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Production of heavy mesons by protons of energy between 2 and 3000 GeV

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The masses of the secondary particles emitted from disintegrations produced by cosmic-ray protons of energy greater than 2 GeV have been determined by observations on the grain density and scattering of their tracks in photographic emulsions. It has thus been possible to determine the yield of the heavy charged mesons with mass between 900 and $1400 m_e$, as a function of the energy of the primary particles.

Among 325 secondary particles which produce tracks with grain density between 1·07 and 2·0 times the minimum value, twenty heavy mesons have been identified. The statistical distribution in the measured values of their mass is consistent with a unique value of $1210 \pm 40 m_e$. The total observed proper time of flight of these particles is $2{\cdot}9 \times 10^{-10}$ s; no example of decay 'in flight' has yet been observed. The rate of production of these heavy mesons, referred to as K-particles, has been compared with the frequency with which heavy mesons are observed to decay at rest; the ratio is consistent with the estimated lifetime of the K-particles.

In the disintegrations produced by primary particles of energy greater than ~20 GeV, approximately equal energy goes into production of π- and K-particles. The yield of K-particles at a primary energy of 2 to 3 GeV is estimated to be a few per cent per primary interaction.

The results suggest that not only π-mesons but also κ-mesons are 'heavy quanta' associated with the nuclear field. If charged mesons of mass between 276 and $900 m_e$ are created directly in showers, they occur with a frequency $< 1\%$ of the π-particles.

Introduction

In a recent paper (Daniel, Davies, Mulvey & Perkins 1952), evidence was given for the creation of heavy mesons of mean mass $1270\ m_e$, in nuclear interactions of protons with energy greater than 50 GeV. The secondary particles were identified by observations on the grain density and scattering in the tracks of those particles emitted from the disintegration with velocity between 0·5 and 0·85 c. Although the results were based on observations of small statistical weight, it was shown that in 'jets'—energetic and well-collimated showers, which result from peripheral collisions with nuclei, or from collisions with hydrogen—the proportion of protons among the shower particles is small. This feature ensured particularly favourable conditions for identifying the K-particles in spite of the relative small difference between their mass and that of the proton.

It was anticipated that in the disintegrations produced by protons of lower energy, the ratio of K-particles to protons among the secondary particles would be much smaller, and that, on account of statistical errors associated with the mass measurements, it would become increasingly difficult to distinguish the heavy mesons from the much greater number of ejected protons. In order to overcome this difficulty, it appeared necessary to increase the accuracy of the mass measurements; first, by restricting the observations to tracks of greater length; and secondly, by improving the accuracy of the measurements on multiple-scattering and grain density along the tracks.

In the present work, we have accepted only those tracks giving a standard error of less than $\pm 15\%$ of the measured mass. The minimum probable error obtained

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was $\sim 8\%$; the mean error on all tracks $\pm 12\frac{1}{2}\%$. It was thus possible to discriminate between protons and particles of mass less than $1410 m_e$, if the latter occurred with a frequency greater than about 5 % of that of the protons with the same range of velocities.

Experimental technique

Measurements of scattering

The most important errors in scattering measurements are due to statistical fluctuations associated with the finite number of cells employed in determining the scattering parameter $\bar{\alpha}$, and the procedure adopted for removing large deviations due to single scattering. In the present investigation, systematic errors, such as those due to distortion, have been reduced to negligible proportions; they are considered later. Statistical errors can be reduced by selecting very long tracks, and by employing the shortest possible 'cell lengths'.

The approximate energy of each of the particles was first determined by approximate measurements using a large value of the cell length, c. A shorter cell length was then chosen such that the contributions to the mean deviation of the track from a straight line, $\bar{d}$, due to 'signal' (i.e. true scattering) and 'noise' (i.e. spurious scattering due to errors in estimation of the true path of the track, irregularities in the stage movement, etc.), were approximately equal. Molière terms this value of c the 'optimum' cell length. The 'noise level' in the measurements on a track depends on the grain density, on the precision with which the track is alined perpendicular to the eyepiece scale, and on the length of track employed. The mean 'noise level' of each of the two 'Cooke' M4000 microscopes employed in the present measurements was $0{\cdot}07\,\mu$ for a cell length of $100\,\mu$. The minimum acceptable value of the mean deviation with the smallest cell length, was therefore $\bar{d}_c = 0{\cdot}07\ \sqrt{2}\,\mu = 0{\cdot}10\,\mu$.

The corresponding values $\bar{d}_{2c}$ and $\bar{d}_{3c}$, for cells of length $2c$ and $3c$, respectively, were next calculated, using completely overlapping cells. All individual values of the deviation $> 4\bar{d}$ were removed before calculating the finally accepted values of the mean (elimination of large-angle scattering). The increase in statistical accuracy obtained by employing overlapping cells is only a few per cent (see, for example, O'Ceallaigh & Rochat 1951), but ambiguities in the procedure for removing the effects of large-angle single scattering are greatly reduced.

The method of deducing the energy of the particle from the observed value of $\bar{\alpha}$ was as follows: The 'noise' contribution to the values of $\bar{\alpha}$ was assumed to be independent of cell size. This is very nearly true for the cell sizes employed, viz. 50, 100, 200 or $300\,\mu$ for all the tracks measured. It is certainly not true for much larger cell sizes, when an M4000 is employed. There are small variations in the noise-level for tracks with different values of the grain density. It was not profitable, therefore, in the present measurements, to allow for the slight variation of noise with cell size. The effect of noise was eliminated by a comparison of the results obtained with cells of magnitude $2c$ and c, and of $3c$ and c. The corresponding value of the scattering parameter ($\bar{\alpha}^{\circ}{}_{100\mu}$) was then computed; see, for example, Fowler (1950).

The quantity $p\beta$ for the particle, the product of the momentum and the velocity, was next determined from the relation $p\beta = K_{c0}/\bar{\alpha}_{100\mu}$, where K_{c0} is the value of the scattering constant appropriate when the present cut-off procedure is employed. The values of K_{c0} for different values of the cell size, c, and velocity β, have been calculated from Williams's theory by Voyvodic & Pickup (1952). The true value of $p\beta$ was taken as the mean of $p\beta_{c \atop 2c}$ and $p\beta_{c \atop 3c}$, weighted according to the corresponding numbers of independent cells. The standard deviation about this value was assumed to correspond to the number of independent cells of length $2c$.

It must be emphasized that there are a number of arbitrary features in the above procedure. For a given amount of labour, however, it appears to combine the maximum statistical weight with a minimum ambiguity in the procedure for removing the effects of single scattering. The use of three cell sizes also ensures the detection of any appreciable contribution due to emulsion distortion.

The convention for determining $p\beta$ was rigidly maintained in all the measurements. The mass values therefore depend on a comparison of sets of measurements performed with a standard procedure, so that they are independent of systematic errors in the absolute value of $p\beta$.

Effects of distortion

A small degree of distortion was detected in the batches of plates used in the present investigation. In nearly all cases, this was of the type known as 'C-shaped' distortion, in which there is a differential shear of the emulsion, which has the same sign throughout the depth. In the plates employed, the 'sagitta' of the 'C', measured on short tracks passing from the glass to the surface, was always less than $\sim 5\mu$. If we assume the curvature to be approximately constant (circular distortion), it follows that the contribution of the distortion to the signal, for cell lengths $2c$, is $\bar{d}_s \leqslant 5/(20)^2\mu$, since $n > 20$ in all cases. The observed value of $\bar{d}_{2c}$ for the measured tracks is greater than $0{\cdot}25\,\mu$, so that

$$\frac{\bar{d}_s}{\bar{d}_{2c}} < 0{\cdot}05,$$

Thus the systematic error in $p\beta$ due to distortion is less than $\frac{1}{2}(\bar{d}_s/\bar{d}_{2c})^2$, or less than $0{\cdot}125\,\%$. This is negligible in comparison with the statistical errors involved in the determination.

Grain counting

Grain counting was performed by the 'blob' method, i.e. all unresolved clusters of grains were treated as single units. The chief advantages of this method are that (*a*) there is a consistency between the results of different observers better than 1 %; (*b*) counting is very rapid; and (*c*) for a given number of counts, the statistical accuracy obtained in 'blob-counting' is considerably better than in 'grain-counting' (see p. 356). In the present work, a total of about 1 100 000 'blobs' were counted.

All blob-counts were normalized by comparison with similar observations on the tracks of electron-pairs recorded in the same plates. The 'blob-density' in these electron tracks was equal, within the statistical errors ($\pm 3\,\%$), to that found for the tracks of primary protons of energy greater than 10 GeV. The plates were accurately calibrated for any variation of grain density with depth in the emulsion. Local variations of grain density in different areas of the same plate are sometimes as great as 2 or 3 % (see also Morrish 1952). It was not profitable, therefore, to determine the value of g_0 with a statistical accuracy much greater than this value. The minimum grain density, g_0, was determined for all plates with a standard error of ± 2 %.

Errors in the measurements of mass

Standard deviations of the values of $p\beta$

The statistical error in a measured value of $p\beta$ depends on the number, n, of independent cells of length $2c$; $\sigma = A/\sqrt{n}$, where A is some constant. We have determined the probable errors experimentally using particles of known mass—protons of energy ~ 240 MeV produced in the Berkeley synchrotron, and π-mesons from the Columbia machine. The distribution in the measured values of $p\beta$ and g^* for these particles is shown in figure 27, and the corresponding mass 'spectrum' in figure 30. All the tracks in these exposures were recorded contemporaneously and in a single plate. No statistical errors are introduced, therefore, as a result of normalizing the grain density by the procedures necessary in the cosmic-ray plates.

The observed distribution in the mass values allows the constant A of equation (1) to be determined, if allowance is made for the small contribution to the errors arising from statistical fluctuations in the measurements of grain density. For each track, between 700 and 800 grains were counted, and the average number of independent cells, n, used in determining $\bar{\alpha}$ was 35 for the protons, and 45 for the pions.

Table 16 shows the values of A deduced from the observations on artificial pions and protons, together with that for 105 MeV positrons deduced from the measurements of Menon, Rochat & O'Ceallaigh (1951).

Table 16

Berkeley protons 150 to 250 MeV	0·71 ($\pm$ 0·1)
Columbia pions 30 to 80 MeV	0·68 ($\pm$ 0·1)
Cornell positrons 105 MeV	0·76 ($\pm$ 0·1)

These results may be compared with the theoretical value, $A = 0{\cdot}80$, calculated by Scott (1952) for chord measurements, assuming a Molière distribution with '$4\bar{d}$ cut-off'. Part of the discrepancy can be attributed to our use of overlapping cells; this will reduce A by about 4 %. It may also be remarked that the tracks selected do not necessarily correspond to a completely random sample from a normal universe. Moreover, averaging of the values $p\beta_{\substack{2c\\1c}}$ and $p\beta_{\substack{3c\\1c}}$ will tend to produce a mass distribution more peaked than normal. The criterion of selection was based solely on track length, and was the same for both the artificially produced particles and the tracks from the cosmic-ray stars. The two sets of measurements are directly comparable, and the value $A = 0{\cdot}70$ was adopted for the cosmic-ray tracks.

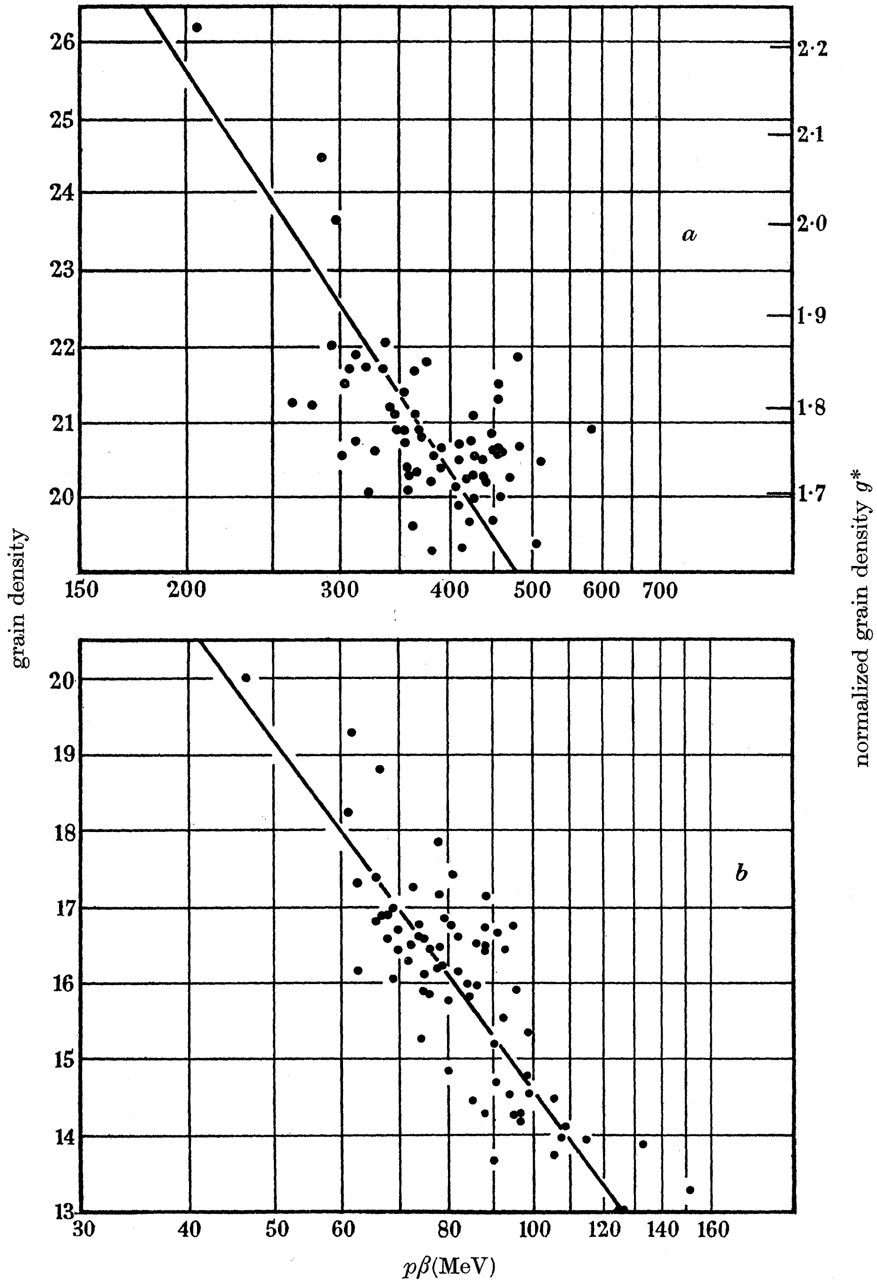

FIGURE 27. Observations of $p\beta$ and g^* for (a) artificially accelerated protons (Berkeley protons 68 tracks), (b) artificial π-mesons (Columbia, 71 tracks).

Deviations in grain density

Many observations have been made on the statistical errors arising in grain-counting and blob-counting. The standard deviation for m grains may be written $\sigma = B/\sqrt{m}$. Several observers report that $B < 1$, i.e. the actual distribution is more 'peaked' than a Poissonian.

The present observations show that in blob-counting, B is a slowly varying function of the velocity of the particle producing a track. Values obtained for a particular batch of plates are shown in table 17. For the present experiments it is sufficient to assume that B is constant and equal to 0·70. The ratio B/R is not significantly different for blob-counts and grain-counts, where R is the slope of the straight line in the equation $g^* = -R \ln p\beta + \text{constant}$, which gives a close approximation to the relation between g^* and R for particles of a given mass. ($B/R = 1\cdot0$

TABLE 17

absolute blob count (per 50μ)	blob density relative to plateau	$\beta = v/c$	B
10·0	1·00	1·00	0·82
12·5	1·25	0·78	0·72
22·0	2·21	0·45	0·59

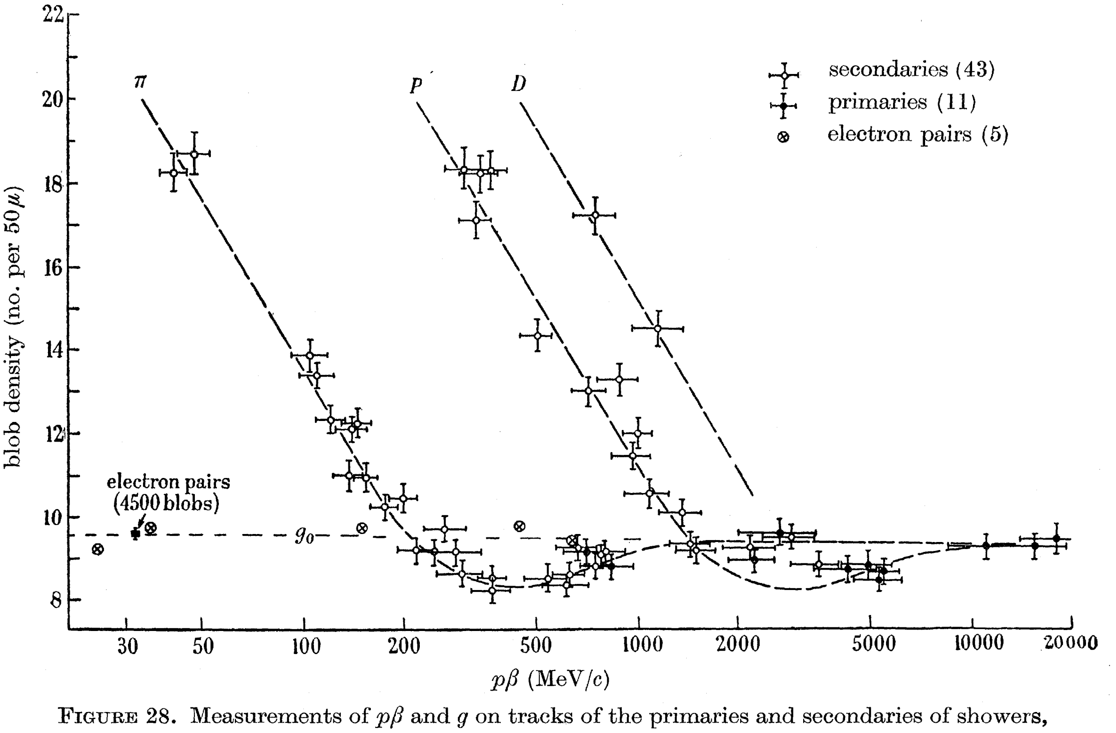

FIGURE 28. Measurements of $p\beta$ and g on tracks of the primaries and secondaries of showers, and on electron pairs, in a single plate (Ha 21: 76, 77, 78). Minimum number of blobs per track = 900.

in both cases, for particles of twice-minimum ionization.) At a given specific ionization, g^* is somewhat greater for grain-counting than for blob-counting ($g^*_{\text{blob}} = g^*_{\text{grain}} \cdot e^{-ag^*_{\text{grain}}}$, where '$a$' is the mean grain diameter). For a given number of counts, m, therefore, the statistical error in the mass is less for blob-counting than for grain-counting (this is not true for a given length of track). In our opinion, the smaller subjective errors associated with blob-counting make this method generally preferable.

The resulting statistical error in the mass M is given approximately by the following equation, if n is large so that the distribution is nearly Gaussian:

$$\frac{\sigma_M}{M} = \left[\frac{A^2}{n} + \frac{B^2 g^{*2}}{R^2}\left\{\frac{1}{m} + \frac{1}{m'}\right\}\right]^{\frac{1}{2}}, \tag{1}$$

where m' is the number of grains counted in determining the minimum grain density, g^0. $R = 0{\cdot}63$ in the interval in g^* from 1·1 to 2·0. With $A = B = 0{\cdot}70$, this formula becomes

$$\frac{\sigma_M}{M} = 0{\cdot}7\left[\frac{1}{n} + \left(\frac{g^*}{R}\right)^2\left\{\frac{1}{m} + \frac{1}{m'}\right\}\right]^{\frac{1}{2}}. \tag{2}$$

In a typical case, $n = 50$, $m = 1000$, $m' = 2000$, $g^* = 1{\cdot}5$. The first term in the bracket $= 0{\cdot}020$, the second 0·008. The total error is $\pm 12\,\%$, of which the root-mean-square contributions from scattering and grain-counting are 10 and 6 % respectively.

Figure 28 shows the quality of the resolution obtained in measurements in a single plate; it has been deduced from observations on forty-three tracks of secondary particles, eleven of primaries and five of energetic electron-pairs.

Observed mass distribution

Mass spectrum

Figure 29 shows the distribution of the values of g^* and $p\beta$ for 325 tracks from cosmic-ray stars, of multiplicity $n_s \geqslant 1$. In this figure the best straight line, 'π-line', has been drawn through the group of points due to particles of small mass. It is indistinguishable from a similar line deduced from previous results (see Daniel *et al.* 1952). The corresponding lines for particles of mass $1210\,m_e$, protons and deuterons, have been inserted by displacing the π-line by the appropriate mass ratio. The line in figure 27 drawn through the experimental points for artificial pions is identical with the 'best π-line'. Similarly, that for the accelerated protons was determined by displacing the π-line by the proton/pion mass ratio.

The mass spectra derived from the figure 29 are shown in figure 30. In plotting the distributions, the logarithm of the mass has been taken as abscissa, and the scale so chosen that there are fifty equal logarithmic intervals of mass between 276 and $1840\,m_e$. The skew-Gaussian curves† in best accord with the observations on artificial π-mesons and protons have been inserted in the figure, and from them the value of the constant A was found in the manner described above.

The full lines drawn through the histograms representing the observations on cosmic-ray particles have been determined in the following way: Figure 31 shows the distribution in length of all measured tracks as a function of the corresponding value of $p\beta$. The minimum number of cells, n, used in the determination of $p\beta$ for all these tracks was 20; for particles of apparent mass $< 900\,m_e$, the average number was 45; and for particles of mass $> 900\,m_e$, 35. The first group, corresponding to particles of smaller mass, has been divided into two, viz. those for which $20 < n < 45$, $\bar{n} = 34$, and for which $45 < n < 100$, $\bar{n} = 55$. The expected mass distribution for

† Even for $n > 20$, slightly better agreement is obtained by allowing for the 'skewness' of the mass spectrum.

π-mesons has then been calculated from equation (2), assuming it to consist half of tracks with $\bar{n} = 34$, and half with $\bar{n} = 55$. The resulting curve has been normalized by assuming all particles (129) of apparent mass $< 500 m_e$ to be π-mesons.

The expected mass distribution for the protons has been similarly calculated assuming it to consist half of tracks with $\bar{n} = 27$, and half with $\bar{n} = 45$. In this case, however, the curve has been normalized to correspond to twice the number of

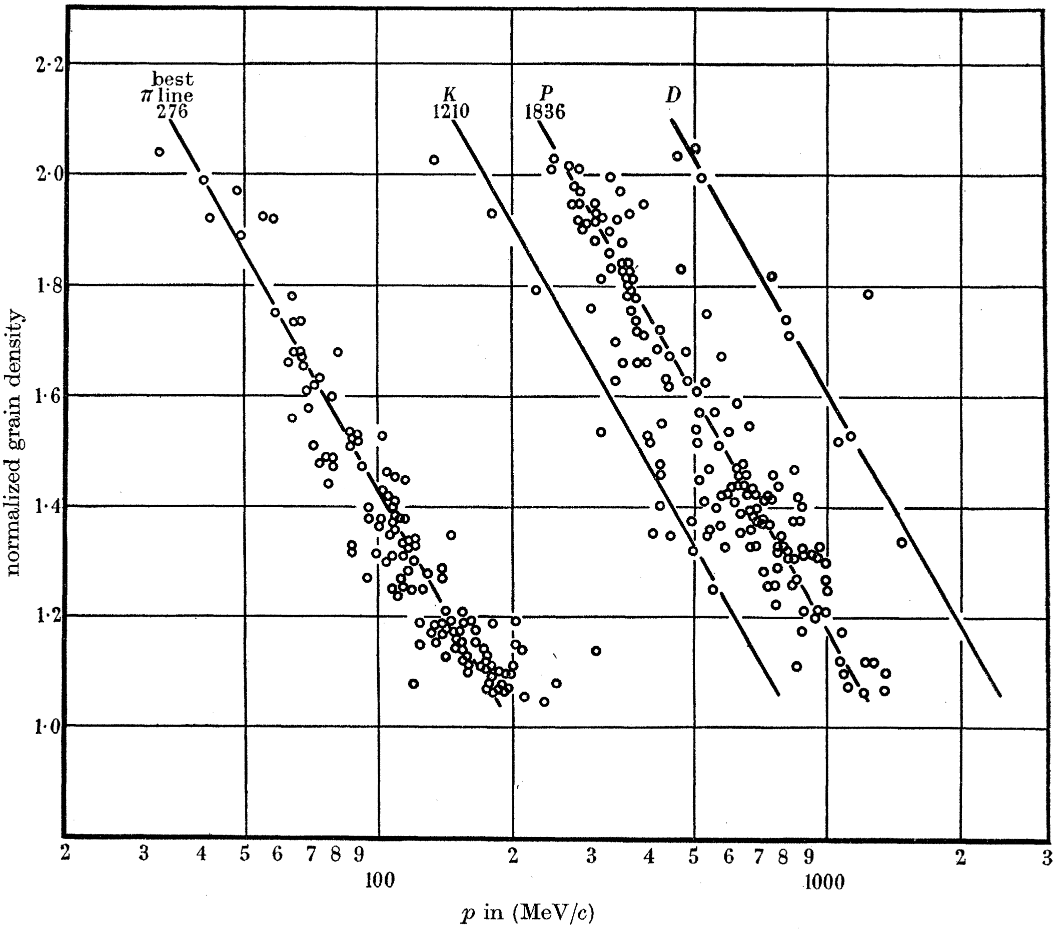

FIGURE 29. Measurements of $p\beta$ and g^* for tracks of 325 secondaries of showers of $n_s \geq 1$.

tracks which yield mass values in the interval from 1836 to $3000 m_e$. This procedure was adopted in order to eliminate any small errors in normalization due to the presence of heavy mesons with masses less than that of the proton.

A comparison of figures 30*a* and 30*b* shows clearly the presence of particles in the cosmic-ray showers with masses less than that of the proton. We attribute them to heavy mesons with masses in the interval from 900 to $1400 m_e$, which it will be convenient to refer to as K-particles. The measurements do not allow the protons to be completely resolved, and many of the individual tracks cannot be allocated with certainty. It has therefore been necessary to make an arbitrary division. We have chosen to ascribe tracks giving an apparent mass between 900 and $1400 m_e$ to

K-particles, and those greater than $1400m_e$ to protons. According to this convention, there are twenty K-particles in the distribution. Assuming a unique mass of $1210m_e$ for these particles, their expected apparent mass distribution is shown by the curve, and the combined distribution for all the tracks by the broken line.

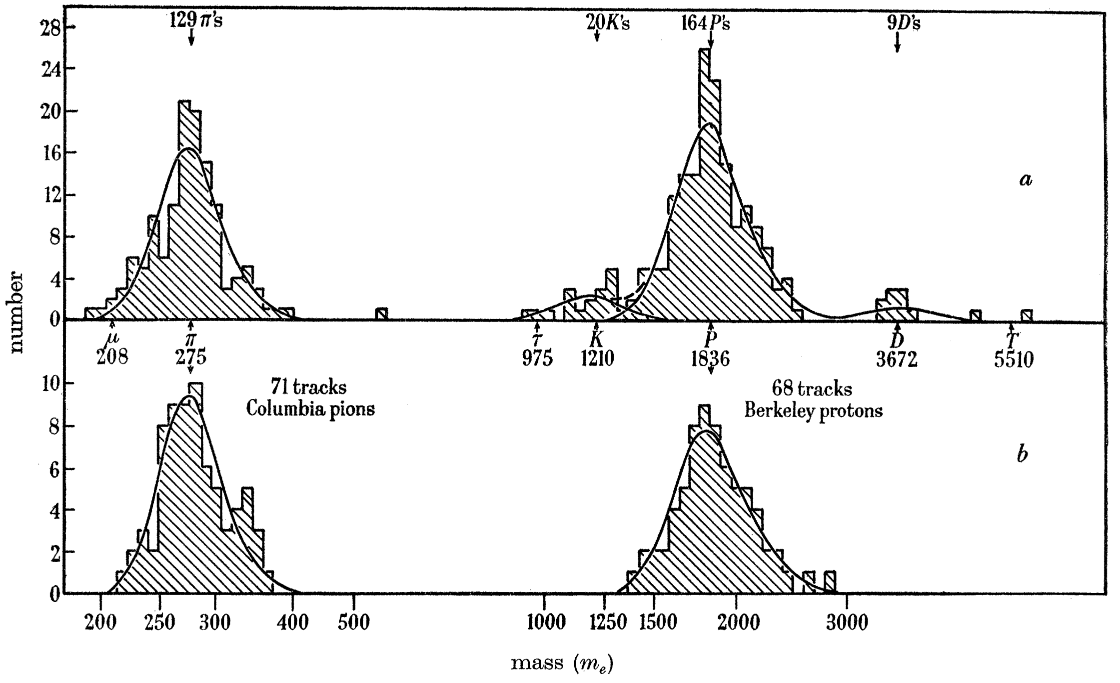

FIGURE 30. Mass spectrum, (*a*) cosmic-ray tracks from figure 29, (*b*) artificial pions and protons. Total 325 tracks, all showers of $n_s \geqslant 1$.

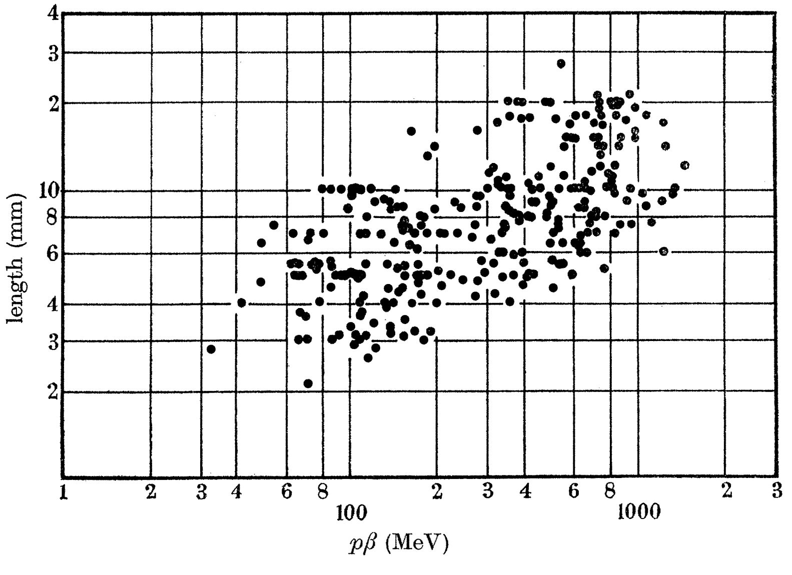

FIGURE 31. Length distribution of tracks as a function of $p\beta$.

The results are, of course, not inconsistent with the assumption that heavy mesons of different mass are present (see p. 362).

It may be objected that the group of tracks attributed to K-particles was in fact produced by protons recorded in anomalous conditions of exposure. If, for example, the emulsions were temporarily subjected to very low temperatures during the balloon flight, the grain density in some proton tracks might be abnormally low. In five instances, however, the K-particles are emitted from

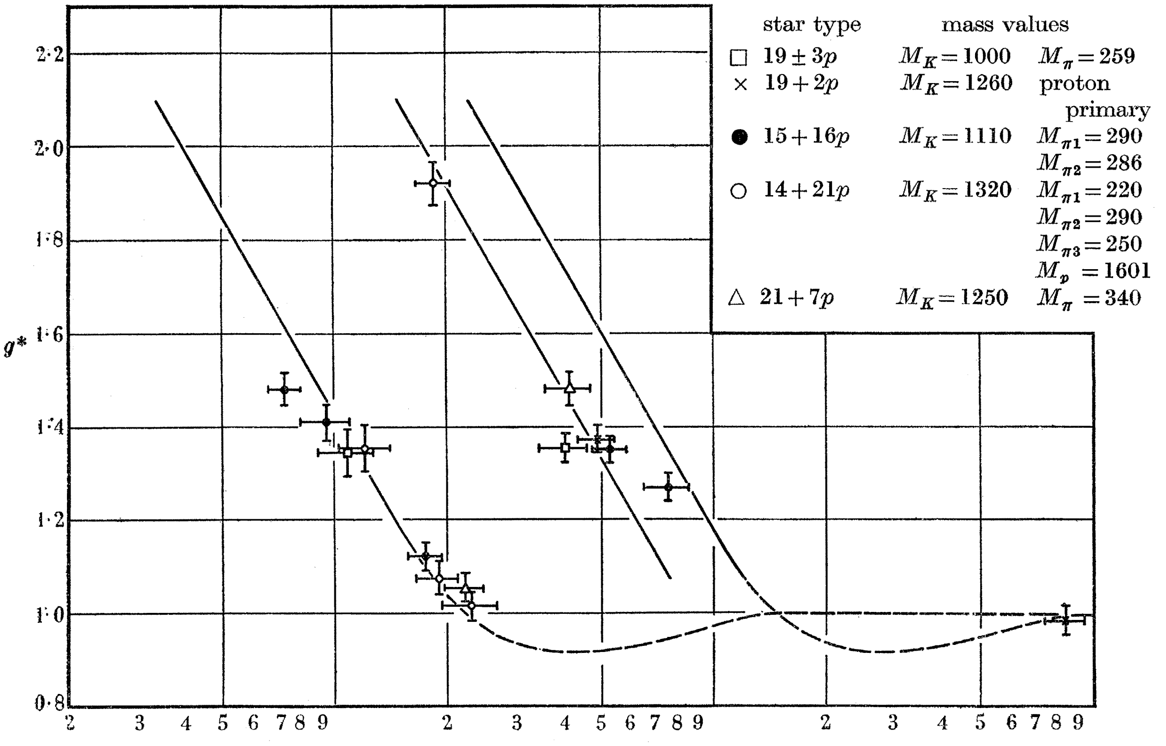

FIGURE 32. Measurements of $p\beta$ and g^* on long tracks of accompanying secondaries in showers containing identified K-particles.

disintegrations accompanied by the emission of other shower particles, of which the tracks are also long enough to allow a determination of the masses. The results, shown in figure 32, show that these particles were either π-mesons or protons. Since these tracks were produced contemporaneously, and in the same region of the emulsion, as the associated tracks ascribed to K-particles, the apparent existence of the latter cannot be due to abnormal conditions of registration in the emulsion. In one event, the second measurable track was produced by the particle which produced the shower—presumably a proton—of energy $7{\cdot}8 \pm 1{\cdot}5$ GeV.

Production of heavy mesons in pairs

In view of its theoretical interest, and because of the possibility of generating heavy mesons in the great accelerators now in operation or under construction, it is of great importance to determine whether the K-particles are generated singly or in pairs. If they are of integral spin, and are strongly coupled with nucleons, they should, like π-mesons, be produced singly, at energies just above the 'threshold'. On the other hand, if they are fermions, the K-particles might be produced in pairs consisting of the particle and its anti-particle, both carrying an electric charge.

If heavy mesons are indeed produced in pairs, it should be possible, occasionally, to find examples in which the tracks of both particles are sufficiently long to allow them to be identified. No such event has been found. Even if the directions of motion of the pair were randomly orientated with respect to one another, the probability that in events in which one track has been identified, the second would be measurable, is at least 1 in 15. Because of the motion of the C-system of the interaction, this value represents a lower limit. Since only twenty K-particles have been identified, two or three events only might have been expected to allow the identification of a pair. The available evidence is therefore not sufficient to exclude the possibility that the K-particles are commonly produced in pairs. In the four showers, in which K-particles are accompanied by other secondary particles of which the mass can be determined—nine in all—the latter are either π-mesons or protons (figure 32).

The present results, whilst indecisive, are consistent with the assumption that the K-particles have integral spin and are produced singly, and this hypothesis is strengthened by the high yield of K-particles produced by primaries of relatively low energy (see next section).

Yield of K-particles as a function of primary energy

In table 18 we show the relative numbers of protons, pions and K-particles produced in stars of different multiplicity. A gradual increase in the ratio, N_K/N_π, of the numbers of K-particles to π-particles, with increasing multiplicity, is immediately apparent. These numbers refer to tracks with grain density, g^*, between 1·07 and 2·0, $(0{\cdot}5 < \beta < 0{\cdot}84)$. In table 19, column 2, appropriate geometrical correction factors have been introduced to take account of the greater average track length of the K-particles compared with the pions. The value $N_K/N_\pi = 0{\cdot}28$, observed for primary energies ~ 15 GeV, and for secondary particles with velocity in the interval between 0·5 and 0·84 c, may be compared with the ratio of 0·4, obtained by Astbury, Chippindale, Millar, Newth, Page, Rytz & Sahiar (1953), for particles with specific ionization between 2 and 10 times minimum.

For particles of mass $1200 m_e$, the values of β between 0·5 and 0·84 corresponds to momenta between 330 and 950 MeV/c. Further, the relative numbers of pions in the velocity interval from 0·5 c to 0·84 c on the one hand, and in the momentum interval from 330 to 950 MeV/c on the other, are known for showers of different multiplicity; (Camerini, Davies, Lock, Franzinetti, Fowler, Perkins & Yekutieli 1951). It is therefore possible to determine the ratio N_K/N_π for the momentum interval from the observed value for the velocity interval. The results are shown in table 19, column 3. Included in this column is the corresponding value for the 'jets', previously published. The last column indicates the mean primary energy for the different classes of showers, together with approximate energy limits which embrace 90 % of the primary particles. The fifth column indicates the proportion of the total energy radiated in the form of pions or K-particles. The results show that, at energies above about 15 GeV, the fractions of the available energy which appear in the form of K-particles and π-mesons are approximately equal.

Table 18. Observed relative numbers of pions, protons, and K-particles

($g^* = 1{\cdot}07$ to $2{\cdot}0$; $\beta = 0{\cdot}5$ to $0{\cdot}84$)

n_s	1	2	3	4	5	6	7 to 10	$\geqslant 11$
N_π	22	27	22	5	7	11	20	15
N_K (900 to 1400m_e)	1	3	3	3	1	0	5	4
N_p	56	23	18	15	6	9	28	9

Table 19. Yield of heavy mesons

star type	N_k/N_π $\beta = 0{\cdot}5$ to $0{\cdot}84$	N_k/N_π $p = 330$ to 950 MeV/c	(identified K shower particles) / (all shower particles) of $g^* \geqslant 1{\cdot}4$)	E_k/R_π $p = 330$ to 950 MeV/c	average primary energy Ep
$n_s = 1, 2, 3$	$0{\cdot}13 \pm 0{\cdot}05$	$0{\cdot}09 \pm 0{\cdot}04$	$0{\cdot}015 \pm 0{\cdot}006$	$0{\cdot}17 \pm 0{\cdot}06$	5 GeV (1·5 to 8)
$n_s \geqslant 4$	$0{\cdot}28 \pm 0{\cdot}08$	$0{\cdot}20 \pm 0{\cdot}06$	$0{\cdot}018 \pm 0{\cdot}004$	$0{\cdot}36 \pm 0{\cdot}1$	20 GeV (6 to 40)
'jets' ($Ep > 50$ GeV)	—	$0{\cdot}5 \pm 0{\cdot}2$	$\sim 0{\cdot}08$	$1{\cdot}0 \pm 0{\cdot}3$	200 GeV (500 to 3000)

The present results do not allow the yield of K-particles to be given directly as a function of primary energy. Making allowance, however, for the spread of multiplicity of the showers produced by particles of a given primary energy, the results appear to be consistent with the yield predicted by the Fermi theory, on the assumption (a) of pure multiple production (Fermi 1950, 1951), and (b) that the heavy mesons are strongly interacting particles of mass 1200m_e which are of spin 0, and not produced in pairs; see also U. Haber-Schaim & G. Yekutieli (1952), Narayan (1953) and Kothari (1953).

The above evidence for the copious generation of K-particles at high energies suggests that they are to be regarded as 'quanta' of the nuclear field in the same sense as pions. This point will be discussed below in more detail (p. 363).

Nature of the K-particles generated in showers

At least three types of charged particles with masses in the interval from 900 to 1400m_e have been observed to decay in emulsions or cloud chambers. They are classified phenomenologically as τ-, κ- and χ-mesons respectively, and they decay according to the schemes (Menon & O'Ceallaigh, p. 292 of this discussion)

$$\tau^\pm \rightarrow \pi^+ + \pi^- + \pi^\pm \qquad M_\tau = 972 \pm 6m_e,$$

$$\left.\begin{array}{l}\kappa^\pm \rightarrow \mu^\pm + \nu + \nu \\ \quad or \;\; \mu^\pm + \pi^0 + \nu\end{array}\right\} \qquad M_\kappa \geqslant 1150m_e,$$

$$\chi^\pm \rightarrow \pi^\pm + N_0, \qquad M_\chi = 900 \text{ to } 1000m_e.$$

All three of these particles have been observed to be emitted directly from nuclear interactions.

The distribution of figure 19 shows at once that the fast K-particles cannot consist exclusively of particles of mass below $1000m_e$. If τ- and χ-mesons are indeed present, we estimate that they constitute less than 20 % of all the K-particles. The experimental distribution is indeed consistent with the assumption that all, or almost all, of the K-particles are to be identified with the κ-mesons.

K-PARTICLES AS A NUCLEAR QUANTA

The evidence summarized in table 19 suggests that at very high primary energies, K-particles and π-mesons are produced in nearly equal numbers. One type of K-particle at least may therefore be regarded as a Yukawa quantum in the same sense as the pion. According to the Fermi statistical theory (which neglects any interactions between the created mesons) in collisions of very great energy, different nuclear quanta should be generated in numbers proportional to their statistical weight. If, for example, the majority of K-particles directly created are particles of a single type and of spin zero, the number of K-particles and pions should be approximately equal when both types have high relativistic velocities in the C-system.

The above conclusion applies strictly only to a collision between pairs of nucleons. In a collision with a nucleus, secondary, plural-type collisions of lower energy, will tend to produce pions rather than K-particles; they will therefore lead to a reduction in the final value of N_K/N_π for the collision. Similarly, any interactions between the created particles, as postulated by Heisenberg (1952), can also result in an increase in the number of pions.

These tentative considerations suggest that the ratio N_K/N_π will tend asymptotically towards unity as the primary energy increases. It appears reasonable to expect it to approach unity at primary energies exceeding say $\sim 10^{13}$ eV, where the average energy of the particles in the C-system is of the order of the rest-mass of three or more protons.

Assuming that neutral pions are the principal source of γ-rays in such high-energy collisions, and that the ratio $N_{\pi^0}/N_{\pi^\pm}$ equals 0·5 (as observed at lower energies) the ratio of neutral pions to shower particles N_{π^0}/N_s should be of the order of 0·25. Recent experimental evidence appears to be consistent with this assumption (see Mulvey, p. 367 of this discussion).

NUCLEAR INTERACTION OF THE K-PARTICLES

The experimental results presented above suggest that the K-particles may have an interaction length for collisions with nuclei close to the geometrical value, i.e. 25 cm.

The experimental evidence is not yet of sufficient weight to allow a direct determination of this quantity. Taking into account the fact that a minimum track length of 4 or 5 mm is required before a K-particle can be identified, the total observed track length of the particles, effective for the detection of an interaction, is only 10·0 cm. No interaction has been observed.

An alternative approach is possible if the evidence is accepted that at very high primary energies nearly half the mesons created are κ-mesons. The observed interaction length of all the shower particles, the great majority of which are unidentified, then allows conclusions to be drawn about the nuclear interactions of the κ-mesons alone. The results correspond to an interaction length equal to 26 ± 6 cm, compared with the geometrical value of 25 cm (Mulvey, p. 367). This result strongly suggests that both π-mesons and K-particles have a cross-section for interaction close to the geometrical value. If the nuclear interaction of K-particles were very weak, the interaction length of all the shower particles, calculated without discriminating between the different types, would be ~ 50 cm.

Lifetime of the K-particles

The total, effective, proper time of flight of identified K-particles observed in the present experiments is $2{\cdot}9 \times 10^{-10}$ s. Since no decay has been observed, this value may be taken as an approximate lower limit to the lifetime.

An estimate of the lifetime of the K-particles may be obtained by assuming them to be identical with the V-particles decaying in flight in cloud chambers. Astbury *et al.* (1953) show that in their particular experimental conditions, about equal numbers of pions and V-particles are observed to decay in the gas of a Wilson chamber under a layer of matter in which 'showers' are produced. In such showers about ten times as many π-mesons as K-particles are produced (table 19); it follows that if equal numbers are observed to decay, the K-particles must have the shorter lifetime. These results suggest a lifetime of the order of 3×10^{-9} s.

The neutral counterpart of the K-particles

It is reasonable to suppose that neutral particles, K^0, uncharged counterparts of the K-particles, will be produced in energetic disintegrations. Indeed, it seems probable that the V_2^0-particles observed to decay in expansion chambers, of mass $\sim 1000 m_e$ and lifetime $\sim 2 \times 10^{-10}$ s, are of such a nature.

In the experiments on 'jets', an attempt was made to study the balance of energy in the disintegrations and thus to establish whether there is any missing energy which could be attributed to the creation of K^0-particles. It was then found that 20 ± 20 % of the total energy in the jets is 'missing' (Perkins, 1951). This result depends on the assumption that most of the particles in the jets originate in a single nucleon-nucleon collision ('pure' multiple production). While it must therefore be accepted with reserve, it shows that the available evidence on high-energy showers is compatible with the creation of K^0-particles.

Support for the above conclusions is provided by the observations on disintegrations of energy $> 10\,000$ GeV, discussed by Mulvey (see p. 367).

Evidence for existence of particles of mass between $276 m_e$ and $900 m_e$

During the past year, tentative evidence has been presented for the existence of charged mesons of mass $530 m_e$, termed ζ-mesons (Perkins 1952*a*). In the light of the more accurate scattering measurements described in this paper, an appraisal can be made of the weight of evidence for the existence of such a particle.

In the earlier measurements, the selection of tracks was less stringent than for the present observations; data from all tracks of length exceeding 3 mm were accepted, if the value of $p\beta$ was less than 400 MeV. The tracks of four secondary particles yielding apparent masses between 480 and $580m_e$ were observed. Of these, one gave a value for the grain density $g^* = 1\cdot04 \pm 0\cdot03$. For particles of the corresponding velocity, the mass measurements are subject to large errors, and the track could have been due to an electron. In the present series, observations were confined to tracks with values of $g^* > 1\cdot07$ and this track was therefore excluded. Two of the remaining tracks are short and yield values of n, the number of independent cells used in determining $\bar{\alpha}$, less than 20. They also were rejected.

The fourth track, while satisfying the new criteria in other respects, occurred near the processed edge of one of the plates of a batch in which the distortion is considerable. For this reason events from this particular batch of plates have been excluded in the present work. Although the measurements of 'third difference' on this particular track did not indicate appreciable errors due to distortion (Fowler 1950) we believe that the mass value cannot be accepted with confidence because of the possible influence of the distortion in the plate.

One further example of a track yielding an apparent mass about twice that of the pion has since been observed. It is of length 11·5 mm and has $g^* = 1\cdot15 \pm 0\cdot03$, $p\beta = 310 \pm 30$. The corresponding value of the mass is $520 \pm 60m_e$. The results for this track are plotted in figures 28 and 30.

In the previous measurements, in addition to those mentioned above, a track was observed, of total length 17 mm, which showed the following characteristics: Scattering measurements on the first 11 mm of the track were consistent with the decay in flight of a particle of about twice the pion mass, into a pion. Over the first 5 mm of track length, the apparent mass was $520 \pm 90m_e$. After a small deflexion (0·5°), the scattering appeared to increase twofold, and indicated a mass $260 \pm 30m_e$. The change in grain density was from $g^* = 1\cdot17 \pm 0\cdot03$ to $1\cdot15 \pm 0\cdot03$. The measurements on the final 6 mm of track gave a mass of $250 \pm 30m_e$. The mass-value from the entire track is $309 \pm 20m_e$, and this is the value plotted in figure 30.

More recently Shapiro (1952) has reported two very similar examples attributed to decay in flight of a particle of mass $500m_e$. In these examples, also, there are deflexions in the tracks of the order of from 0·5 to 1°, but no significant change in grain density. The ratios of $\bar{\alpha}$ before and after the deflexions are given as $1\cdot8 \pm 0\cdot3$ and $2\cdot0 \pm 0\cdot4$. The number of identified π-meson tracks from the stars observed is not given.

The probability that such a large change in $\bar{\alpha}$ can arise purely from random fluctuations, is less than 0·5%. Since 170 tracks of π-mesons have now been measured, the observed change in scattering can be attributed to such fluctuations. The fact that the angular deflexions at the 'points of decay' are very small, and are not associated with a significant change in velocity, must also be regarded as a suspicious feature tending to reinforce this view.

It may be remarked that the evidence obtained by Voyvodic (1952) and Shapiro (1952) for the decay in flight of a κ-meson from a star is of quite a different order of significance. In their events, the angular deflexion at the point of decay is very large compared with the root-mean-square angle of scattering, and there is a definite change in velocity of the particle at the point where the deviation occurs. The point of decay is therefore established independently of any change in scattering along the track.

The evidence for the existence of the charged ζ-particles therefore rests at present only on one track which gives an apparent mass of $520 \pm 50 m_e$. From the total number of pion tracks measured, the probability that one could give such a high apparent mass is estimated at 6%. As has been emphasized previously (Daniel *et al.* 1952; Perkins 1952*b*), no conclusions can be drawn from measurements on single tracks. Decisive evidence would be provided by a well-resolved group in a mass spectrum, as observed for the K-particles. If the ζ-particles were of very short lifetime, such a peak might be accompanied by a 'tail' extending down to the pion mass.

The present observations, if charged ζ-particles exist, establish that their frequency of emission from showers, produced by protons of energy greater than 2 GeV, is less than 1% that of the pions.

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