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Observation of Cosmic Ray Events in Nuclear Emulsions Exposed in a Glacier at 3550 m.

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ABSTRACT.

Photographic emulsions have been exposed at various depths under ice at 3550 m. The variation in the numbers of slow μ-mesons with depth is in fair agreement with a predicted variation.

From the variation of the numbers of "stars" with depth, the best estimate for the absorption mean free path of the star producing radiation is 170 ± 10 gm./cm.^{2}.

The variation of the numbers of π^+-mesons with depth is consistent with an absorption path length for nuclear interaction corresponding to a few times the geometric value. A large upward stream of π-mesons has been observed and possible interpretations are discussed.

§1. INTRODUCTION.

IN previous notes (Harding *et al.* 1949 a and b) we have reported results on the absorption of the star producing radiation and on the variation of the number of π-mesons with depth in ice. In order to improve the statistics and the geometry, the experiment at the Jungfraujoch 3550 m. has been repeated. Experimental results for stars and mesons will be given.

§ 2. EXPERIMENTAL DETAILS.

In order to obtain good geometry a steel pipe ($2\frac{1}{8}$-in. internal diameter, $\frac{3}{16}$-in. wall thickness) closed at the lower end was sunk vertically to a depth of 9 m. into a glacier. Boxes of plates coated with Ilford G.5 "Nuclear Research" emulsion 200 μ thick were exposed vertically at depths down to 5 m. for 89 days. The pre- and post-exposure amounted to about four days spent mainly at sea level. Plates were also exposed at depths of $6\frac{1}{2}$ and $8\frac{1}{2}$ m., but these emulsions were poured at the Jungfraujoch under a large thickness of rock. The pre- and post-exposure of these plates amounted to 2 hours at 3550 m. The spaces between the boxes in the top 3 m. of pipe were filled with cylinders of paraffin wax, density 0·9 gm./c.c., which should produce nearly the same effects on cosmic ray particles as ice itself.

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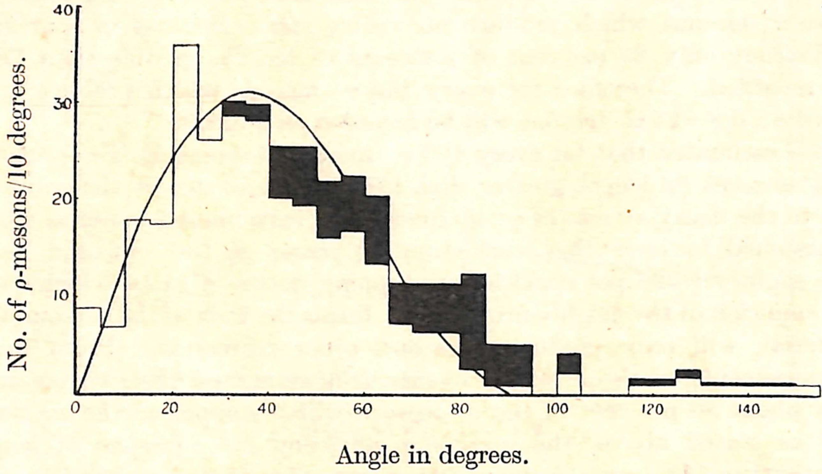
TABLE I.

1.	Depth in gm./cm.^{2} ice	0	45	90	135	180	225	270	360	450	585	765
2.	Stars observed	905	455	470	530	543	238	262	114	108	32	16
3.	Stars/c.c./day	16·2 ± 0·5	10·6 ± 0·5	6·6 ± 0·3	5·3 ± 0·2	3·8 ± 0·16	2·8 ± 0·15	1·8 ± 0·11	1·07 ± 0·1	0·52 ± 0·05	0·19 ± 0·03	0·08 ± 0·02
4.	Star rate corrected for pre-exposure	16·2 ± 0·5	10·6 ± 0·5	6·6 ± 0·3	5·3 ± 0·2	3·8 ± 0·16	2·8 ± 0·15	1·8 ± 0·11	1·02 ± 0·1	0·48 ± 0·05	0·18 ± 0·03	0·07 ± 0·02
5.	No. of π^+-mesons 0–60°	1	10	16	20	16	10	9	3	4	1	1
6.	60–90°	2	4	10	10	7	3	5	3	1	1	1
7.	90–120°	10	9	4	10	4	2	7	1	0	1	1
8.	120–180°	8	3	3	8	2	1	3	2	1	0	0
9.	No. of $\pi^{\overset{-}{\cancel{+}}}$-mesons 0–60°	1	12	18	27	16	12	12	8	5	2	1
10.	60–90°	8	7	11	15	9	5	9	6	3	1	1
11.	90–120°	14	5	6	9	4	4	6	1	3	1	0
12.	120–180°	10	7	6	9	6	4	7	2	2	2	1
13.	[π^+-mesons (0–60°)/stars] 10~~0~~	0·022 ± 0·016	0·48 ± 0·11	0·72 ~~0·68~~ ± 0·12	0·89 ± 0·13	0·59 ± 0·10	0·92 ± 0·21	0·80 ± 0·17	0·96 ± 0·30	0·84 ± 0·28	0·94 ± 0·53	1·25 ± 0·89
14.	ρ-mesons/c.c./day 0–90°	2·56 ± 0·21	2·70 ± 0·25	2·35 ± 0·18	2·50 ± 0·16	2·03 ± 0·12	2·08 ± 0·14	2·03 ± 0·12	1·41 ± 0·12	1·30 ± 0·08	1·17 ± 0·09	1·04 ± 0·09
15.	90–180°	0·26 ± 0·06	0·23 ± 0·07	0·23 ± 0·06	0·19 ± 0·04	0·16 ± 0·04	0·16 ± 0·14	0·16 ± 0·13	0·09 ± 0·03	0·07 ± 0·02	0·04 ± 0·01	0·01 0·01
16.	μ-mesons/c.c./day 0–90°	2·50 ± 0·23	2·48 ± 0·28	2·09 ± 0·20	2·28 ± 0·16	1·94 ± 0·13	1·99 ± 0·15	1·95 ± 0·13	1·37 ± 0·13	1·28 ± 0·08	1·16 ± 0·09	1·04 ± 0·07
17.	90–180°	0·04 ± 0·08	0·08 ± 0·08	0·09 ± 0·07	0·07 ± 0·05	0·12 ± 0·04	0·08 ± 0·04	0·12 ± 0·03	0·06 ± 0·03	0·06 ± 0·02	0·03 ± 0·03	— —

§ 3. EXPERIMENTAL RESULTS.

In Table I. the frequency of occurrence of the various events are shown. We have assumed that the density of ice was uniform and equal to 0·9 gm./c.c. Only ρ-mesons of projected lengths greater than 130 μ have been recorded; a ρ-meson being defined as one that does not produce a visible star nor that gives rise to a secondary meson. The numbers of π^+-mesons which stop in the emulsions and are travelling at angles 0–60°, 60–90°, 90–120°, 120–180° with the downward vertical at their points of entry, are given. All errors given represent standard deviation, based on the numbers of events recorded. Non-uniformity of the emulsion thickness may introduce additional errors of about 5 per cent. A random sample of plates were searched twice and by this means the overall efficiency for recording stars was estimated as 97 per cent, while for ρ-mesons the efficiency was about 80 per cent.

Fig. 1.



Angular distribution of ρ-mesons. The shaded areas must be added to the observed distribution (unshaded histogram) in order to correct for loss of tracks at large zenith angles caused by the thinness of the emulsion.

The angular distribution of ρ-mesons arriving at the plate is shown in fig. 1. This distribution has been obtained by measuring 100 mesons at each of the following depths :—0, 180 and 585 gm./cm.^{2}. Since mesons making large zenith angles have a smaller chance than those of small zenith angles of producing a track of at least 130 μ (and therefore of being recorded), this distribution is weighted to small angles. By considering the distribution in the angle of dip for various zenith angles approximate correction factors have been obtained and the corrected distribution is shown by the addition of shaded areas. The curve in this figure represents a $\cos^2 \theta$ distribution per unit solid angle.

The ρ-mesons that we observe represent three types of events :—

(*a*) 28 per cent of π^--mesons leave no visible star on coming to rest in the emulsion (Bradner 1949) and these will be recorded as ρ-mesons.

(*b*) Some will be μ^+-mesons produced from decay at rest of π^+-mesons in the immediate neighbourhood of the emulsion, the π^+-mesons having been locally created.

(*c*) The majority are the μ^+-mesons which form the hard component of cosmic rays.

We shall now estimate the quantities (*a*) and (*b*) and obtain by subtraction those mesons which form the hard component.

For every 100 π^--mesons which produce stars,

$$28\left(\frac{100}{100-28}\right)=39\ \pi^-\text{-mesons}$$

stop in the emulsion and fail to produce stars. Only 80 per cent of the π^--mesons which produce stars have ranges exceeding 130 μ and there is no reason to suppose that this ratio will be different for those π^--mesons which produce no visible star. Because of searching inefficiency only 80 per cent of ρ-mesons of lengths greater than 130 μ are recorded. Therefore for every 100 π^--mesons which produce stars $39\times0{\cdot}8\times0{\cdot}8=25$ π^--mesons will be recorded as ρ-mesons.

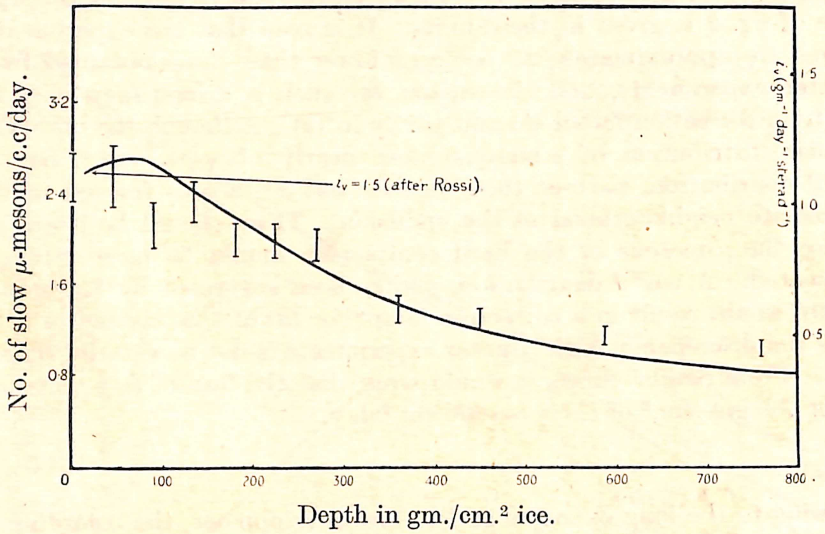
It is estimated that for every 100 π^+-mesons stopping in the emulsion, 37 μ^+-mesons (of length greater than 130 μ) will also stop in the emulsion due to the decay at rest of π^+-mesons in the surrounding material which is assumed to have the same stopping power as the emulsion itself. The slightly ($\sim$20 per cent) lower stopping power of glass, which, with the emulsion of the neighbouring plates, forms the bulk of the surrounding material, will only produce a second order correction. From range measurements on the μ^+ of π–μ events, it is estimated that we recorded only about 80 per cent of the π^+-mesons which stopped in the emulsion and as stated above, the searching efficiency for ρ-mesons of length greater than 130 μ was also about 80 per cent. Thus for every 80 π^+-mesons observed to stop in the emulsion approximately $37\times0{\cdot}8=30$ μ^+-mesons are observed as ρ-mesons.

Therefore, for every 180 π-mesons (80 π^+- and 100 π^--mesons) observed to stop, $30+25=55$ mesons are recorded as ρ-mesons, and must be associated with the π-mesons rather than with the μ^+-meson of the hard component. By subtracting $55/180\sim30$ per cent of the numbers of π-mesons at any depth from the numbers of ρ-mesons observed, we are left with the numbers of μ-mesons of the hard component. The values are shown in rows 16 and 17 of Table I. It is seen that only about 4 per cent of the μ-mesons travel upwards, and this upward stream can reasonably be attributed to Coulomb scattering.

Working from the energy spectrum of μ-mesons at sea level, and the variation of the μ-meson intensity with altitude, Sands (1950) has derived the expected form of the differential range distribution of μ-mesons in air at mountain altitudes. The experimental results for the numbers of μ-mesons (Table I. row 16) travelling downwards and coming to rest in the emulsion, are plotted against depth of ice in fig. 2. Sands' curve, in arbitrary units, has been corrected for the different medium (ice instead of air) and is shown in this figure. Thus assuming no μ-mesons are produced in the ice, other than by the decay of π-mesons, the variation with depth in ice of the number of slow mesons, is in fair agreement with the predicted variation.

As regards the absolute flux of μ-mesons, Rossi (1948) has given the absolute value i_v of the differential range spectrum at 10 gm./cm.^{2} at various atmospheric depths, *i. e.* the number of μ-mesons/day/steradian in the vertical direction, which stop in one gram of air at various depths in

Fig. 2.



the atmosphere. At 3550 m. $i_v = 1\cdot5$ gm.$^{-1}$ diem.$^{-1}$ sterad^{-1}. This fixes the ordinate of Sands' curve. In order to compare our intensity with Rossi's value we have to correct for

(*a*) the angular distribution of the mesons ($\cos^2\theta$ per sterad),

(*b*) loss due to thin emulsions. We have recorded only mesons of length $\geqslant 130\,\mu$ whereas we require the numbers of mesons of length greater than zero,

(*c*) relative stopping powers per gram of air and emulsion (1 gm. air $\equiv$ 1·7 gm. emulsion $\equiv$ 0·43 c.c. emulsion),

(*d*) correction factor for searching efficiency is 1/0·8.

We have recorded μ-mesons arriving at the plate and coming from the upper hemisphere. It is to be expected that a photographic emulsion records the " integrated intensity " of slow mesons, *i. e.* the number of mesons recorded depends on the volume, but not the shape of the emulsion. Correction (*a*) is straightforward inasmuch as we have to compare the integrated intensity per sterad around the vertical with that of the upper hemisphere-correction factor is

$$\operatorname*{limit}_{\epsilon\to 0}\frac{\int_0^\epsilon 2\pi\cos^2\theta\sin\theta\,d\theta\Big/\int_0^\epsilon 2\pi\sin\theta\,d\theta}{\int_0^{\pi/2}2\pi\cos^2\theta\sin d\theta}=\frac{3}{2\pi}.$$

Scattering, when once the mesons have entered the emulsion, will make their distribution more nearly isotropic and thus we obtain a factor to correct for (*b*) in the manner described by Lattes *et al.* (1947). The factor so obtained is 1·7 and we feel confident that this is correct to $\sim$20 per cent. We can now convert our intensities to Rossi's units by multiplying by $3/2\pi\times 1{\cdot}7\times 0{\cdot}43\times 1/0{\cdot}8=0{\cdot}44$. The right-hand ordinate scale of fig. 2 is given in these units. It is seen that the experimental figures are approximately 25 per cent lower than those obtained from counter experiments, and the reason for such a discrepancy may be partly in correction factor (*b*) and partly in (*a*). Although the observed angular distribution of ρ-mesons more nearly obeys a $\cos^2\theta$ than a $\cos^3\theta$ distribution, part of these mesons are μ^+-mesons formed in the immediate neighbourhood of the emulsion. These should be isotropic. Hence the μ-mesons of the hard component should be more strongly collimated. A $\cos^3\theta$ distribution, as has been suggested by Krauchaar (1949), would result in a correction factor for (*a*) of $4/2\pi$ instead of $3/2\pi$. Thus the discrepancy with counter experiments is not necessarily significant. From Sands' curve, it would seem that the flux of fast μ-mesons under 760 gm./cm.^{2} of ice is $\sim$1000/cm.^{2}/day.

Stars.

Owing to the long exposure and to low development, the recording of tracks of particles at minimum ionization was not reliable. This introduces a small uncertainty, which should be the same at all depths, in the classification of a star. We have recorded stars which have (*a*) at least one track longer than 60 μ (*b*) at least three tracks with grain-densities greater than 30 grains/100 μ, *i. e.* $\sim 1\frac{1}{2}\times$minimum, (*c*) a spur of less than 10 μ was not counted as a track. The number of stars per c.c. of emulsion per day are plotted on a logarithmic scale against depth in fig. 3.

If the star producing radiation is coming vertically downward and is absorbed with a mean free path α, then the intensity at a depth x is given by

$$I=I_0e^{-x/\alpha}. \qquad (1)$$

The results do not fit such a relationship too well, though the best value of α for the first 300 gm./cm.^{2} of ice would be 130–140 gm./cm.^{2}. There is a discrepancy with our earlier results (Harding *et al.* 1949 a) from which a value of $\alpha=200$ gm./cm.^{2} was obtained. The difference can only be explained by poor geometry, *e. g.* large holes in the ice in the first experiment.

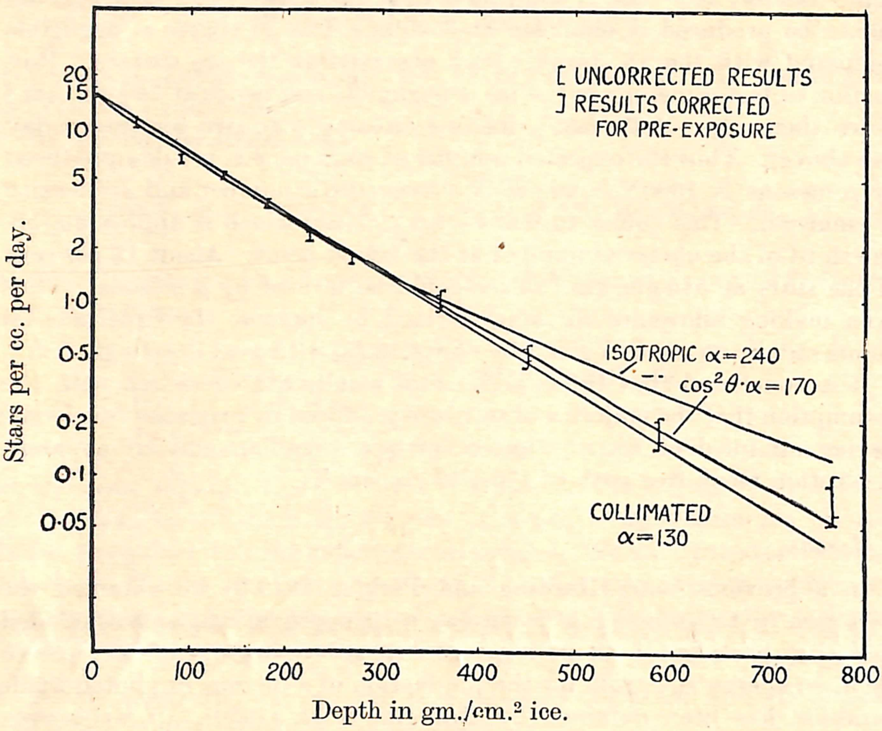
It may be argued that, because of an angular distribution of the star producing radiation, we should not expect exponential absorption. For an isotropic distribution at the ice surface of primaries, which are assumed to travel in straight lines, we would expect (see Rossi 1948)

$$I/I_0=e^{-x/\alpha}-(x/\alpha)\mathrm{E}i(-x/\alpha) \quad . \ . \ . \ . \ . \ . \ . \quad (2)$$

or for a $\cos^2\theta$ distribution per unit solid angle

$$I/I_0=e^{-x/\alpha}(1-\tfrac{1}{2}(x/\alpha)+\tfrac{1}{2}(x/\alpha)^2)-\tfrac{1}{2}(x/\alpha)^3\mathrm{E}i(-x/\alpha). \quad . \ . \ . \quad (3)$$

Fig. 3.



In order to obtain agreement between the experimental results and a theoretical curve over the first 300 gm./cm.^{2} in the case of equation (2). There is then poor agreement for depths beyond 450 gm./cm.^{2}. In the case of equation (3), if we take $160<\alpha<180$ gm./cm.^{2} good agreement is obtained between the theoretical curve and the experimental points even down to 765 gm./cm.^{2} of ice.

So far we have taken an exceptionally simple picture of the star production process inasmuch as we have assumed that all stars are produced by one component which is incident on the ice surface with a certain ($\cos^2\theta$) angular distribution. It seems likely that the star producing particles are not absorbed in a single nuclear encounter, or, what probably comes to the same thing, that in producing a star, the primary also produces one or more particles which can then act as primary particles for further stars, *i. e.* a cascade process. Provided these secondary particles have the same mean free path for star production and are produced at any depth with an angular distribution similar to that of the primary particles at that depth, then the above equations should equally apply for such a cascade process, but α no longer represents the absorption path length of the star producing radiations.

It is thought that the nucleonic component is mainly responsible for the production of stars. However George *et al.* (1950) have suggested a cross-section, σ, per nucleon for star production by μ-mesons of approximately 10^{-29} cm.^{2}. They have therefore shown $\sim 0{\cdot}1$ stars/c.c./day should be produced in emulsion at 3550 m. This of course is negligible compared with the 16 stars/c.c./day observed at the ice surface. Production of fast μ-mesons in the ice is negligible and hence at 760 gm./cm.^{2} of ice there are ~ 1000 fast μ-mesons crossing a square centimetre/day (see above). Thus the expected number of stars per c.c. per day produced by μ-mesons is $1000\mathrm{N}\rho\sigma$ where N=Avagadro's number and ρ=density of emulsion. This comes to $0{\cdot}024$ stars/c.c./day which is approximately one-third of the observed number at the lowest point. About 15 per cent of the stars at 585 gm./cm.^{2} of ice could be formed by μ-mesons. Thus even making allowance for stars formed by mesons, the experimental points still lie on a curve given by equation (3) with $\alpha=170\pm10$ gm./cm.^{2}.

It is concluded that the experimental results are consistent with the assumption that the majority of stars are produced by primaries (nucleons) having an incident distribution $\cos^2\theta$ per steradian and an apparent absorption mean free path of 170 ± 10 gm./cm.^{2}.

π-*Mesons.*

In a previous note (Harding and Perkins 1949 b) we obtained the variation in the number of π-mesons with depth in ice, and concluded that they were produced with a mean range ~ 100 gm./cm.^{2} ice. Since then, an energy spectrum for the production of π-mesons in photographic emulsion has been obtained by Camerini *et al.* (1950). If we *assume* that this spectrum can be used to represent the production spectrum *in ice* we can obtain certain limits for λ, the absorption mean free path in nuclear interactions for fast π-mesons in ice.

It is assumed :—

(*a*) the rate of production of mesons at a given depth is proportional to the star intensity at that depth,

(*b*) mesons travel in straight lines,

(*c*) the energy, or range distribution of mesons at production is independent of angle. Thus $q(\mathrm{R})\,d\mathrm{R}\,.\,f(\theta)\,d\theta$ is the probability that a meson is produced with a range R to R$+d$R at θ to $\theta+d\theta$ with the downward vertical. The spectrum $q(\mathrm{R})\,d\mathrm{R}$ is obtained from Camerini's spectrum using a theoretical range-energy relation.

Let $\mathrm{P}(x, \theta)\,d\theta$

$$=\frac{\text{No. of mesons stopping at depth } (x, dx) \text{ travelling at angle } (\theta, d\theta)}{\text{No. of stars at depth } (x, dx)},$$

where the star intensity (see above) can be approximated by

$$\mathrm{I}/\mathrm{I}_0=e^{-x/\alpha}.$$

Let $g(\mathrm{R})\,d\mathrm{R}$ be the probability that a meson of range R gm./cm.^{2} ice will not decay in flight, *i. e.*

$$g(\mathrm{R})=\exp\left[-\int_0^{\mathrm{R}} \frac{\mathrm{E}_0\,d\mathrm{R}'}{c\beta\tau_0(\mathrm{E}+\mathrm{E}_0)}\right]$$

E being the kinetic, and E_0 the rest energy of a meson. The lifetime τ_0 is taken as $7 \,.\, 10^{-9}$ secs.

It can then be shown that

$$\mathrm{P}(x, \theta)\,d\theta \propto \int f(\theta)/\cos\theta \int_{\mathrm{R}=0}^{x/\cos\theta} e^{\frac{\mathrm{R}/\cos\theta}{\alpha}}\, e^{-\mathrm{R}/\lambda}\, g(\mathrm{R})q(\mathrm{R})\,d\mathrm{R}\,d\theta.$$

Considering mesons in the angular range 0–60°, we can write as a sufficient approximation

$$\mathrm{P}(x)\bar{\theta} \propto \int_{\mathrm{R}=0}^{x/\overline{\cos\theta}} e^{\frac{\mathrm{R}\,\overline{\cos\theta}}{\alpha}}\, e^{-\mathrm{R}/\lambda}\, g(\mathrm{R})q(\mathrm{R})\,d\mathrm{R},$$

where we take $\overline{\cos\theta}$ as the average value of $\cos\theta$ for mesons arriving at the plate (fig. 5). $\overline{\mathrm{Cos}\,\theta}=0{\cdot}77$. We take $\alpha=130$ gm./cm.^{2}. The form of $\mathrm{P}(x)$ can be obtained for various values of λ, and these are plotted in fig. 4 together with the experimental results. We have fitted theoretical curves to obtain the best agreement with the experimental points by a method somewhat analogous to least squares. We choose the ordinate scale for the theoretical curves such that $\underset{i}{\Sigma} e_i^2/\sigma_i^2$ is a minimum, where e_i is the difference between the experimental ith point and the curve, and σ_i is the uncertainty of the ith point.

On this criterion, the experimental points best fit the curve for $\lambda=150$ gm./cm.^{2}. The fit is about three times better than for $\lambda=75$ and 90 times better than for $\lambda=500$ gm./cm.^{2}. We conclude that the variation with depth of the number of π-mesons is consistent with an absorption path length for nuclear interaction corresponding to the geometric, or to a few times the geometric value of 70 gm./cm.^{2} (neglecting the effect of hydrogen). If the proper lifetime of π-mesons is larger than we have assumed, say 10^{-8} instead of $7 \,.\, 10^{-9}$ seconds, then small values of λ are still further favoured.

Assuming :—

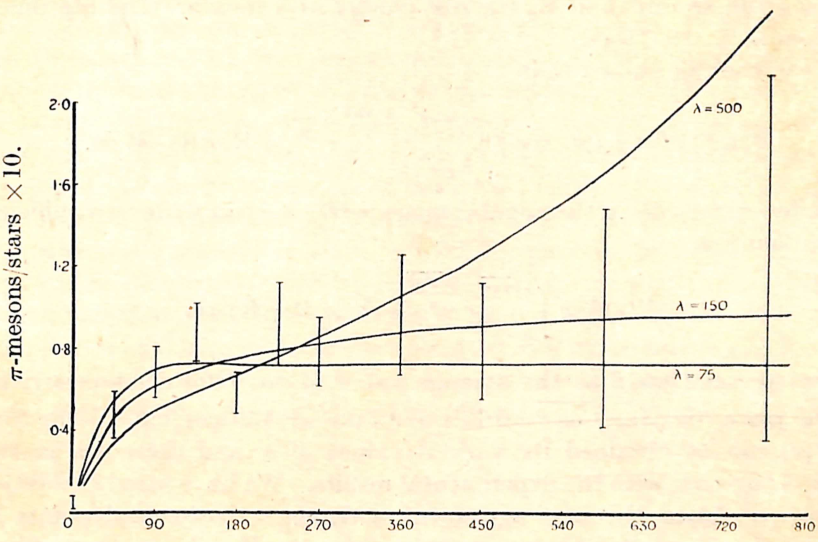
(a) mesons are produced only in oxygen in the ice ;

(b) on the average the same number of mesons are produced in oxygen disintegrations, as in disintegrations of nuclei in photographic emulsion ;

(c) the rate of nuclear disintegrations (and hence meson production) is proportional to the total geometrical cross-section of the nuclei, then we observe about $1\frac{1}{2}$ times as many mesons stopping as we would expect from a calculation in which a value of $\lambda = 75$ gm./cm.^{2} was used. This shows that the numbers of mesons observed is of the magnitude expected : no particular significance is attached to the ratio of $1\frac{1}{2}$.

Since equilibrium between mesons and stars seems to be established for depths below 225 gm./cm.^{2} ice, we should expect the angular distribution of π-mesons to be constant at these depths. We are therefore justified in classing together mesons at all these depths when considering the angular distribution of mesons arriving at the plate. This distribution is shown in fig. 5 in which a correction has been applied (shaded histogram) for loss of steeply dipping tracks. It is seen that approximately one-third of all π-mesons were travelling in an upward direction when coming to rest in the emulsion. Unfortunately, complete data on the angular distribution at production of mesons have not been published. Brown *et al.* (1949) have shown that at 3550 m. in showers of more than five particles 93 per cent of the shower particles (the majority of which are mesons with energies above 60 MeV.) are directed downwards and nearly obey a $\cos\theta \sin\theta \, d\theta$ distribution. We may assume the lower

Fig. 4.



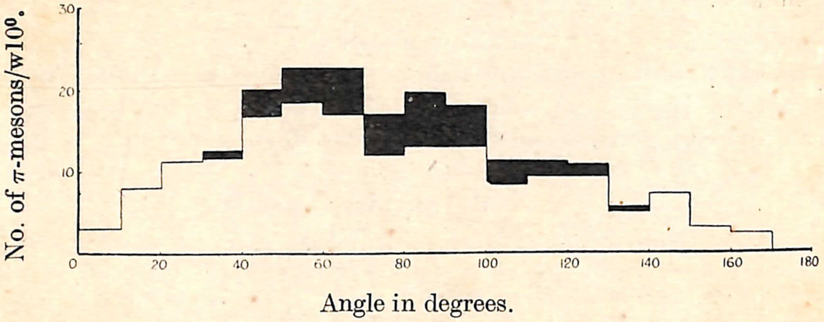
Depth in gm./cm.^{2} ice.

energy mesons to be isotropic. From an analysis of stars formed at 70,000 ft. Perkins (private communication) concludes that in light elements about 10 per cent of shower particles travel backwards with respect to the incident star producing radiation. Due to the angular distribution about the zenith of the meson producing radiation (which is likely to be more collimated than the total star producing radiation since higher energy events are involved), the percentage of upward travelling shower particles at production will exceed 10 per cent. A liberal estimate of this percentage would be 20 per cent. We make the following assumption about the angular distribution of mesons at production and will then calculate the expected ratio of the numbers of mesons coming to rest after travelling in an upward cone of 60° to the number of those coming to rest after travelling in a downward cone of 60°.

Assume :—

(*a*) Mesons of energy below 60 MeV. are produced isotropically in the laboratory system. These form 12 per cent of the total number of mesons.

Fig. 5.



Angular distribution of π=mesons. Shaded areas represent corrections for loss of steeply dipping tracks.

(*b*) Twenty per cent of mesons of energy greater than 60 MeV. are produced isotropically in the upper hemisphere.

(*c*) The remainder of the mesons are produced downward with a cos θ distribution per unit solid angle.

Consider one meson produced in the upward 60° cone and one in the downward 60° cone due to group (*a*) mesons. Then it can be shown that there will be three mesons produced in the upward cone due to class (*b*) mesons and 18 in the downward cone due to class (*c*) mesons. With these assumptions we find that four mesons are produced in an upward cone to 19 in the downward cone. However, the downward moving mesons, being produced with higher average energies have longer ranges (electronic stopping) than the upward moving mesons. Therefore they should stand more chance of being lost through nuclear interactions (for $\lambda=75$ gm./cm.^{2}). Taking this into account, in a calculation somewhat similar to the above, it is deduced that one slow meson should be observed in the upward cone for every 3·6 in the downward cone. The experimental figure is 1 : $2\cdot7\pm0\cdot6$.

The calculations have been carried through on the assumption that mesons travel in straight lines. We have seen that the Coulomb scattering of μ-mesons is small ($\sim$4 per cent are back-scattered) and the scattering of π-mesons is expected to be of the same order. We therefore conclude that for the given assumptions concerning the angular distribution at production of π-mesons, the observed ratio of the upward to downward flux of π-mesons is not significantly different from the expected ratio. If, however, the results of further experiments should show that π-mesons are more strongly collimated than has been assumed above, then the observed upward flux would suggest that nuclear scattering of π-mesons is an important process. Indeed, preliminary results of Bernadini *et al.* 1950, suggest that π-mesons are scattered in flight through angles of greater than 30° with a cross-section of about one-quarter of the geometrical value. Scattering of this magnitude would lead to almost perfect agreement between the observed and calculated upward flux of π-mesons.

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