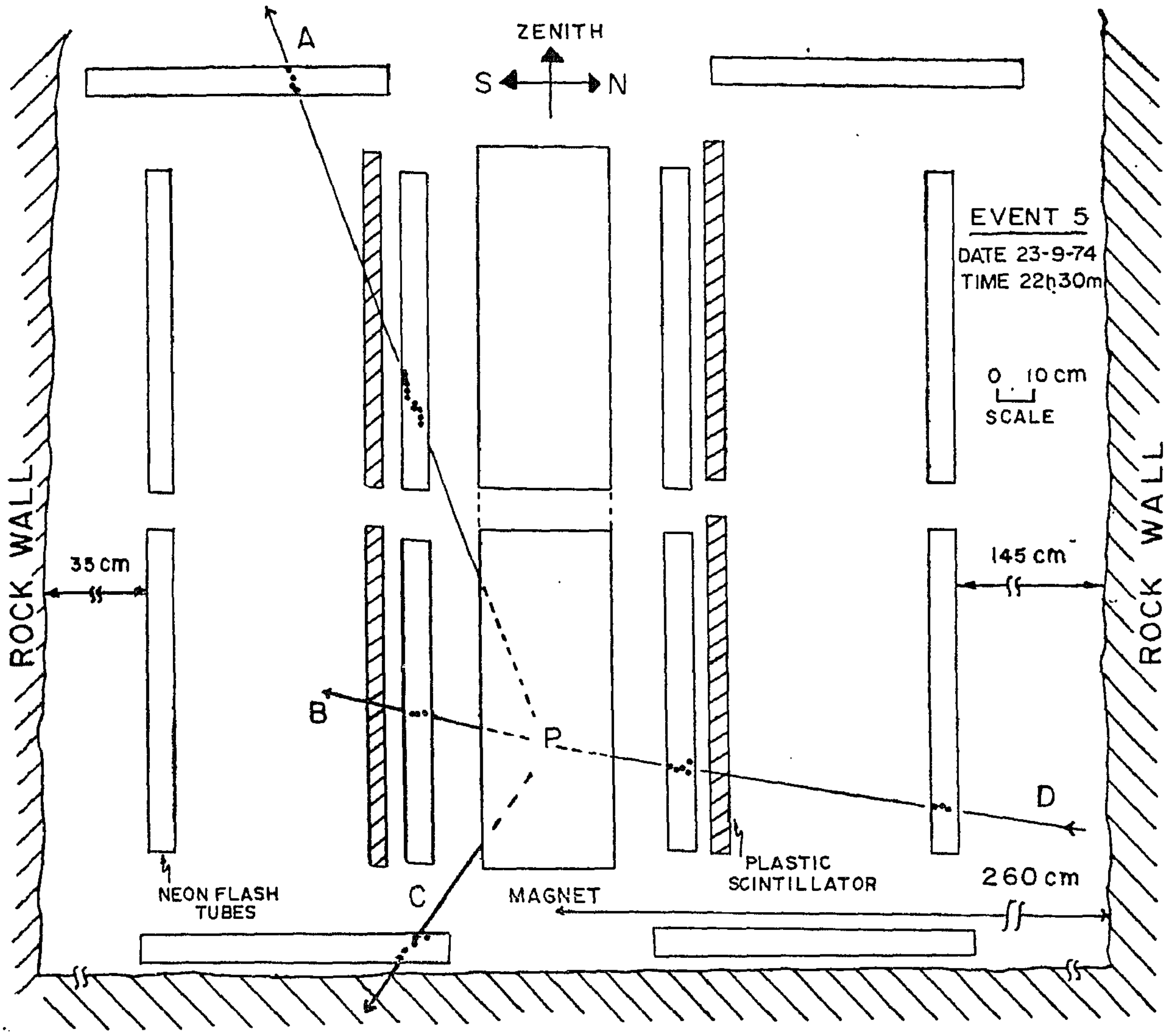

Figure 5. A sketch of event 5 recorded at the depth of 3375 hg/cm^2 in a magnet spectrograph; there are 4 charged particles which most probably have a meeting point inside the magnet.

on, in view of the possible magnetic deflection of any of them it is not possible to provide an unique reconstruction of the vertex 'P'; we have therefore shown in figure 5 the trajectories within the magnet by broken lines. The probability that this event is due to the inelastic scattering of an atmospheric muon, (say track 'A') is very small, since three particles (tracks 'B', 'C' and 'D'), nearly perpendicular to the direction of the assumed muon have to come out of the iron wall with a minimum energy loss of about 300 MeV; and none of these three tracks was likely to have been due to pions as they had to traverse at least 1–3 λ_π without any trace of subsequent interactions inside the magnet. Thus the hypothesis that the event is due to a muon interaction is considered to be highly improbable. The most natural explanation is that this event is similar to the four events mentioned previously; in this case it is a charged particle that decays inside the magnet into 3 particles. If this is so, then there is the possibility that all these 3 secondary particles are muons and the mass of the parent particle is larger than about 2 GeV.

Table 2. A detailed description of the 7 tracks seen in event No. 6

Track	Projected† zenith angle	Characteristics of Penetration	Nature of particles
A_1	16° Upwards	> 50 MeV*	e, μ or hadron
A_2	40° Upwards	> 18 MeV*	e, μ or hadron
A_3	19°	> 50 MeV*	e, μ or hadron
B_1 (L_1)**	58°	> 10 cm of Fe	New particle L_1 (probably)
B_2	11°	> 53 cm of Fe	μ
B_3	34°	> 54 cm of Fe	μ
C	60°	$\gtrsim 10$ cm of Fe	μ or hadron

* The minimum energy loss of a relativistic particle in traversing the neon flash tube tray.

** Minimum path length of the particle L_1 is 115 cms.

† These angles correspond to the reconstruction of tracks as shown in figure 6. All the particles, except B_3, traversed only one tray of neon flash tubes, and thus, taken individually, their angles are known to a limited accuracy.

2.4 *Event* 6

We have recently observed this rather striking event in the magnet spectrograph experiment at 3655 ft. A schematic diagram of the new event is shown in figure 6. There are 7 tracks caused by charged particles (tracks A_1, A_2, A_3, B_1, B_2, B_3 and C) in this event. Complete details concerning the projected angles of tracks, the material traversed by the particles and information on the type of particle are given in table 2.

The meeting point ' P ' of the tracks A_1, A_2 and A_3 is most probably in air. This configuration of tracks suggests the decay at the point ' P ' of a particle slowly moving from right to left (in the diagram) rather than an interaction. The nature of the decay products, A_1, A_2 and A_3, cannot be ascertained from the present observations as they passed through only a small amount of material inside the detector. They could in principle have been electrons, muons or hadrons.

A second vertex can be constructed for the three tracks B_1, B_2 and B_3 at the point " Q " as shown in the diagram. The assumption here is that the three particles do not suffer measurable deflections in the magnet. The particles B_1, B_2 and B_3 must have traversed a minimum length of 10, 53 and 54 cms of iron respectively; this is a *lower limit* since we have available only the projections of the tracks. Since the particles B_2 and B_3 traversed a minimum of $3\frac{1}{2}$ interaction lengths (λ_π), and came out of the iron without accompaniment, we consider that these are most probably muons**. The particle B_1 is unlikely to be an electron as

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** We estimate the probability that B_2 and B_3 are either p, π or K as very low ($\lesssim 3\%$). The probability that any of them is a muon arising through the decay of π or K is even smaller.

it traversed at least 5 radiation lengths without shower production. If this reconstruction of tracks is correct, then, within the uncertainty of the angle measurement, the momenta of B_2 and B_3 have each to be at least 3–4 GeV/c. The vertex 'Q' could be: anywhere in air in the winding gap between the upper and lower sections of the two magnets; in the keepers used to close the magnetic path at the two ends; or in the magnet itself. The opening angles of the 3 tracks, in all possible configurations, are very large. Since the iron is magnetised and has a field of 14·5 K gauss, it is possible to shift the vertex 'Q' around, by allowing for deflection of tracks B_1, B_2 and B_3 by a certain amount within the magnet. We have shown in figure 6 the point 'R' corresponding to an extreme case of reconstruction of the vertex such that all the four tracks (B_1, B_2, B_3 and C) meet at this vertex. In this situation, the momenta of B_2 and B_3 would be very low, and lie in the range 1–2 GeV/c at the vertex. The particle 'C' could be a muon or hadron since its path length in iron has to be at least 10 cms. The particle 'C' probably went out of geometry at one of the edges of the extreme NFT trays; only 2 tubes at the outer edge of the tray near the rock wall have flashed as can be seen in the diagram.

From the alignment of track B_1 with vertex 'P' it would appear that it is this particle B_1 that has decayed at 'P' into 3 charged particles. The path length traversed by this particle is at least 115 cms and less than about 230 cms (since our information is restricted to projected angles). In view of the large opening angles of its secondaries (*i.e.* A_1, A_2 and A_3) it would appear to be a slow particle, and the Lorentz factor is estimated as 2–3. The lifetime of the particle is then $\sim 10^{-9}$ sec. This section of the present event (with the vertex in air, decay into 3 charged particles with large opening angles, the path length traversed, and the estimated lifetime) is similar to the events 1–5 that we have just described. In our earlier brief report on events 1 to 5 (Krishnaswamy *et al* 1975) we had concluded that the most plausible explanation of the 5 events is in terms of the decay of a new, massive ($\gtrsim 2$ GeV) and long-lived ($\tau_0 \gtrsim 10^{-9}$ sec) particle. Let us call this heavy particle 'L_1' and tentatively identify it with the particle B_1 in event 6.

As mentioned earlier, the lack of information on the possible deflection of the tracks L_1, B_2, B_3 and C does not allow a clear-cut identification of the mechanism by which they are created. We shall consider here two extreme situations.

Case I: *Vertex 'Q'*

This corresponds to the case where the tracks B_2, B_3 suffer very little deflection in the magnet, in which case they have momenta $\gtrsim 4$ GeV/c. If 'Q' was located in air (*i.e.* in the winding gap of the magnet), it would correspond to a decay rather than an interaction vertex. The decay products will then be 3 charged particles L_1, B_2 and B_3. The particles B_2 and B_3 are most probably muons, whereas L_1, in analogy with earlier events 1–5, moving at non-relativistic velocity decays at vertex 'P' and could have an energy around 4 GeV. The projected angles between L_1, B_2 and B_2, B_3 are each about 46°. Then the mass of the new particle (say L_2), that decayed at 'Q' would have to be very large ($M_{L_2} > M_{L_1}$).

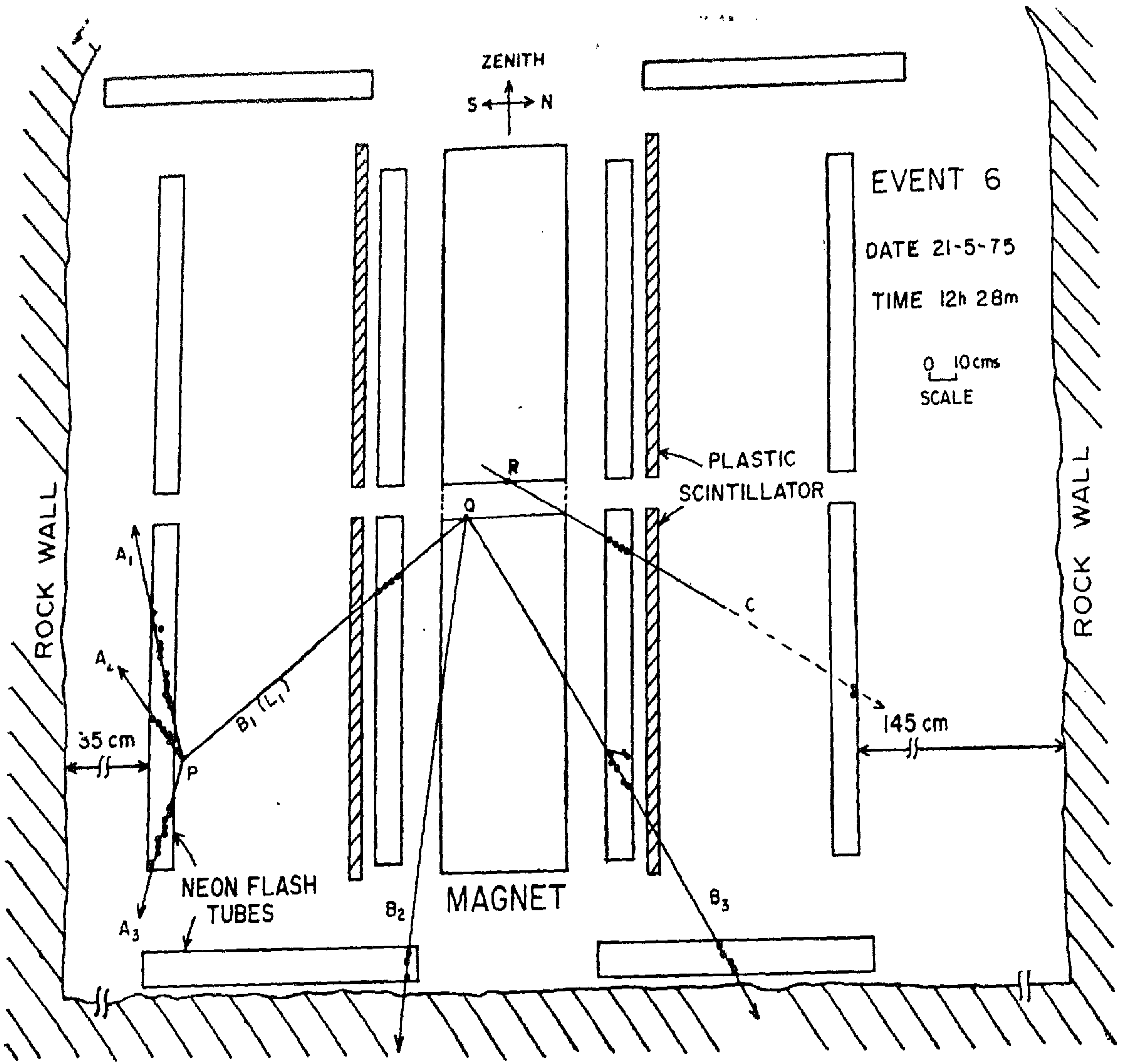

Figure 6. A sketch of event 6 recorded at the depth of 3375 hg/cm^2 in a magnet spectrograph; there are a total of 7 charged particles in this event. The vertex 'P' lies most probably in air. Vertices Q and R correspond to the extreme cases I and II respectively as discussed in the text.

The minimum distance of ' Q ' from the point of primary interaction giving rise to the charged particle ' C ' and the new particle L_2 would determine the lifetime of L_2; this is estimated to be of the order of 10^{-10} sec. To summarise this discussion, vertex ' Q ' would correspond to $L_2 \rightarrow L_1 + \mu + \mu + ?$

However, Q could actually have been in the magnet itself; then the three particles L_1, B_2 and B_3 could be products of either an interaction or decay. We consider the interaction hypothesis as unlikely since two of the resultant particles from the interaction, B_2 and B_3, are most probably high energy muons; also the transverse momenta involved are large as evident from the opening angles of the three tracks. These arguments concerning the improbability of an interaction having taken place at ' Q ' apply equally to Case II (vertex at ' R ') that we shall discuss next *i.e.* even if the vertex is at ' R ', we are dealing most probably with a decay rather than an interaction at that point. If we are dealing with the vertex ' Q ', then the particle L_2 responsible for the decay (or interaction) at Q has to be related to particle C at yet another decay or interaction vertex. The particle responsible for this vertex is likely to be neutral since there is no evidence of charged particles in the upper NFT trays of the detector.

Case II: Vertex at ' R '

This corresponds to the case where all the four tracks B_1, B_2, B_3 and C have a common point of origin ' R '. The vertex at R would correspond to an extreme situation involving large magnetic deflections. This will have two immediate consequences: (i) the momenta of B_2 and B_3 would have to be very small to permit such large magnetic deflection; and (ii) B_2 and B_3 would have had the same sign of charge (*e.g.* μ^+, μ^+). Thus, from vertex R, a minimum of 4 particles have emerged: 2 low energy ($\sim$ 1 GeV) positive muons (or with much lower probability hadrons), one heavy particle L_1 of energy around 4 GeV, and the particle ' C ' which is either a muon or a hadron. There could have been at this vertex, additional particles that were either neutral or charged that completely missed the detector geometry.

In this extreme situation also, we are most probably dealing with decay rather than an interaction at ' R ', since one has to account for the production of at least 2 muons B_2 and B_3 and the heavy particle L_1 at very large angles.

Alternative reconstructions of the tracks, assuming different values for the deflection in the magnet, are feasible; but these would essentially fall into one of the two categories considered above.

To summarise, in all methods of reconstruction of tracks in the magnet, we have most probably a decay vertex, either at Q, R or some other intermediate points, giving rise to at least 3 particles. Particles B_2, B_3 are most likely muons; L_1 is a heavy particle decaying into 3 charged particles A_1, A_2 and A_3 at vertex ' P '; and ' C ' is either a muon or hadron. Thus, we have probably two heavy particles L_1 and L_2 with L_2 decaying into L_1, and $M_{L_2} > M_{L_1}$.

The primary particle responsible for the ultimate production of 7 charged particles in all, is probably neutral if it entered the detector within the geometry, since otherwise it would have produced a track in any of the NFT trays in the upper half of the magnet. In such a case it could be a neutrino (or analogous neutral particle) colliding inside the magnet.

The primary particle could have entered with a smaller probability, either in the near vertical direction from the top of the magnet or from the front end of the spectrograph where there are no visual detectors. It could then be a charged particle. Even in such an eventuality, we are dealing with an unknown phenomenon giving rise to heavy particles L_1 (and probably L_2) and the conclusions concerning heavy particle production remain valid.

3. Interpretation

We first consider below the possibility that these events can be explained in terms of known processes:

(*a*) *Non-contemporary tracks*—This possibility can be ruled out, since the rate of incidence of atmospheric muons within the detector area is about 1 in 5 hours, and 1 in 6 days, at the depths 3375 hg/cm^2 and 7000 hg/cm^2 respectively. In the measurements at the shallow depth† (events 4, 5 and 6) the detector is sensitive only for 4 microseconds after being triggered by charged particles. In the experiment at 7000 hg/cm^2, however, the visual detectors are triggered about 30 microseconds after the passage of the charged particle (as indicated by the 4-fold coincidence of pulses from the two scintillator walls). It may be pointed out that for events 1, 2 and 3, recorded at 7000 hg/cm^3, pulse profiles from the scintillation detectors have been measured; these establish the time coincidence of the particles in each event within the resolving time of 2 microseconds.

The tracks recorded in these events can be classified into 2 categories: (*a*) clear penetrating tracks involving at least 2 trays of NFT, with lead or iron absorbers interposed between them; and (*b*) tracks leaving the detector geometry at large angles after passing through only one NFT tray. We have examined the possibility that some of the 1-tray tracks might have been due to chance alignment of stray flashes due to the inherent characteristics of the tubes, or through radioactivity‡ in the rock surrounding the detector assembly. We find this probability to be extremely small.

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† No pulse information is available for events recorded in the magnetic spectrograph at 3375 hg/cm^2. Thus, in principle, tracks that traverse the detector in an out of geometry configuration, prior to the trigger (by an in-geometry muon), may also be seen up to a certain time. However, for NFTs employed in this experiment (filled with neon at 30 cm of Hg pressure) the efficiency for recording such early tracks drops to about 50% at 30 μ sec delay and to much smaller values at larger delays. Even if we consider a time window of 30 μ sec for reasonable efficiency the conclusions arrived at here concerning contemporaneity of tracks remain unaltered.

‡ It is known that there is considerable amount of radioactivity in the Kolar rock primarily in the form of Th C′ which gives rise to γ-rays of maximum energy of $\sim$ 2 MeV. A Compton electron produced by this γ-ray cannot traverse the whole of an NFT tray as it would require energies larger than 10 MeV for this. We have actually examined an extensive sample of film to look for random tracks involving $\geqslant$ 3NFTs. Whilst a negligibly small fraction of 3-tube tracks have been seen number 4-tube random track has been recorded. In addition one has to consider the chance that such tracks are oriented in a direction as seen in the present observations and point to a vertex, otherwise already established. We therefore believe that flashes seen in three or more tubes, though only in a single tray, and aligned as a track pointing to a vertex are due to a particle emerging from the vertex and not due to random effects in the flash tubes nor to radioactivity in the environment.

(*b*) *Interactions due to atmospheric muons*—A well established, predominant, known component at these depths is the atmospheric muon component. We therefore examine whether these events could have been caused by atmospheric muons acting through known processes. To simulate these events the muon has to arrive at the level of observation at a large zenith angle and produce an inelastic collision. At the depth of 7000 hg/cm^2, the angular distribution is peaked in the vertical direction and is expressed approximately as $1 \cdot 1 \times 10^{-10} \sec\theta \exp[-9(\sec\theta - 1)]$ cm^{-2} . sec^{-1} . st^{-1}. Thus their flux is very small at angles $> 45°$.

Among the 6 events, events 1, 3 and 4 are clearly due to incident particles moving upwards or at zenith angles $\sim 90°$. The flux of atmospheric muons at such angles at the two depths of observations is essentially zero. Event 2 has 2 penetrating tracks at angles $\gtrsim 50°$ and this also could not be due to an atmospheric muon interaction; unless one wishes to interpret track 'C' as the vertically incident muon, interacting in the scintillator to produce two hadrons at large angles (tracks 'A' and 'B'), with corresponding other unseen particles to balance momenta, the probability for all of which is very low. The reasons for not considering event 5 as due to a muon interaction have been presented in the earlier section.

One could argue that the new massive particle has in fact been produced by an atmospheric muon arriving in the near vertical directions; and that in some cases the new particle has emerged out of the rock at very large angles. This also seems to be improbable from the following simple considerations on the relative numbers of observed events at the two depths of 3375 and 7000 hg/cm^2.

The average muon energies at these two depths are in the region of 300–400 GeV, while the fluxes of atmospheric muons are different by a factor of 100. (At $\theta = 0$ the fluxes are $1 \cdot 2 \times 10^{-8}$ and $1 \cdot 1 \times 10^{-10}$ cm^{-2} sec^{-1} st^{-1}, at the depths of 3375 and 7000 hg/cm^2 respectively). Since the experimental conditions at the two levels of observation are essentially the same, we would expect, taking into account the differences in exposure of the detectors at the two depths, at least a factor of 20 more " new particle events " at the shallower depth. However, so far we have seen only 3 such events at the depth of 3375 hg/cm^2.

The rate of rock showers (namely muon interactions with rock) with respect to the number of muons passing through the detector, is of the order of 10^{-3}, so that special types of rock showers, or the effects of their secondary particles, must be regarded as negligible in terms of contributing to the present type of phenomena.

We should emphasise here that reconstruction of these events in the most plausible manner indicates that the vertices were in air or the thin material of the detector assembly. Whilst for each event individually one might be able to alter this fact by opting for highly improbable possibilities, it would be difficult to do this for all the six events that we report here.

We are thus led to the position that it is very unlikely that these events were caused by atmospheric muons acting in known ways.

(*c*) *Normal inelastic neutrino interaction*—We consider here the possibility that these events are simulated by the presently known neutrino interactions such as

$$\nu_\mu (\bar{\nu}_\mu) + \text{target} \rightarrow \text{target} + \mu^- (\mu^+) + \pi\text{'s and strange particles, etc,}$$

In the present observations we have clear examples of large angle events with multiple tracks whose vertex is in air at an average distance of 70–100 cms from the rock wall. If these were produced by neutrino collisions, the interaction presumably occurred within the rock, and one of the secondary particles leaked out and decayed at the vertex into 2–3 charged particles. If a neutral pion had been created at the vertex then the secondary gamma rays would have produced showers that should have been seen here unless the π° was out of geometry; the observed single tracks could not have been due to such π°s. We now consider known particles that can be produced in neutrino collisions inside the rock with the required amplitude, and decay into the observed configurations after traversing a minimum of 70–100 cm in air. In events 1, 2, 4, 5 and 6, there are 3 charged particles arising from the vertex P; these could, in principle, be due to the 3-body decay of $K^\pm \rightarrow 3\pi^\pm$. In event 3, there are only 2 particles arising from the vertex P and these could be produced in any of the known 2-charged particle decay modes such as of K° or even in the $K^\pm \rightarrow 3\pi^\pm$ mode with one of the pions being out of geometry of the detector. However, one has to take into account the frequency of strange particle production in a weak interaction, the branching ratio to 3 charged pions (5·6%), and the decay probability in a distance of about 1–2 m after production inside rock, which taken together reduces the overall probability to negligible levels ($\lesssim 10^{-5}$). The same arguments apply to the normal neutral current interaction, which is different to the above case only in that the muon is not produced directly. It may be pointed out that in the total path length seen in these events, *i.e.* about 350 g/cm^2 of lead, 400 g/cm^2 of iron and traversal through some other parts of the apparatus, no nuclear interaction has been observed, and at least one of the traversing particles has been identified as a muon. If event number 5 is an event similar to the other four considered in sections 2.1 and 2.2 the three secondary particles may be muons. Thus, the $K^\pm \rightarrow 3\pi^\pm$ decay mode appears to be extremely improbable. Similar arguments are applicable for normal electron-neutrino (ν_e, $\bar{\nu}_e$) interactions, either through charged or neutral current modes. In fact, they are further suppressed in view of their smaller flux, (by a factor of 4–5 at large angles as compared to ν_μ, $\bar{\nu}_\mu$), in the cosmic ray beam.

We thus conclude that these events could not have been produced by any known normal processes. The most plausible explanation of this data is in terms of the production of new, heavy, long-lived particles; these particles traverse distances of the order of 1–2 m before they decay in air, in a multiparticle mode. We present below estimates of the lifetime, mass and cross-section for the new particles on the basis of information available from the events 1–6.

3.1 *Lifetime*: The average projected path length traversed by the hypothesised new particle, L_1, is estimated as 70–100 cm in air, plus some unknown amount inside rock. If the particle is hadronic in nature, it has to be produced on the average within one mean free path in rock *i.e.* about 50 cm. Therefore, the average value of the projected path length is 1–1·5 m and the lifetime is estimated to be $\gtrsim 10^{-9}$ sec., since the Lorentz factor will be small (perhaps only 2–3) in view of the large opening angles of the events. Such a lifetime is typical of weak decays.

3.2. *Mass*: In the absence of definite knowledge concerning the nature of all the secondary particles and their momenta in each event, one can only make guess about the mass of the parent particles. Taking the probable case of 3 uons as secondaries, and the totality of the available data, in particular the sible energy losses in the detector and the large opening angles of the tracks, e estimate that the transverse momentum (P_t) of the secondary particles is of ie order of a few hundred MeV/c at least. This agrees with the observations:) that some of large angle tracks ('A' in event 1 and 'C' in event 2) have sociated knock-on electrons of a few MeV; (ii) the large angle track 'A' in ent 3 has a minimum energy loss of 300 MeV in the detector; and (iii) that in ent number 5, tracks 'A' and 'C' have path lengths of about 58 cm and 33 cm iron respectively. A crude estimation of mass in this case will be $M \simeq 3$ (m_μ $2P_t$); and we estimate the mass to be at least a few proton masses (about 2–5 eV). Other more elaborate simulations to arrive at the observed configurations e not in contradiction with this estimation.

3.3 *Cross-section*: If these events are due to neutrino interactions in rock en we have to compare the frequency of these multi-track events with that of l neutrino-induced events involving tracks at large zenith angles.

These special multi-track events constitute about 18% (*i.e.* 3 out of 17) of the tal number of neutrino-induced events identified in the large angle region at 00 hg/cm^2. For the charged current mode, the muons seen in the detector would ve been produced with approximately equal intensity from each decade of cident ν-energy, *i.e.* 1–10, 10–100 and 100–1000 GeV, under the assumption at the total cross-section for ν-interaction rises linearly with ν-energy. Thus a first approximation the cross-section for the new particle production is in e same domain as the weak cross-section for neutrino interactions at energies several tens of GeV. For accurate estimates, however, one has to take into count: (i) the relevant energy range, which depends on the threshold energy r the production of particles of given mass; (ii) the nature of the interaction, hich in the case of neutrino collisions could be either in the charged or neutral rrent modes; (iii) the geometrical efficiency for detection of a multi-track verx with large opening angles as compared to that for the detection of single uons; (iv) the production region in rock, on which depends the probability of e new particle escaping either interaction or decay in the rock; and finally, (v) e mean angle of emission of the new particle at production, as this would termine the solid angle offered by the detector, as well as the relevant flux neutrinos to be considered. An order-of-magnitude analysis would indicate at the cross-section required for the production of these new particles by neutrinos much larger than the total cross-section measured at accelerator energies. It possible that we are concerned here with neutrinos of much larger energies; in ch a case the neutrino cross-section will have to be increasing more rapidly an a simple linear extrapolation of accelerator data to higher energies.

We have considered the possibility that the heavy particle is generated by , $\bar{\nu}_e$ collisions inside the rock. In such a case, the cross-sections will have to even larger (by a factor of 4–5 compared to the ν_μ, $\bar{\nu}_\mu$ interaction) to compente for their lower fluxes in the cosmic ray beam. On the other hand, very tle information is available about ν_e, $\bar{\nu}_e$ interaction cross-sections as a funtion energy up to high energies.

4. Discussions and conclusions

The events that we have seen and reported here, on the basis of cosmic ray measurements over the past decade, indicate the existence of phenomena deep underground in which massive, hitherto unknown particles are created. The new particle has to be massive, 2–5 GeV.

If these are generated in neutrino interactions an interesting aspect of the first 5 events is the absence of a 'prompt' muon in a reaction of the

$$\text{type: } \nu + \text{target} \rightarrow \text{target} + \mu + \text{new particle (decay particles)}$$

A prompt muon (of low energy) could have been absorbed in the rock or missed the detector geometry in all cases by pure chance; but it is also possible that the interaction is of the neutral current type, or that the new particle has a lepton number. If it is the latter, it may explain the decay mode into 3 muons; it may then be a type of *heavy lepton*.

These events could not have been produced through the decay of the newly found "ψ" particles in accelerator experiments or the hypothesised W-boson, in view of the very long lifetime estimated here. More detailed information would be needed on the nature and momenta of all the secondary products to confirm the characteristics of the new particle and its role in weak interaction phenomena.

Very recently, it has been reported by Benvenuti *et al* (1975) that di-muon events observed in the neutrino experiment at the Fermilab require the existence of one or more new massive (2–4 GeV) particles that decay through weak interaction. This result is somewhat similar to that presented here particularly in the estimated mass of the new particle. However, as the data stands, there are important differences in the cross-section, lifetime and decay characteristics of the particles under consideration. We feel that the events seen in our work have a low probability of being identified in the accelerator experiment of Benvenuti *et al* (1975) mainly due to the large opening angles of the three secondary tracks. Since the two experiments are conducted in entirely different experimental situations, we have not presented here detailed comparisons, and wish to leave the results on their own for the present.

All the events discussed in this paper need not be a homogeneous group with an unique explanation in terms of the processes of production and decay. Also, we have in our experimental data a large sample of events, at the two depths of observation, comprising of single tracks, showers, parallel muons and a certain number of 2 and 3 track events, at a variety of zenith angles; these would have to be subjected to a detailed analysis (in terms of the relevant times of observation, efficiencies of detection, classification of events, etc.), before one can estimate reasonably the relative frequency of the multi-track events discussed in this paper, with the other categories.

We are aware of the difficulties involved in reconciling the lifetime and cross-section for production of these new massive particles with hitherto known phenomena. In this paper we have not attempted to examine these questions from the viewpoint of various speculative possibilities. We have presented, as experimentalists, what we have seen in as much detail as is relevant for an understanding of these observations. In our view, it is extremely improbable that these observations correspond to *known processes* involving either muons or neutrinos deep underground, *i.e.* the two components that essentially constitute the particle beam at these depths. We may, however, be dealing with new phenomena related to these particles, or with a completely new situation. It is hoped that the reporting of these observations will encourage other experiments and a deeper examination of these possibilities.

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