Observations of Cosmic-Ray Events in Nuclear Emulsions Exposed below Ground

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ABSTRACT. Ilford Nuclear research plates were manufactured in a laboratory at an equivalent depth of 60 m. of water below ground. After having been stored at various depths, the plates were processed below ground. The observed frequencies of μ-mesons stopped in the plates are consistent with those expected from measurements on the energy-spectrum of cosmic rays. Several π-mesons stopping in the plates were observed, and reasons for believing these to have been locally produced in the matter near the plates are discussed.

Forty-two nuclear disintegrations have been observed, the frequency at a depth of 60 m. water equivalent being of the order of 5×10^{-3} stars/cm^3/day. Approximately one third of these are attributed to the electromagnetic interaction of μ-mesons on their passage through nuclei. The remainder are attributed in part to neutrons from this first group of stars, and in part to the photons of the soft component underground.

Four examples of stars accompanied by showers of particles at minimum ionization have been observed, and are discussed.

§ 1. INTRODUCTION

In the last few years, many studies have been made of the frequency of occurrence of nuclear disintegrations observed in nuclear emulsions exposed under absorbers of various thicknesses. The frequency had been determined at many points in the atmosphere by Addario and Tamburino, Powell, Page, Bernadini, George and Jason, Harding *et al.*, and many others. At mountain altitudes, several of these workers have determined the frequency of stars in plates exposed under ice, carbon, aluminium and lead. The absorption length of the radiation causing the stars has been found to vary from about 150 gm/cm^2 in air and other light materials to about 300 gm/cm^2 in lead. These results support the general view that most of the stars are produced by particles possessing a strong interaction with atomic nuclei, presumably the primary protons and the secondary nucleons to which they give rise in the atmosphere. The frequency of stars produced by these nucleons at a depth below ground equivalent to 60 m. of water would be undetectably small, of the order of exp (-40) per cm^3 per day.

On the other hand, evidence for the production of meson pairs at this depth has been reported by Braddick and Hensby (1939), and one would conclude that the processes leading to the production of these meson pairs would be likely to result in the disintegration of atomic nuclei also.

It therefore seemed worth while to determine whether stars could be detected underground, and if so to determine their frequency and general properties. In order to ensure that any stars observed were actually produced below ground, Ilford Nuclear research plates were prepared in our underground laboratory, and were brought to the surface only after they had been processed.

In the plates obtained in this way, a small but finite rate of production of stars was recorded, and the preliminary results were described in a note in *Nature*

(Evans and George 1949). A fuller account of the observations is given in the present paper. The statistical accuracy of the results is poor, but as it will take some time to improve this aspect of the investigation, it was thought that the present interim report would be of some interest.

§ 2. EXPERIMENTAL DETAILS

The coatings were performed in our underground laboratory on a disused part of Holborn Station, and at a depth equivalent to 60 m. of water. Up to the present, two separate batches of plates have been coated; for the first batch, Ilford type C2 emulsions were used, for the second, the Ilford 'electron sensitive' type, G5. The emulsion for both batches was brought molten from the factory and poured on to glass plates at Holborn. In each case emulsions 200 microns thick were used.

The C2 plates of the first batch were left at a depth of 60 m., while the G5 plates of the second batch were divided into three groups: one group was left in the laboratory at 60 m. water depth, one group was taken to another platform at a different depth at Holborn (34 m. water) and the remaining group was taken by Underground train and left at Arsenal Station which is at an equivalent depth of 20 m. water.

§ 3. THE FREQUENCY OF SLOW MESONS

In the examination of 144 cm^3 of emulsion, a total of 363 mesons have been observed to come to rest of which the greater part were μ-mesons. A few π-mesons have been observed also. We give our results for these mesons separately.

3.1. μ-*Mesons*

Table 1 shows the observed frequencies of occurrence of μ-mesons brought to rest in plates exposed at sea level and the three different depths underground.

Table 1

Depth (m. water)	0	20	34	60
μ-meson per cm^3/day	$0{\cdot}70 \pm 0{\cdot}05$	$0{\cdot}091 \pm 0{\cdot}009$	$0{\cdot}055 \pm 0{\cdot}004$	$0{\cdot}017 \pm 0{\cdot}002$

Rossi (1948) has given a curve showing the expected numbers of mesons stopping per gramme of air, per unit solid angle in the vertical direction, and our results are compared with his curve in Figure 1. In reducing our results to standard units, we have allowed for the mesons lost due to plate geometry (cf. Lattes, Occhialini and Powell 1947), and for the relative stopping powers of air and nuclear emulsion, and have assumed that the frequency of slow mesons travelling in a direction θ from the vertical varies as $\cos^3\theta$ (cf. Kraushaar 1949).

From Figure 1, it is seen that the observed numbers of slow mesons are in fair agreement with the expected values, the underground results being low by a mean value of $35 \pm 6\%$. Some part of the difference must be attributed to the fact that under the conditions of microscopic examination of the underground plates ($\times 10$ objective, $\times 6$ eyepieces), some of the mesons probably escaped observation. The question of the angular distribution of slow μ-mesons will be taken up later, when we have observed a sufficient number. If the distribution were proportional to $\cos^2\theta$ underground, the experimental points would have to be lowered by 25%.

Approximately one half of the plates were developed after 6 weeks exposure, and the rest after 12 weeks. Of the μ-mesons ending in G5 plates, $50 \pm 5\%$ were accompanied by the track of the characteristic decay-electron. Cosyns *et al.* (1949), using exposures of 6 and 12 days, have shown that $62 \pm 4\%$ of the mesons above ground decay in G5 emulsions, but that in plates 200 microns thick, 20% of the decay tracks would not be observed for reasons of geometry. Assuming

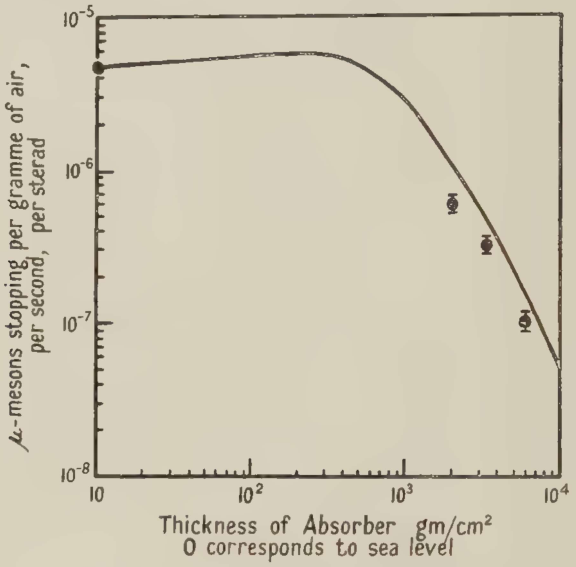

Figure 1. Slow μ-mesons as a function of depth below sea level.

the ratio of positive to negative μ-mesons to be the same below ground, we see that the observed number agrees well with the expected number of μ-mesons showing β-decay. From this we may conclude that the loss of minimum tracks even after three months was negligible under our conditions of exposure.

Out of a total of 363 μ-mesons, 10 (i.e. $2{\cdot}7 \pm 0{\cdot}9\%$) were observed to enter the emulsion from below the horizontal.

3.2. π-*Mesons*

Eight π-mesons have been observed to come to rest in our underground emulsions, of which four were positive and four were negative. Figure 2 (Plate I) shows a mosaic of photographs in which a positive π-meson stops in one of the G5 plates and emits a μ-meson which also ends in the emulsion. The decay electron which originates from the end of the μ-meson can be clearly seen. The number observed is too small to enable us to determine the variation of slow π-mesons with depth below ground. We accordingly group the results together, and divide by the total exposure of all the underground plates ($= 8{\cdot}8 \times 10^3\,\text{cm}^3 \times \text{days}$) and obtain a mean figure for the frequency of slow π-mesons at the mean depth of 34 m. water:

$$N_\pi' = (9{\cdot}1 \pm 3{\cdot}2) \times 10^{-4} \text{ per cm}^3 \text{ per day.} \qquad \ldots\ldots(1)$$

Since the plates were exposed at a mean distance of about three metres from the walls of the tunnel, and since we may take 10^{-8} sec. as the lifetime of the π-meson at rest, we may infer that, but for decay in the air gap between the tunnel walls and the plates, about three times as many π-mesons would have been observed:

$$N_\pi \sim (2{\cdot}7 \pm 1{\cdot}0) \times 10^{-3} \text{ per cm}^3 \text{ per day.} \qquad \ldots\ldots(2)$$

In other words, 24 π-mesons were travelling with suitable values of direction and energy to come to rest in our plates, of which 16 decayed in flight in the air space. Of the eight that arrived, four entered the emulsion from above the horizontal and four from below. If we assume that the 16 decaying π-mesons were similarly distributed in direction, then we may infer that, during the sensitive time of the plates, about eight π-mesons travelling towards the plates from below decayed in flight, giving rise to μ-mesons. The actual number of upward travelling μ-mesons observed was 10 (see above), and therefore may be accounted for by the decay of the observed upward stream of π-mesons. A similar interpretation of the upward stream of μ-mesons observed at the Jungfraujoch was advanced by Camerini, Muirhead, Powell and Ritson (1948). The question of the origin of the π-mesons is discussed below.

§ 4. NUCLEAR DISINTEGRATIONS

Up to the present we have observed 42 nuclear disintegrations giving rise to 'stars' with three or more branches, which have been produced below ground, 18 in C2 plates and 24 in G5 plates. Of the 24 observed in the G5 plates, 10 were stars with charged primary particles and 14 stars with neutral primary particles. Four stars were associated with showers of fast electrons.

4.1. *The Size–Frequency Distribution*

In Figure 3 (*a*) is plotted a histogram showing the number of stars observed with a given number of heavy tracks, N_h, as a function of N_h. In Figure 3 (*b*)

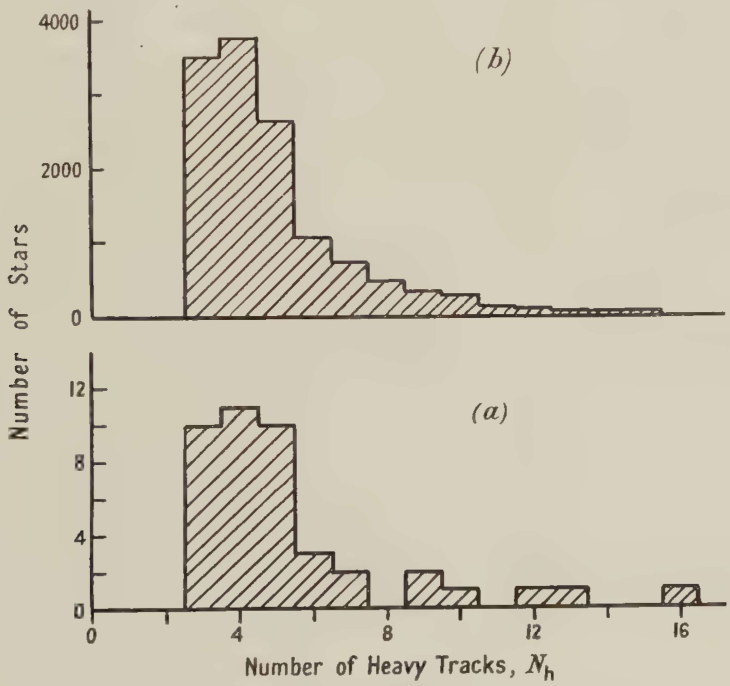

Figure 3. Distribution of the numbers of heavy tracks for stars observed (*a*) underground and (*b*) at the Jungfraujoch.

is plotted for comparison the corresponding histogram for about 10,000 stars observed in our laboratory in plates exposed at the Jungfraujoch. Within the rather wide limits of statistical error, the two size–frequency distributions appear to be similar.

4.2. *The Frequency of Stars versus Depth below Ground*

In Table 2 are given the details of the star-frequencies observed at sea level and at the three different depths below ground at which the plates were exposed. The results from C2 and G5 type emulsions are included together.

Table 2

Depth below ground (m. H_2O)	No. of stars observed	Frequency of stars per cm^3 per day
0	383	$1{\cdot}46 \pm 0{\cdot}07$
20	7	$0{\cdot}0066 \pm 0{\cdot}0025$
34	13	$0{\cdot}0044 \pm 0{\cdot}0012$
60	22	$0{\cdot}0050 \pm 0{\cdot}001$

The statistical accuracy is poor, and is not likely to be greatly improved using nuclear emulsion techniques. It appears however that there is only a slow variation in the frequency of occurrence of stars with depth below ground. It is exceedingly unlikely, for example, that the frequency differs by as much as 4 : 1 between 20 and 60 m. water.

The star frequency varies by a factor of approximately 10^3 between the top and bottom of the atmosphere, equivalent to 10 m. water, and this would correspond to a variation of the order of 10^{12} for an absorber equivalent to 40 m. water. The particles responsible for the stars below ground may with confidence be assumed to be different from those responsible for the bulk of the stars observed above ground.

4.3. *Stars associated with Fast Particles*

Using the G5 plates, the grain density, g_{min}, corresponding to particles with minimum ionization was determined from the many straight tracks produced by cosmic-ray particles of great energy. The value so obtained was $g_{\mathrm{min}} = 340$ grains/mm. Following Brown *et al.*, a 'fast' particle is defined as one producing a grain density less than $1{\cdot}5\, g_{\mathrm{min}}$. A star was assumed to be produced by a charged primary particle if it was associated with a fast particle at an angle less than 90° to the vertical (cf. Brown *et al.* 1949 b). In the event of two or more tracks satisfying this condition, the track nearest the vertical was taken.

Of the 42 stars discussed above, 18 were in C2 emulsion in which the tracks of fast particles would not have been observed. The remainder were observed in G5 emulsion, and of these 24 stars, 10 (i.e. 42%) were produced by fast charged primary particles. Brown *et al.* (1949 a, b) and Page (1950) have reported that in plates exposed at the Jungfraujoch 17% of the stars are produced by fast charged particles. If this proportion were maintained in the underground events then, out of 24 stars, four would be expected to show charged primary particles. The probability of observing ten instead of four on account of a fluctuation is 0·013. It appears likely therefore that the fraction of stars with charged primaries is greater below ground than it is at mountain altitudes.

For each of these ten stars, we have measured the angle θ between the vertical and the projection in the plane of the emulsion of the track of the fast primary particle. The values thus obtained are 4, 10, 12, 18, 27, 31, 33, 36, 37 and 48 degrees respectively.

In five of these stars produced by fast charged particles, a single fast particle was observed on the lower side of the star. Two photo-micrographs of events

Figure 2. A positive π-meson, observed at a depth of 60 m. water, entered the emulsion from below the horizontal, showing the characteristic π–μ decay and also the β-decay of the μ-meson. Observer: J. EVANS.

Figure 5. A disintegration produced by a fast charged particle at a depth of 20 m. water. The angle of deviation of the fast particle is 30°, the largest that has so far been observed in underground stars of this type. Observer: E. P. GEORGE.

PLATE I.

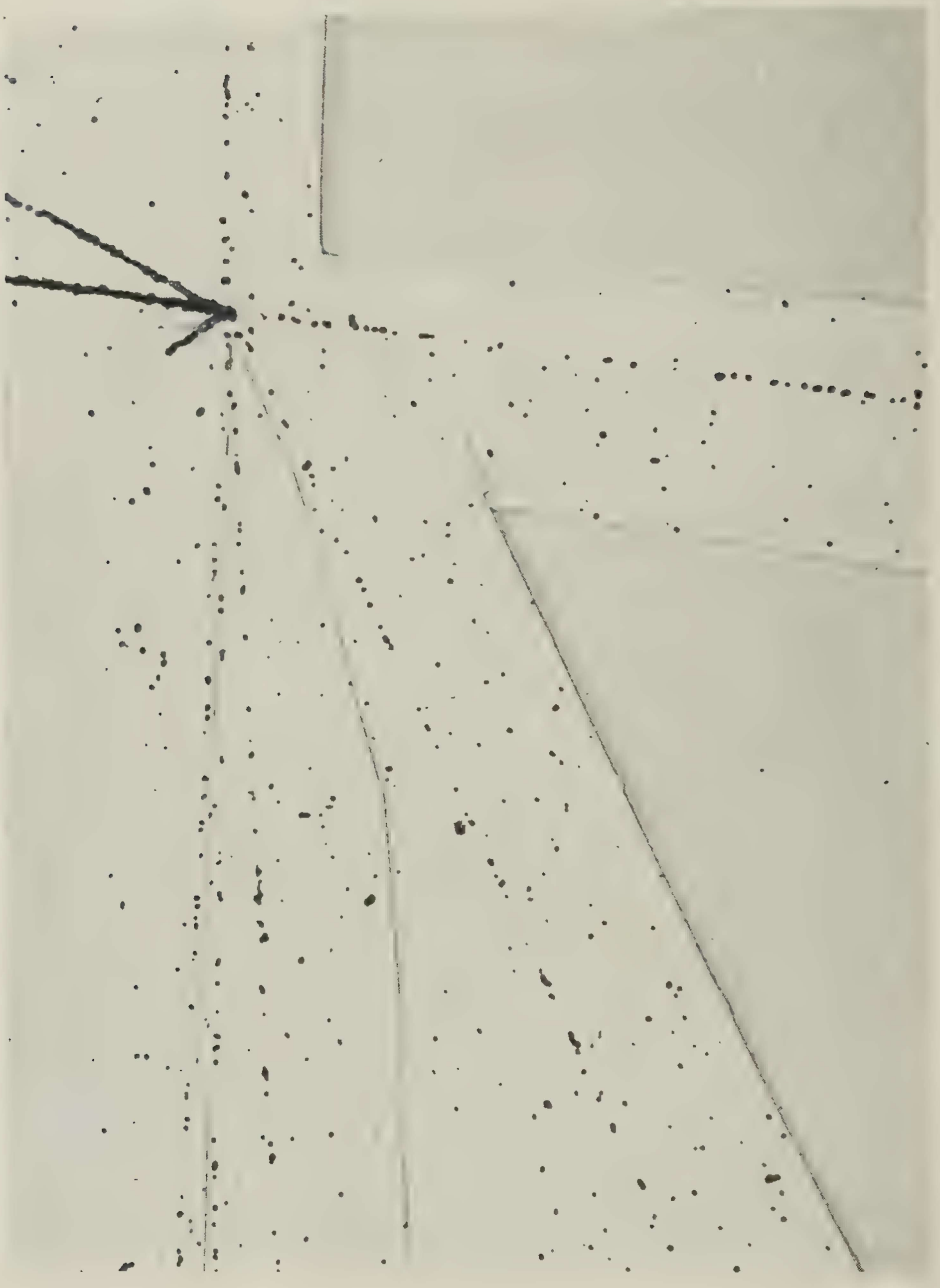

Figure 8. A disintegration, produced by a fast charged particle at a depth of 34 m. water and accompanied by a shower of 5 fast particles. Observer: Mrs. M. H. GEORGE.

PLATE IV.

of this type are shown in Figures 4 and 5 (Plates I and II). The simplest interpretation of this type of event is that the energetic fast particle is scattered by a nucleon inside an atomic nucleus. The recoil momentum of the scattered nucleon then leads to the disintegration of the nucleus. From the fact that the size–frequency distribution of the underground stars is similar to that for stars observed at mountain altitudes, we may make use of the analysis of Brown *et al.* (1949 b) in order to determine the mean energy of a star having a given number, N_h, of heavy tracks. These authors give the relation between energy and N_h:

$$E(\text{Mev.}) = 37N_h + 4N_h^2. \qquad \ldots\ldots(3)$$

Assuming a value for the mass of the fast particle, and that the collisions are elastic, then equation (3) combined with a knowledge of the angle of deflection

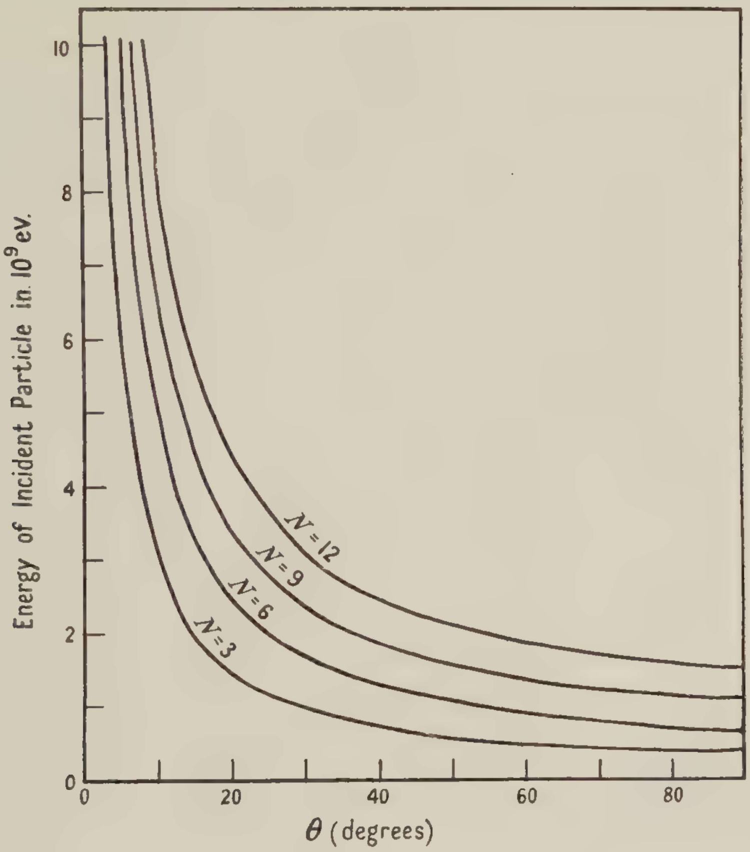

Figure 6. Relation between the angle of deflection and energy of the incident particle, for stars produced by the elastic scatter of μ-mesons. Plotted for various values of N, the number of tracks per star.

of the incident particle leads to an estimate of its energy from the conservation laws. For the angles of deflection observed, the energies of the fast particles calculated in this way depend very little on their assumed mass. By way of illustration, a series of curves showing the relation between the energy and angle of scatter for fast μ-mesons has been evaluated for various values of N_h, and is plotted in Figure 6. Using these curves, the energies of the initial particles, assumed therefore to be μ-mesons, are given in Table 3. Other assumptions concerning the nature of the initial particles will be discussed in §5. Event No. 5, in Table 3, occurred too near the emulsion surface to enable a reliable estimate of the deflection to be made. From Figure 6 it is seen that the deduced energies increase rapidly for small angles of deflection. The energies in the bottom line of Table 3 should therefore be treated with some reserve and taken merely as an indication of the order of magnitude. They are seen to lie in the region 10^9–10^{10} ev., values which are not unreasonable.

In one of these ten stars, produced by fast charged particles, no fast particles leaving the point of collision could be identified.

Table 3

Event No.	1	2	3	4	5
Depth below ground (m. H_2O)	20	34	60	60	60
Size of star N_h	3	4	5	4	10
Energy of star (Mev.)	147	212	285	212	770
Angle of deflection of fast particle (deg.)	30	5	12	2·5	—
Energy of fast particle (assumed μ-meson) (Mev.)	1000	7300	3500	15000	—

Assuming the stars are produced by the μ-mesons of the penetrating component, an estimate may be made of the cross section for the production of stars by μ-mesons. We use the results at the greatest depth, 60 m. water, as they have the greatest statistical weight. The vertical intensity at this depth was measured by Follett and Crawshaw (1936) and found by them to be 6% of the sea-level value. This corresponds to a flux of 80 fast μ-mesons per cm^2 per day. This figure has since been confirmed by many measurements in our laboratory. The frequency of stars with charged primaries is

$$2 \times 10^{-3}/\text{cm}^3/\text{day} = 5 \times 10^{-4}/\text{gm}/\text{day}.$$

Hence the cross section for star production by fast μ-mesons is given by

$$\sigma = \frac{5 \times 10^{-4}}{80 \times 6 \times 10^{23}} \simeq 10^{-29}\ \text{cm}^2/\text{nucleon}. \qquad \ldots\ldots(4)$$

4.4. *Stars associated with Showers of Fast Particles*

One of the more interesting features of the underground stars is that four of the ten disintegrations produced by fast charged particles were accompanied by the emission of showers of fast particles, while none of the disintegrations produced by neutral particles was accompanied by showers. Mosaics of photo-micrographs of two examples with five shower particles are shown in Figures 7 and 8 (Plates III and IV). The other two examples were associated with showers of three fast particles. The values of the grain density of the shower particles all lie between 0·93 and 1·14 g_{min}. The angles ϕ in the plane of the emulsion, between the direction of the incident particle and the shower particles were measured, and a histogram showing the distribution in ϕ is given in Figure 9. A comparison with the angular distributions of Brown *et al.* (1949 b) for similar showers observed at the Jungfraujoch suggests that the angular distribution of the underground shower particles is rather similar to that in showers at mountain altitudes, though again it is recognized that our observations need to be extended before detailed comparisons can be made.

Of the stars observed with charged primaries at 70,000 ft. by Camerini *et al.* (1949) and at 11,000 ft. by Brown *et al.* (1949 b), 18% were accompanied by showers of three or more particles. If this fraction were the same below ground, then out of a total of ten events, the expected number of showers would be 1·8 and the probability of observing four instead due to fluctuation is 0·06.

The showers seem very similar in appearance and general properties to those observed in similar plates exposed above ground except for the fact that all those observed below ground are associated with charged primary particles.

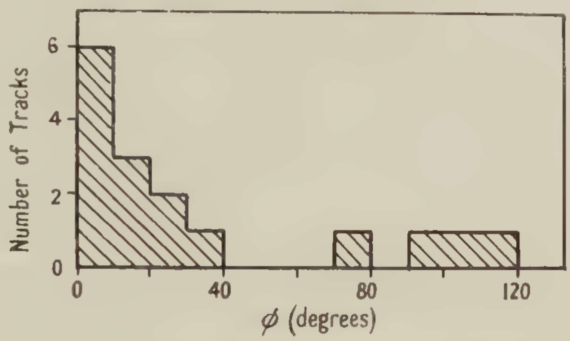

Figure 9. Distribution in the values of ϕ of the tracks of shower particles. ϕ is the angle in the plane of the emulsion, between the incident particle (produced) and a shower particle.

§ 5. DISCUSSION OF RESULTS

The frequency of slow μ-mesons underground is seen to be close to the expected value, and does not therefore call for further comment. The remaining features of our observations, for which an explanation is sought, may be summarized as follows:

(i) The frequency of slow π-mesons stopping in solid matter is approximately $2{\cdot}7 \times 10^{-3}$ per cm^3 per day (equation (2)).

(ii) The frequency of stars is approximately 5×10^{-3} per cm^3 per day at a depth of 60 m. water.

(iii) The variation of the star frequency between 20 m. and 60 m. water depth below ground is small.

(iv) The size–frequency distribution of the underground stars is not very different from that of the stars observed at sea level and mountain altitudes.

(v) About 40% of the underground stars are produced by charged particles.

(vi) Four out of ten stars produced by fast charged particles are associated with showers of fast particles.

We will discuss in the first place those stars produced by fast charged particles. There are two questions to be answered: what are the particles producing the stars? and what is the mechanism of the interaction?

As to the first question, we think the charged particles producing the underground stars must in nearly all cases be assumed to be the μ-mesons. This is suggested by the slow variation of star frequency with depth, and is justified in the following argument.

5.1. *The Charged Particles producing Underground Stars*

The grain density in the tracks of the fast particles is close to $g_{\min}$, and hence the particles possess charge $\boldsymbol{e}$ and kinetic energy greater than or equal to $2\boldsymbol{mc}^2$, where $\boldsymbol{m}$ is their rest mass. They might therefore be protons, π-mesons, μ-mesons or electrons.

From the fact that the general features of the underground stars are rather similar to those of the stars observed at mountain altitudes, except for a reduction in frequency of about 2,000, one might be tempted to assume that the particles causing the stars are the same in both places, i.e. principally cosmic-ray nucleons. On this viewpoint, the stars with fast charged primaries would be due to protons and possibly to some extent to π-mesons. However, this is completely at variance with the observed slow variation of star frequency with depth, the discrepancy being a factor of 10^{12}. It would be necessary to postulate some process leading to the generation underground of energetic protons by the μ-mesons forming the penetrating component. In general, such a process would lead to the simultaneous disintegration of the nucleus supplying these fast protons, i.e. to the production of stars by μ-mesons. This contradicts the premise from which we started, that the fast particles causing stars are protons. The only condition under which protons could be accepted as the primary agent would be that relativistic protons be generated by μ-mesons underground in a process not associated, in general, with a nuclear disintegration, and this seems a rather artificial assumption.

The possibility that the charged primary particles are π-mesons may be eliminated on two grounds. One of the arguments is the same as that used above against protons. The absorption length, L_A, of π-mesons in the energy interval 200–800 MeV., reported by Camerini *et al.* (private communication), is approximately 100 gm/cm^2 of nuclear emulsion, which corresponds to a cross section for absorption close to the nuclear geometric cross section. This figure is at variance with the figure $L_A > 1{,}200$ gm/cm^2 reported by Piccioni, who measured the absorption of penetrating shower particles with a system of counters. However, the former result, based on a more direct measurement seems much less open to doubt and is to be preferred. Accepting this figure of $L_A \sim 100$ gm/cm^2, all the arguments against identifying as protons the fast charged particles causing the stars may be taken as applying to π-mesons also. A further argument against π-mesons may be based on the observation of Camerini *et al.* that of 25 stars in which they were able to identify the fast primary particle as a π-meson, in 20 cases the incident particle was absorbed and no fast particle was detectable on the other side of the star (called by these authors O_p-type stars). In the remaining cases, one fast track was observed on the further side of the star (type I_p in their nomenclature). The situation is reversed in our stars. Out of a total of six, five were of type I_p (see Figures 4 and 5), and one was of type O_p. Hence we think it safe to assume that the charged particles producing stars underground are, in general, not π-mesons.

The ionization loss of particles penetrating to our deepest level is $1{\cdot}2 \times 10^{10}$ ev., and we have based part of our argument against π-mesons on the observation that the absorption length of these particles is of the order of 100 gm/cm^2 at lower energies. Heitler (1941) and Wilson (1941) have shown that taking radiation damping into account, the cross section for collision with nucleons is proportional to $1/E$, at high energies; this raises the possibility that π-mesons of sufficient energy to penetrate below ground may have a nuclear cross section sufficiently small that they may arrive in large enough numbers and yet sufficiently large that they can cause the observed stars. The situation at these high energies is by no means clear, as we have no direct evidence concerning the penetration of π-mesons in the energy range in which we are interested. Basing our argument on the theories of Heitler and Wilson, it is again concluded that π-mesons are unlikely to be responsible for the underground stars.

Electrons may be eliminated by referring to the estimated energies of the charged particles in Table 3. Here they were assumed to be μ-mesons, but the energies of the particles if assumed to be electrons would be comparable. Energetic electrons, arising from knock-on collisions with μ-mesons, are known to exist below ground, and it may be shown that the path length of the electrons with energies greater than 10^9 ev. is 3×10^{-4} times that of the μ-mesons. In order to account for the observed frequency of stars it would be necessary to assume a collison cross section of 3×10^{-26} cm^2 per nucleon for these electrons, i.e. a cross section of the same order of magnitude as that for nucleon–nucleon collisions. Hence, we need not consider electrons as the agents causing the stars with fast charged primary particles.

This leaves us as the only alternative the μ-mesons. There is no difficulty in accounting for the presence of these particles, since they are considered to constitute the main component of the cosmic-ray flux at sea level and below ground, and we have shown that the number stopping and identified as μ-mesons in the photographic emulsions is close to the number expected. The only objection that may be advanced is that μ-mesons are thought to have such a weak interaction with nuclear matter that they could not cause the observed frequency of occurrence of stars. In fact, from observations of the β-decay of μ-mesons in solid matter, it may be concluded that the cross section for the nuclear collision of μ-mesons is of the order of 10^{-39} cm^2 per nucleon, whereas in order to account for the observed star frequency we would need to assume a cross section of the order of 10^{-29} cm^2 per nucleon. However, the μ-mesons, being charged, experience an electromagnetic interaction with nucleons, and it is shown below that this mechanism leads to a cross section of the right order of magnitude.

5.2. *Nuclear Collisions of Fast Charged Particles by the Coulomb Interaction*

Consider a proton at rest which is passed at a distance a by a fast singly charged particle. Due to the Coulomb interaction, the proton recoils with momentum P, given by (cf. Jánossy 1948, p. 89):

$$P = \frac{2\mathbf{e}^2}{a\mathbf{c}}. \qquad \text{......(5)}$$

Assuming the fast particle to be traversing an absorber, the effective cross section averaged over all collisions in which the proton recoils with momentum greater than P is $\sigma = 4\pi\mathbf{e}^4/P^2\mathbf{c}^2$.

Inserting for $P\mathbf{c}$ the value 430 Mev., corresponding to a minimum recoil energy of 100 Mev. sufficient to cause the stars observed, we obtain a cross section of the order of 10^{-30} cm^2. Allowing for the fact that there would be no such interaction with neutrons, this would give a cross section of about

$$4 \times 10^{-31} \text{ cm}^2 \text{ per nucleon.} \qquad \text{......(6)}$$

Assuming this argument may be applied to the μ-meson component below ground, we see that this figure is much smaller than the observed figure of the order of 10^{-29} cm^2 per nucleon. However, this theoretical figure is likely to be an over-estimate as the distance of closest approach, a, from (5) is of the order of 5×10^{-16} cm., and the usual considerations of screening would suggest therefore that the Coulomb interaction hardly applies to impact parameters as small as this. Thus, at first, we were inclined to discount the possibility that the stars could be caused by the Coulomb interactions of fast μ-mesons below ground.

However, it was pointed out to us by Heisenberg, at the Como Conference, that the Coulomb cross section is likely to be greater than that given by equation (6) on account of the stronger interaction between the electromagnetic field and the nuclear meson fields.

This suggestion has recently received support from the observations of McMillan *et al.* (1949) of the production of π-mesons by the photons of the Berkeley electron synchrotron. These authors give a cross section for the production of π-mesons by photons of 5×10^{-28} cm² per carbon nucleus. Heitler and Peng (1943) have shown that the cross sections for the anomalous scatter of photons with or without the production of free mesons are expected to be about the same. Hence we may take as a probable figure for the total cross section for star production by photons:

$$\sigma_\nu = 10^{-28}\ \text{cm}^2 \text{ per nucleon} \qquad \ldots\ldots(7)$$

from the observations of McMillan *et al.* Following Williams (1933), a fast μ-meson of energy E is regarded as being accompanied by the following number of photons in the frequency interval $d\nu$ at ν:

$$N(\nu)d\nu = \frac{2\alpha}{\pi}\frac{d\nu}{\nu} \log \frac{E}{\boldsymbol{h}\nu}. \qquad \ldots\ldots(8)$$

The cross section for the production of stars by μ-mesons would be from (7) and (8)

$$\sigma_\mu = \frac{2\alpha}{\pi}\int_{E_{\min}}^{E} \frac{\sigma_\nu}{\nu}\, d\nu \,\log\left(\frac{E}{\boldsymbol{h}\nu}\right), \qquad \ldots\ldots(9)$$

where $E_{\min}$ is the minimum energy for star production, which we may conveniently take to be $m_\pi \boldsymbol{c}^2$. Substituting the observed value (7) for σ_ν, we get the following approximate expression for σ_μ:

$$\sigma_\mu = \frac{2\alpha}{\pi}\left[\log \frac{E}{m_\pi \boldsymbol{c}^2}\right]^2 \times 10^{-28}\ \text{cm}^2. \qquad \ldots\ldots(10)$$

At 60 m. water depth, the mean energy of the μ-mesons is approximately $1{\cdot}4 \times 10^{10}$ ev., and substituting this value in (10) we obtain the numerical value:

$$\sigma_\mu = 10^{-29}\ \text{cm}^2 \qquad \ldots\ldots(11)$$

which is quite close to the observed value.

In arriving at the expression (10) we have ignored the variation of σ_ν with ν. This is unlikely to introduce serious errors however, for the numerical value (7) is already a mean value averaged over the frequency interval which begins at the threshold for meson production, 150 Mev., and extends to the maximum energy of the particles produced by the synchrotron, viz. 335 Mev. Since the photon energy enters (10) in the logarithmic term, any variation of σ_ν above 335 Mev. will not make a great difference in the numerical value (11).

Basing our confidence in the numerical value (7), derived from the observations of McMillan *et al.*, we believe that the stars observed below ground which have charged primary particles may be ascribed to Coulomb interactions of fast μ-mesons. As the depth below ground is increased, the mean energy of the mesons increases also, and from (10) this would cause the star frequency to decrease less rapidly than the total meson flux. The results of § 4 although of poor statistical weight, indicate a trend in this direction as the variation in the total meson flux between the depths 20 and 60 m. water is about 4 : 1.

The above argument, based on the Williams–Weiszäcker method of replacing the Coulomb field of a fast particle by its equivalent photon spectrum would of course apply to any charged particle and not only to μ-mesons. But below ground, electrons form about 14 % of the total radiation, their energy is rather low, and their contribution to the star frequency may be safely ignored. Above ground, however, all the charged particles of the cosmic radiation may be considered as making a contribution to the star frequency by the Coulomb interaction discussed here. The magnitude of the contribution will be considered below.

The stars above ground are produced by particles with a strong interaction which leads to the well-known $A^{1\cdot3}$ law connecting the range of the particles with atomic number. If the interaction is much weaker—as we believe it to be for the particles producing the underground stars—this law no longer holds and the collision length is independent of Z or A. This follows from the fact that if the collision cross section per nucleon, σ, is very much less than the geometric cross section, the individual nucleons of a given nucleus no longer screen each other to any appreciable extent, and the probability of a collision per gm/cm² is simply $N\sigma$. This justifies the procedure adopted in arriving at equation (4).

5.3. *Underground Stars produced by Neutral Particles*

For every star produced by a charged particle there are 1·4 produced by neutral particles.

A simple explanation of these stars with neutral primary particles is the assumption that they are produced mainly by neutrons and to a lesser extent by photons. The presence of these neutral particles below ground would be expected in any case, and it only remains to be seen whether they occur in sufficient numbers to account for the observed frequency of stars with neutral primaries.

(*a*) *Neutrons.*

Brown *et al.* (1949 b) and Page (1950) have given details of the energies of the protons emitted in stars observed at mountain altitudes. These authors report that the number of protons per star with energy greater than 70 Mev. is approximately 0·5. It is reasonable to assume that the energy distribution of the neutrons from stars is similar to that of the protons, and allowing for the neutron excess in atomic nuclei, we arrive at a figure of 0·6 neutron per star with energy greater than 70 Mev.

We have already seen that the size distributions of the underground stars and stars at mountain altitudes are similar, and it therefore seems reasonable to us to assume that for every star produced underground by a fast meson, there is 0·6 neutron with E greater than 70 Mev. These neutrons will be in equilibrium with the μ-mesons at great depths, and the disintegrations which they produce will be included in our category of stars. It follows therefore that for every star with a charged primary particle, there should be about $0\cdot6+0\cdot6^2+0\cdot6^3+\ldots=1\cdot5$ stars produced by locally generated secondary neutrons. In general, if r is the number of neutrons per star capable of producing further stars, the ratio of the numbers of stars with neutral and charged particles is given by

$$\frac{N_n}{N_p}=\frac{r}{r-1}. \qquad \ldots\ldots(12)$$

For $r=0{\cdot}5$ and $0{\cdot}7$ this gives 1 and 2·3 respectively for the ratio N_n/N_p. We do not know the value of r with any certainty. The value $r=0{\cdot}6$ is a reasonable estimate, and leads to the conclusion that most of the stars with neutral primaries are produced by neutrons.

(*b*) *Photons.*

From absorption measurements carried out in this same laboratory (George 1946), and elsewhere (Wilson 1938), it is known that the cosmic radiation below ground may be divided into the usual hard and soft components. The soft component at our depth of operation comprises about 14 % of the total radiation. The photons of sufficient energy in this soft component would be expected to produce stars with neutral primary particles, as discussed in § 5.2. This contribution, however, will be rather small, on account of the small number of photons of sufficient energy.

The photons of the soft component underground can arise from the following processes: (*a*) cascade development of the knock-on electrons from μ-mesons; (*b*) bremsstrahlung by μ-mesons; (*c*) γ-rays from the nuclear disintegrations produced by μ-mesons. The contribution from (*b*) is negligible, and as we have no data concerning (*c*), this process will be ignored. A detailed calculation based on process (*a*) shows that the number of photons with energy above 100 Mev. (sufficient to cause a small star) is only about 2 % of the flux of fast mesons. This figure is consistent with the frequency of occurrence of electron pairs in our G 5 plates. Bearing in mind that the cross section for star production by photons is about ten times that for star production by μ-mesons (equations (7) and (11)), we see that the number of stars produced by photons is expected to be about 20% of the number produced by fast μ-mesons. In other words, of the 14 stars, observed in G5 plates, with neutral primary particles something like two might have been produced by photons. Thus most of the stars with neutral primaries may be attributed to the locally produced secondary neutrons, while some small contribution may be ascribed to the photons of the soft component.

One question that may be raised is as follows: if photons of sufficient energy do indeed produce stars with the cross section (7), then is this consistent with the well established observation in cloud chamber studies that stars are not usually associated with cascade showers? A simple calculation shows that there is no contradiction. Assume we have a cloud chamber containing a large number of separated lead plates in which the development of a cascade shower may be observed. The path length of the visible tracks in the gas is proportional to their path length in the lead. Assume an electron of energy E_0 falls on the top plate. The total path length of the cascade electrons in the lead is approximately (Rossi and Greisen 1941):

$$x_e = l_c \times 0{\cdot}5 \frac{E_0}{E_c} \text{ cm.,} \qquad \ldots\ldots(13)$$

where l_c and E_c are the cascade unit of length and the critical energy respectively. Let E_s be the threshold energy for the production of stars by photons. Then a similar formulr to (13) gives the photon path length, and the stars produced during the development of the cascade will be given by

$$n = l_c \times \frac{0{\cdot}5E_0}{E_s} \rho N \sigma_\nu \qquad \ldots\ldots(14)$$

$$= 1{\cdot}7 \times 10^{-4} E_0/E_s, \text{ using (7).}$$

N is Avogadro's number.

We estimate that a reasonable figure for the total path length of the heavy fragments of the average star in lead would be about 0·6 cm., giving a total path length of heavy fragments per cascade shower:

$$x_s = l_c \times \frac{0{\cdot}5E_0}{E_s}\, \rho N \sigma_\nu \times 0{\cdot}6 \text{ cm.}$$

Hence

$$\frac{x_s}{x_e} = 0{\cdot}6\,\frac{E_c}{E_s}\,\rho N \sigma_\nu. \qquad \ldots\ldots(15)$$

Substituting $\sigma_\nu = 10^{-28}$ cm^2, $E_s = 100$ MeV., we get

$$\frac{x_s}{x_e} = 2{\cdot}8 \times 10^{-5}. \qquad \ldots\ldots(16)$$

This number gives the relative probabilities of seeing the track of a cascade electron and a fragment of a star produced by one of the cascade photons, accepting the value (7) of σ_ν. It is seen to be very low, about 1 in 35,000 electron tracks for lead, a value, as far as we can tell, not inconsistent with the results of cloud chamber studies of cascade showers.

Thus there is no objection to accepting the cross section (7) in order to account for the underground stars.

5.4. *Showers of Fast Particles.*

From the arguments used already in § 5.1 we may assume that showers of fast particles are produced by μ-mesons. The cross section for the production of these showers by μ-mesons is then

$$\sigma_s = 4 \times 10^{-30} \text{ cm}^2 \text{ per nucleon} \qquad \ldots\ldots(17)$$

(this is only an order of magnitude) for μ-mesons of mean energy of order 10^{10} ev.

Concerning the nature of the shower particles, we have to consider the following three features: (*a*) they have charge $\boldsymbol{e}$; (*b*) the values of their kinetic energy are all more than 50 MeV., and are probably much greater than this figure, which has been determined from rather limited measurements of the multiple scattering along the tracks of the shower particles; (*c*) the shower particles are frequently found at wide angles from the axis of the primary particle (Figure 9).

Considerations (*b*) and (*c*) taken together make it unlikely that the shower particles are electrons, as secondary electrons of energy E are usually found at an angle $\boldsymbol{m}_0\mathbf{c}^2/E$ from the axis of the initial particle. Thus, all electrons with E greater than 50 MeV. would be expected at angles less than 0·5 degree from the initial particle, whereas, of the 16 shower particles, one was at 3°, two were at 4° and the rest at greater angles.

We think it unlikely that the shower particles are protons for the following reason. In the 24 stars observed in electron sensitive plates, 133 slow tracks and 16 shower tracks were observed. Of the 133 slow tracks, 14 had a grain density between 3·5 and 7 times minimum, corresponding to energy limits for protons 40 MeV. and 100 MeV. (cf. Page 1950). The shower particles, if protons, would have energies greater than 1,000 MeV., and it seems unreasonable that the energy spectrum of the star particles should contain a number of particles with energy greater than 1,000 MeV. equal to those lying in the interval 40 to 100 MeV.

The underground shower particles are probably mesons, and we may assume they are π-mesons, as has been confirmed by Fowler (1950) for the showers observed in plates exposed at great heights in the atmosphere.

In § 3.2 we reported that eight π-mesons had been observed to come to rest in the plates, equation (1), and we multiplied this by three to account for the loss by decay in the air path from tunnel wall to the plates, equation (2). One half of the observed slow π-mesons entered the emulsion from below and one half from above. This strongly suggests that the π-mesons are created in the local material. The observed numbers are consistent with the assumption that the showers are in fact the process in which the underground slow π-mesons are generated.

A certain interest lies in the question of the multiplicity of meson production. The limiting viewpoints of Heisenberg (multiple meson emission) and Heitler (single meson emission) are well known. On the latter viewpoint showers are explained on the basis of a plurality of collisions inside an atomic nucleus. One hesitates to draw collisions concerning multiplicity of emission from observations on meson showers, as all the available experimental evidence has so far been adequately explained by both schools of thought (Heisenberg 1949, Heitler and Jánossy 1949). The plural theory depends on the fact that the cross section for meson production is comparable with the geometric cross section of nucleons ($\sim 6 \times 10^{-26}$ cm^2). However, if the showers are produced by the μ-mesons below ground, with a cross section not very different from (17), then the chance of a nuclear collision occurring in crossing a silver nucleus is only about 1 in 1,000, and thus the observed showers would be difficult to reconcile with the plural theory. The alternative would be to assume that some unknown process leads to the production of relativistic protons below ground, and then the interpretation of the showers would be as ambiguous as before.

§ 6. COMPARISON WITH OTHER OBSERVATIONS

Our results confirm the observations of Braddick and Hensby (1939) that nuclear interactions occur below ground, and it would seem possible that the showers we have reported are related to the meson pairs observed by them in a cloud chamber. A more quantitative comparison is not possible owing to the large differences in experimental conditions.

Attempts were made by George and Jason (1947) to record penetrating showers in the same laboratory, using a system of shielded Geiger counters similar to that used by Jánossy, with a negative result. From our present results we conclude that something like 200 showers of the type observed in nuclear emulsions were produced in their top absorber during the period of observation. From the fact that no penetrating showers were recorded, we may conclude that the counter system had a low efficiency for the detection of these underground showers. This might be due to the low mean energy of the shower particles, or to their low density.

Using a counter system less selective for high density penetrating showers, a positive result was reported by George and Trent (1949). The cross section reported by them for the production of groups of penetrating particles was 5×10^{-29} cm^2 per nucleon, and later measurements have shown that this must be reduced to 2×10^{-29} cm^2, as the effect of knock-on electron showers had not been sufficiently eliminated in the initial measurements. This cross section may be compared with our figure for shower production (17) of approximately $4 \times 10^{-30}\,\mathrm{cm}^2$, and is seen to be of a similar order of magnitude. The nuclear emulsion measurements need to be extended before a more detailed quantitative comparison can be usefully made.

Fast μ-mesons at the Jungfraujoch are about 50 times more frequent than they are at 60 m. water depth, but from equation (10) we should expect their efficiency for star production by electromagnetic interaction to be reduced by a factor of about three on account of the difference in mean energy. Hence, if our interpretation of the underground stars is correct, one would expect approximately $50 \times 2 \times 10^{-3}/3 = 0{\cdot}033$ stars per cm³ per day to be caused directly by them, due to their electromagnetic interactions with nuclei. Brown *et al.* (1949 b) report that the number of stars of type I_p, in their nomenclature (similar to our stars shown in Figures 4 and 5), is 0·45/cm³/day at the Jungfraujoch. Thus it seems possible that an appreciable fraction of the stars of this type at altitude may be due to fast μ-mesons.

§ 7. CONCLUSIONS

The conclusions that have been reached are as follows :

(i) The frequency of slow μ-mesons observed to come to rest is close to the number expected from the μ-meson spectrum deduced from cloud chamber measurements and the depth–intensity curve.

(ii) Nuclear disintegrations occur at depths 20 to 60 m. water below ground with a frequency detectable in nuclear emulsions.

(iii) The slow variation of the frequency with depth suggests that they are produced by fast μ-mesons.

(iv) Assuming the primary agent producing the stars to be μ-mesons, the cross section per nucleon for star production is $10^{-29}\,\mathrm{cm}^2$.

(v) From the experiments on nuclear photo-disintegrations at high energies, a cross section of this magnitude may be understood in terms of the Coulomb interaction of the μ-mesons with nucleons.

(vi) Further stars, not caused directly by μ-mesons are thought to be due in part to neutrons, arising from the disintegrations due to μ-mesons, and in part to the photons of the underground soft component of cosmic rays.

(vii) Some showers have been observed associated with stars; these are thought to be showers of π-mesons also produced presumably by the Coulomb interaction of μ-mesons.

(viii) Slow π-mesons have been observed below ground, in number comparable to the number of observed shower particles, and are thought to be the end-points of similar showers occurring in the local material.

(ix) The cross section for shower production by photons must be similar to that for star-production, of the order of $10^{-28}\,\mathrm{cm}^2$ per nucleon.

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REFERENCES

BRADDICK, H. J. J., and HENSBY, G. S., 1939, *Nature, Lond.*, **144**, 1012.
BROWN, R., CAMERINI, U., FOWLER, P. H., MUIRHEAD, H., POWELL, C. F., and RITSON, D. M., 1949 a, *Nature, Lond.*, **163**, 47.
BROWN, R., CAMERINI, U., FOWLER, P. H., HEITLER, H., KING, D. T., and POWELL, C. F., 1949 b, *Phil. Mag.*, **40**, 862.
CAMERINI, U., MUIRHEAD, H., POWELL, C. F., and RITSON, D. M., 1948, *Nature, Lond.*, **162**, 433.
CAMERINI, U., COOR, T., DAVIES, J. H., FOWLER, P. H., LOCK, W. O., MUIRHEAD, H., and TOBIN, N., 1949, *Phil. Mag.*, **40**, 1073.
CAMERINI, U. FOWLER, P. H., LOCK, W. O., and MUIRHEAD, H., 1950, private communication.
COSYNS, M. G. E., DILWORTH, C. C., OCCHIALINI, G. P. S., SHOENBERG, M., and PAGE, N., 1949, *Proc. Phys. Soc.* A, **62**, 801.
EVANS, J., and GEORGE, E. P., 1949, *Nature, Lond.*, **164**, 20.
FOLLETT, D. H., and CRAWSHAW, J. D., 1936, *Proc. Roy. Soc.* A, **155**, 546.
FOWLER, P. H., 1950, *Phil. Mag.*, **41**, 169.
GEORGE, E. P., 1946, *Nature, Lond.*, **157**, 296.
GEORGE, E. P., and JASON, A. C., 1947, *Nature, Lond.*, **160**, 327.
GEORGE, E. P., and TRENT, P. T., 1949, *Nature, Lond.*, **164**, 838.
HEISENBERG, W., 1949, *Nature, Lond.*, **164**, 67.
HEITLER, W., 1941, *Proc. Camb. Phil. Soc.*, **37**, 291.
HEITLER, W., and JÁNOSSY, L., 1949, *Proc. Phys. Soc.* A, **62**, 669.
HEITLER, W., and PENG, H. W., 1943, *Proc. R. Irish Acad.*, **49**, A7.
JÁNOSSY, L., 1948, *Cosmic Rays* (Oxford : University Press), p. 89.
KRAUSHAAR, W. L., 1949, *Phys. Rev.*, **76**, 1045.
LATTES, C. M. G., OCCHIALINI, G. P. S., and POWELL, C. F., 1947, *Nature. Lond,*, **160**, 486.
MCMILLAN, E. M., PETERSON, J. M., and WHITE, R. D., 1949, *Science*, **110**, 579.
PAGE, N., 1950, *Proc. Phys. Soc.* A, **63**, 250.
PICCIONI, O., 1950, *Phys. Rev.*, **77**, 6.
ROSSI, B., 1948, *Rev. Mod. Phys.*, **20**, 537.
ROSSI, B., and GREISEN, K. I., 1941, *Rev. Mod. Phys.*, **13**, 240.
WILLIAMS, E. J., 1933, *Proc. Roy. Soc.* A, **139**, 163.
WILSON, A. H., 1941, *Proc. Camb. Phil. Soc.*, **37**, 301.
WILSON, V. C., 1938, *Phys. Rev.*, **53**, 337.

Note added in proof. Concerning the showers, Professors Marshak and Heitler have pointed out that if a single π-meson is produced it could itself generate a shower inside the same nucleus by the plural process. Thus the smallness of the cross section for shower production (17) does not necessarily imply a multiple production of π-mesons.