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Multiple penetrating particles with narrow separation associated with extensive air showers (EAS)

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Abstract. An experiment has been carried out at a vertical depth of 580 m.w.e. at Kolar Gold Fields, to investigate various characteristics of energetic muons ($E_{min} \simeq 150$ GeV) associated with extensive air showers (EAS). Double parallel penetrating particles with narrow separations (< 1m) have an exponential decoherence distribution with *e*-folding separation of $\simeq$ 25 cm.

Keywords. Penetrating particles, extensive air showers, high energy muons.

1. Introduction

A number of experiments have been carried out by various investigators, on the multiple muons at various depths underground (UG) to study the production mechanism of high energy muons (Barrett *et al* 1952, Morris and Stenorsen 1968, Krishnaswamy *et al* 1969, Barton and Roggers 1969). All these investigations excepting the one by Barrett *et al* were made with UG muons only, without the associated ground level air showers. In the present investigation a visual detector together with a scintillator has been used at the underground level (580 m.w.e.) to detect high energy muons accompanied by a ground level EAS (size $10^4 - 10^6$ particles). Results on multiple penetrating particles observed in this investigation are presented in this paper.

2. Experimental arrangement

The scintillator in the underground level has an area of $1 \cdot 5$ m $\times$ $1 \cdot 5$ m under which a Neon flash tube (NFT) telescope is placed. The flash tubes ($0 \cdot 98$ cm dia) are placed horizontally covering an area of $1 \cdot 2$ m $\times$ $1 \cdot 2$ m. The photographs are taken at the end-on position from the front only in one vertical plane. Between the two trays of the NFT telescope 10 cm lead and 1 cm ion absorbers are placed (figure 1). To trigger the NFT telescope an underground particle associated with ground level EAS is required. The centre of the EAS array is 70 cm south–west of the vertical projection of the underground detector. Thus the effective depth of the investigation is 625 m.w.e. The underground NFT telescope detects mostly

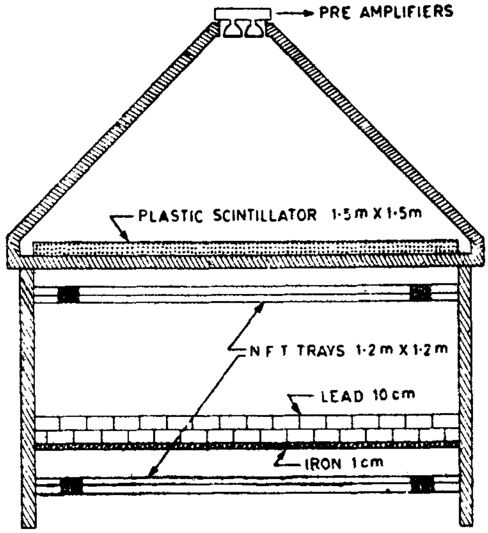

Figure 1. Schematics of the penetrating particle detector, located underground at depth of 580 m.w.e.

Table 1.

No. of parallel pair particles	No. of pair particles		Running time in sec.	*Average size of EAS N	Effective aperture m^2 st.	Rate of parallel pair/ m^2 st sec.
	Convergent	Divergent				
38	4	2	$5 \cdot 38 \times 10^6$	$1 \cdot 53 \times 10^5$ particles	·21	$(3 \cdot 3 \pm \cdot 45) \times 10^{-5}$

Total No. of single muons = 1400
* Minimum size of EAS, associated with singles = 10^4 particles (Information available from TIFR Air shower experiment at KGF).

those showers, which have inclinations within 20°–30° to the vertical. The distance between the roof of the rock and the UG detector is 2 m. The air shower array at the ground level forms part of the TIFR air shower project.

3. Experimental data

We have detected 38 events involving double parallel penetrating particles; during the same running time 1400 single penetrating particles have been detected. These events are in addition to the events involving small cascade showers and large bursts generated by the muons which have been reported earlier (Chowdhuri and Saxena 1975). The projected angle of any track in the vertical plane can be measured with an accuracy of $\pm$ 1°. The criteria for observing the double penetrating parallel particles in the projected plane, is that they should be detected in both upper and lower NFT trays, traversing 18 radiation lengths of the absorber and the angle between them should be $< 2°$. The minimum projected separation between two such tracks is found to be ~ 2 cm. The relevant data about these pair particles are given in table 1.

4. Data analysis and results

A decoherence curve of the events consisting of double penetrating particles is plotted to get more information about these particles. The observed numbers are grouped in intervals of $dx = 10$ cm and plotted against 'x' the corresponding separation between the pair particles in the projected plane (figure 2 *a*). The errors shown in this curve are the probable errors. This curve shows a rapid fall in the frequency of events for separations $x > 35$ cm. This depression towards large separations may be partly due to geometrical effect, *i.e.*, a pair of particles with small separation may have a greater chance to be detected than when the two particles have separation comparable with the dimension of the detector. We find in our apparatus the detection efficiency for events with separation 5 cm is 95% whereas it is only 42% for 60 cm separation. Also the events consisting of the pairs with separation 1–10 cm may include a spurious effect due to multiple knock-on electrons generated in the rock and lead absorbers above each of the two NFT trays of the UG detector. Thus if two knock-on electrons, one produced in the rock and another inside the lead absorber, both emerge in the same direction parallel to the parent muon, then they may give an appearance continuous track nearly parallel to the direction of the parent particle. However the number of the double knock-on electrons, accompanied by 1400 single muons detected during the same interval of time is found to be 17. The directions of these knock-on particles are distributed uniformly over all angles to the direction of incident muon. Thus the probability that both the knock-on electrons are in one particular direction parallel to the parent particle will be extremely small. Hence the contribution due to this effect can be neglected. Another effect which may produce enhancement in the rate of events in the smaller separation group arises because we detect only the projected image of the particle track. The projected distance between the particles is given by $x = r \cos \theta$, where r is the

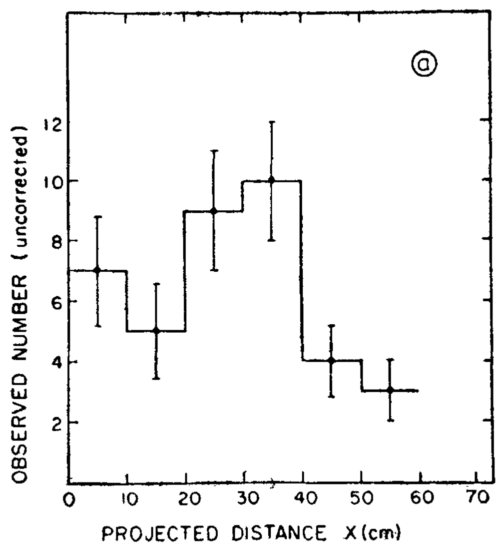

Figure 2 *a*. Frequency distribution for the observed double parallel particle events in projected plane.

true separation between the pair particles and $x < r$ unless the plane containing the pair is parallel to the projected plane. This effect may also produce a depression in the frequency of the events with larger separations. In order to get the true separations, between the pair particles from their projected image, the probabilities of events with various separation r up to 100 cm for each projected separation x have been computed, on the assumption that the particles are randomly distributed over the detector. After taking account of all these effects, the corrected number of events are grouped in 10 cm intervals. The frequency of events at each interval $dr = 10$ cm, divided by the corresponding area $2\pi r dr$, has been plotted against r in figure 2 *b*. It is found that though this decoherence distribution (figure 2 *b*) is more spread out than that in the projected plane (figure 2 *a*), it peaks towards smaller separations. It seems that this distribution can be expressed as an exponential function of the form $R = Ae^{-r/r_0}$ where R is the rate of events and r is the true separation between the pairs. The curve fitting is done by applying the method of least square. The linear relation between ln$R$ and r which gives a best fit to the observed data is given in figure 3. The values of constants obtained through the least square fit are $A = (1\cdot258 \pm \cdot32) \times 10^{-2}/\text{cm}^2$ and $r_0 = (25 \pm 5\cdot5)$ cm. With these values the exponential distribution curve is drawn and shown as the solid line in figure 2 *b*.

5. Discussion

Krishnaswamy *et al* (1975) have reported the results of their experiment on parallel muons at the underground level of 754 hg/cm² which are recorded without ground level EAS trigger. It is noticeable that their data on double parallel particles

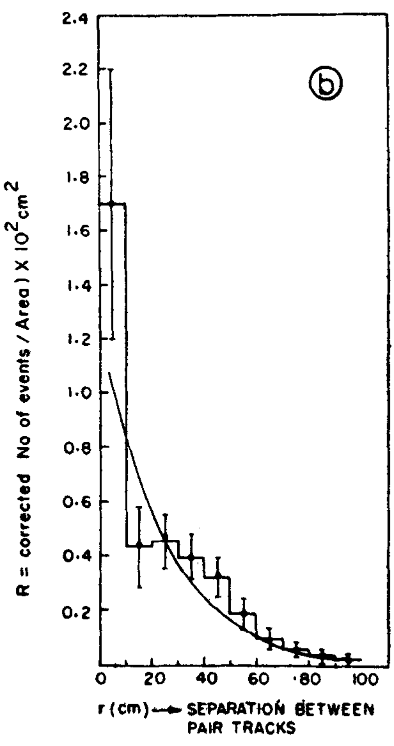

Figure 2 *b*. Frequency distribution of the observed double-parallel particles events after corrections.

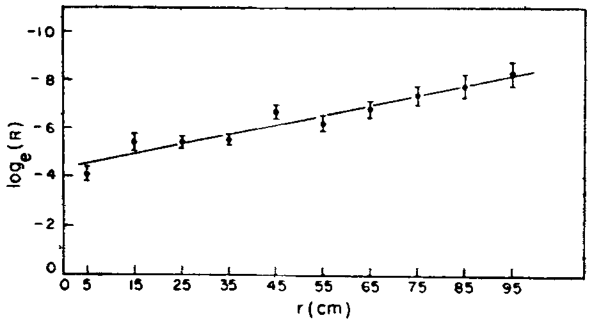

Figure 3. Decoherence distribution of double parallel penetrating particles. Rate of events (after correction) is plotted on a logarithmic scale on y-axis against the separation between pairs on x-axis. Solid line is least square fit to the data.

with separation in the range 0–2 m also exhibit a sharp fall in intensity up to a separation $\leq 1 \cdot 25$ m; later there is an increase in the intensity in the range at about 2 m. They have also plotted the decoherence relation for the events in the range 1–10 m separation, which could be expressed best by an exponential distribution of the form. $A \exp(-r/r_0)$ with $r_0 = (28 \pm 5)$ m. This shows that the distribution for the events with separation larger than 1 m is much broader than what is found in the present experiment for the narrow showers with spread < 1 m, where $r_0 = 25$ cm. A similar steep distribution for the events with separation of the tracks < 1 m has been reported by Barrett *et al* (1952), from their observations at an underground level of 1600 m.w.e. with G–M counters accompanied by ground level EAS. In their decoherence curve they obtained two distributions, one very steep for the separation < 1 m and the other was a broad one for the separation > 1 m. The distribution of the parallel muons with separation 1–10 m reported by Krishnaswamy *et al* (1975) is similar to the broad portion of the decoherence curve of Barrett *et al* (1952). This distribution may be interpreted as the lateral distribution of muons generated in air along with air showers. But the steepness of the decoherence curve for $r < 1$ m, as found in the present experiment as well as by Barrett *et al* (1952), indicates that these events cannot be produced in air at very high altitude. These particles are, probably, produced locally in the rock, within 3–4 m above the underground apparatus and hence viewed by the detector as particles with narrow separation. In this case it is also possible that one of the particles of the pair may be a muon associated with EAS, and the other a secondary particle produced locally.

Furthermore, we have compared the rate of occurrence of the narrow showers with the result reported by Barrett *et al* (1952). Their observed value for the ratio of narrow pairs involving parallel penetrating particles to single muons is of the order of 2 events per 1000 single muons, whereas our calculated ratio turns out to be of the order of $(2 \cdot 7 \pm 1) \times 10^{-2}$. So the results of these two experiments regarding the rate of occurrences of the narrow showers differ by more than a factor of 10.

However, it may be noted that there is some difference in the experimental condition of these two investigations. In the investigation of Barrett *et al* (1952) the thickness of lead absorber is 50 cm which is more than three times the interaction mean free path of pions in lead. In the present experiment the absorber thickness is only 10 cm lead and 1 cm iron, which is even less than an interaction length. Thus if at least one of the particles of the pairs is a pion, it is possible that due to nuclear absorption of pions in the large thickness of lead, Barrett *et al* (1952) detected less number of narrow pairs than obtained in the present experiment.

It thus seems, that the observed parallel pairs of particles are generated locally in the rock somewhere by interaction of high energy muons above 3 m from the underground detector. Further the comparison between the rate of occurrences of the observed events of the present experiment and that of Barrett *et al* (1952) indicates that at least one of the particles of the pairs may be a pion. More data for each separation r of the pairs with different absorber thickness are necessary to get further detailed information about these events.

6. Conclusion

The decoherence distribution of parallel pairs of high energy penetrating particles associated with EAS for separations < 1 m follows a exponential law $A \exp(-r/r_0)$ with $r_0 = (25 \cdot 0 \pm 8 \cdot 5)$ cm. Comparison with other experiments suggests that the observed parallel pairs of particles may be generated by high energy muons in the rock and one of the particles may be a pion.

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