Mass Spectrum of Shower Particles from Cosmic-Ray Interactions

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The masses of particles with an ionization less than about twice the minimum value emitted in cosmic-ray stars in a photographic emulsion have been determined by observations on the grain density and scattering of suitably long tracks. About 100 tracks with an average length of 16.5 mm were analyzed using a single emulsion exposed to cosmic rays in a high-altitude balloon flight of nine hours duration. The results show groups of pions, protons, deuterons, heavy mesons with mass $\sim 925m_e$ and the possibility of a group with mass closer to that of the proton. This latter is uncertain, however, with the present resolution and could be a statistical fluctuation on the edge of the proton distribution.

I. INTRODUCTION

EVIDENCE for the production of heavy mesons with mass ~ 1200–$1300m_e$, obtained by measurements of grain density and scattering of secondary particles emitted in cosmic-ray disintegrations, was submitted by Daniel *et al.*[1] and Daniel and Perkins,[2] although the statistical accuracy of this work was not very good. The present work was started in the hope of improving the resolution between the heavy meson and proton groups by using longer track lengths. An extension of the Bristol work has been made since by Fowler and Perkins,[3,4] using longer track lengths, from which they obtain evidence for a heavy-meson group with mass 900–$1000m_e$ and a possible group with mass intermediate between this and the proton mass. This latter group is considered uncertain yet, however, being close to the edge of the proton distribution. The present measurements, while using shorter track lengths than in the latest work of Fowler and Perkins, gives similar results. In addition, measurements have also been made in the region of the ionization minimum and the results give an indication of the possibility for discrimination in this region and some information about the energy spectrum of the heavy mesons.

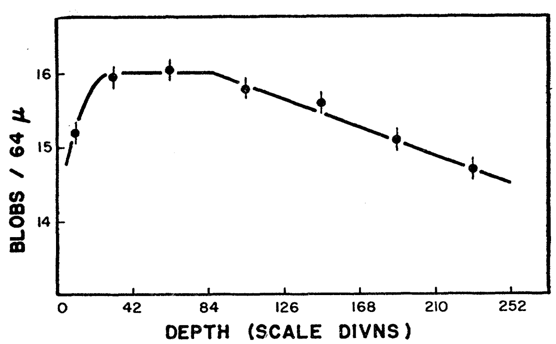

FIG. 1. Variation of plateau blob density with depth in the emulsion. The drop in blob density near the air surface indicates grain corrosion here.

II. EXPERIMENTAL PROCEDURE

1. Exposure and Processing

Ilford *G*5 emulsions, 600μ thick, 4 in.$\times$4 in. and mounted on glass, 2 mm thick for rigidity, were exposed in a "Skyhook" balloon flight for nine hours at about 95 000 feet. The emulsions were developed by the hot-plate method, using acid amidol after which they were kept in a room with controlled temperature and humidity where the measurements were made.

2. Grain Density

Ionization was measured by counting blobs (unresolved groups of grains) along the tracks using a Leitz microscope with 90/1 objective and 15$\times$ Kellner eyepieces, the electron plateau blob density being about 25 blobs per 100μ. Since the star population density was fairly high, it was decided at first to make as many measurements as possible in one emulsion. This obviated the necessity of normalizing results because of possible differences between emulsions. There was a variation of grain density with depth in the emulsion used, and this is shown in Fig. 1. High-energy "plateau" electron pairs were used to obtain this curve and it was also verified by blob counting on long tracks with grain density $\sim 1.5\times$ the plateau value. Blob counts on all shower tracks measured were then normalized to the electron plateau value corresponding to the appropriate depth in the emulsion. It is estimated that any error due to this correction is not more than 1 percent. Blob counting was not made within 50μ from the surface since there was evidence of grain corrosion here, the effect of this being shown in Fig. 1. No correction was made for background grains since the measurements are all relative ones. The standard error for blob counting was taken to be $(70/\sqrt{n})$ percent, where n is the number of blobs.

3. Scattering

Values of $p\beta$ were obtained by the usual multiple-scattering procedure. The cell size was always chosen

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[1] Daniel, Davies, Mulvey, and Perkins, Phil. Mag. 43, 753 (1952).
[2] R. R. Daniel and D. H. Perkins, Proc. Roy. Soc. (London) A221, 351 (1954).
[3] Proceedings of the Duke University Cosmic-Ray Conference, 1953 (unpublished).
[4] C. F. Powell, Nuovo cimento Suppl. No. 2, 165 (1954).

to be about six times the noise level and overlapping cells were used. Since measurements are relative ones, no correction was made for noise. Any distortion correction was estimated to be $\gtrsim 1$ percent. Theoretical values with cutoff were used for the scattering constant[5] and, in assessing the errors, no account was taken of the fact that there is still doubt about the agreement between theory and experimental scattering calibrations for emulsions using protons of several hundred Mev. The standard error was taken as $(75/\sqrt{n})$ percent, where n is the number of independent nonoverlapping cells used for any track.[6] The validity of this relation was checked in the present work by calculating the standard deviation of the measurements for several tracks.

III. RESULTS

1. Track Length and Statistics

The track-length distribution is shown in Fig. 2, the average length being 16.5 mm. For the four groups of particles (pions, K-mesons, protons, and deuterons) the average number of second differences in scattering was 82, 110, 37, and 47, respectively, giving standard errors of 8.3, 7.1, 12.3, and 10.9 percent. Since the standard error for blob counting was $\gtrsim 1$ percent, the total experimental standard error used in assessing the accuracy for the four groups was taken as 9, 8, 13, and 11 percent. The doubtful heavy-meson group at mass $\sim 1250 m_e$ was considered as belonging to the proton group for this purpose.

2. Mass Spectrum

In Fig. 3, $p\beta$ (the scattering parameter) is plotted against blob density (corresponding to ionization) for the tracks measured, the points above the ionization plateau resolving themselves into a family of curves corresponding to different masses. The best curve was drawn through the proton group of points and the other full line curves were calculated from this assuming a proton mass, $1837 m_e$, pion mass, $273 m_e$, and deuteron mass, $3674 m_e$. The K-meson curve was drawn parallel to the other curves passing through the point at normalized blob density$=1.5$, and corresponds to a mass, $925 m_e$. It should be noted that, with the plateau blob density of 25 blobs per 100μ in this emulsion, 1.8 was about the useful upper limit of normalized blob density which could be used since saturation occurred in this region below which the blob density decreased with $p\beta$. This is shown for pions in the dotted part of the curve in Fig. 3. A similar curve, not shown, was measured for protons. Protons are losing energy rapidly here and can be distinguished from K-mesons on this account. The assignment of the lower-energy K-meson in Fig. 3 as such was partly based on comparison with a proton of similar $p\beta$ which came to rest in the emulsion. However, for work in the region above a normalized blob density of about 1.5, it is more desirable to have a plateau blob density <25 blobs per 100μ (e.g., ~ 20 blobs per 100μ, as used in the Bristol work).

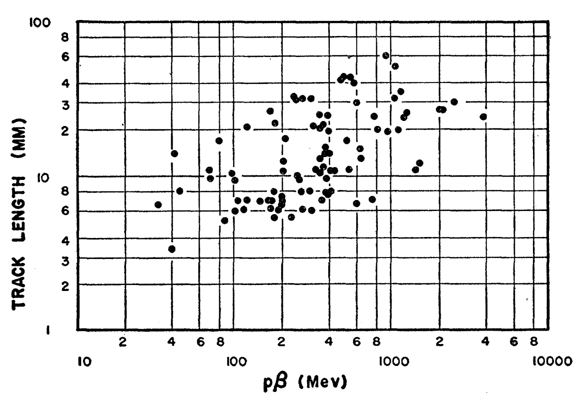

FIG. 2. Length distribution of tracks measured; mean length$=16.5$ mm.

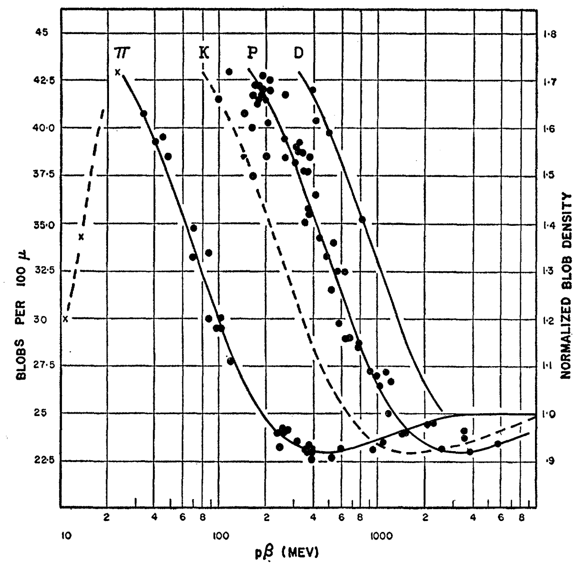

FIG. 3. Variation of blob density with $p\beta$ for all tracks in single G5 emulsion. Above the plateau the best curve is drawn through the proton group of points, and the π and d curves calculated from this. The K curve is drawn parallel to the other curves passing through the point at normalized blob density$=1.5$.

Taking the best curve through the proton points in Fig. 3 as the curve representing mass $1837 m_e$, the masses corresponding to all points were calculated. The resulting mass spectrum is shown in the histogram in Fig. 4. Superimposed on this histogram are the expected normal distribution curves corresponding to the mean standard errors for each group. Although the number of particles is small, the agreement between the different groups is very reasonable and there is little doubt about the meson group with mass, $925 m_e$ ± 8 percent. Fowler and Perkins appear to have another mass group at about $1400 m_e$. There could be a group

[5] L. Voyvodic and E. Pickup, Phys. Rev. **85**, 91 (1952).
[6] See Nuovo cimento Suppl. No. 2, 228 (1954).

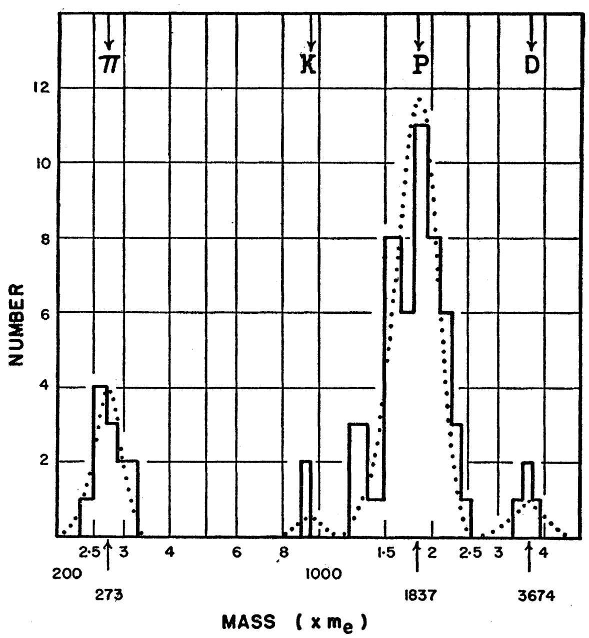

FIG. 4. Histogram showing the mass spectrum calculated from the results in Fig. 3. Mass units (abscissal) for the different groups were taken as $20m_e$ (π); $50m_e$ (K); $150m_e$ (p); $250m_e$ (d). The dotted curves show the normal distribution calculated using the mean experimental standard deviations for each group. The abscissas are plotted on a logarithmic scale for convenience.

with a similar mass ($\sim 1250m_e$) in the present work, but this could also be a statistical fluctuation on the edge of the proton group. It should also be noted that, as in the case of the latest Bristol work,[3,4] the heavy mesons are all of relatively low energies, so far.

3. Measurements Below the Ionization Plateau

Some measurements were also made on particles in the region of minimum ionization. As seen in Fig. 3, there is a well-defined group of pions showing a minimum of ionization at $p\beta \sim 500$ Mev and 8 percent below the plateau. This is in reasonably good agreement with some recent results on the relativistic increase in ionization by Judek and Pickup[7] using artificially produced particles and the same degree of emulsion development and is taken as an indication of the reliability of measurements in this emulsion. It may also be taken to indicate the absence of any fading effects due to events being formed at different times,[7] or perhaps under different conditions of temperature and humidity throughout the balloon flight.

On the high-energy side of the minimum it will be seen that it should be possible to distinguish between the pion, $925m_e$ and proton curves up to $p\beta \simeq 2$ Bev with tracks of lengths suitable for scattering. The present precision of scattering stages is also good enough for this limit. The presence of a group of mesons between $925m_e$ and the proton mass could, of course, lower the limit. Above 2 Bev the heavy meson and proton curves lie so close together that differentiation would be difficult even with very precise measurements, and only a marked change in the depth of the ionization minimum could help here. It may be possible to separate pions from K-mesons and protons up to about 8 Bev.

Referring to Fig. 3 again, it may be noted that there is no definite evidence for any K-mesons about or below the plateau. The two points at $p\beta \sim 3.5$ Bev were put on the graph, although the tracks were rather short, but, in any case, these could be interpreted as due to deuterons. Even allowing for the "loss" of particles of higher $p\beta$ in an emulsion of finite thickness, since longer tracks are needed to give similar statistics as for particles with lower $p\beta$, there does not seem to be a grouping of heavy mesons in the neighborhood of minimum ionization as there is for pions.

4. Nature of Stars Whose Secondary Tracks Were Measured

Defining, for this purpose, the number of shower particles produced in a star, n_s as the number with a normalized blob density $\leqslant 1.5$, six stars were measured with $n_s = 0$, 32 with $n_s = 1-3$ and for the remainder n_s was $\geqslant 4$. Most of the stars were probably in the 1–50-Bev region and there were no high-energy "jets." The star primaries were protons and a few neutrons, α particles and heavier nuclei. The two K-mesons were produced in stars of type $(7+1p)$ and $(13+1\alpha)$. The present sample thus probably included some stars of lower energy than those used in the Bristol work.

5. Secondary Star Production

Seven secondary stars were observed giving an interaction length $= 24 \pm 9$ cm or, considering only tracks with a normalized blob density < 1.6, the interaction length was 21.7 ± 8 cm.

IV. COMMENTS

(1) There is a small peak in the mass spectrum for mass $\sim 925m_e$ and the presence of a peak between this and the proton mass is uncertain from the present work. The observations are being extended using longer track lengths.

(2) Considering the present observations and those of Fowler and Perkins,[3,4] the frequency of heavy mesons, mass $\sim 925m_e$, appears to be about two percent of the number of protons measured. If the particles with mass closer to the proton mass are real, they are surprisingly frequent and, as yet, there is no evidence for such a group from other work. The number of deuterons is about six percent of the number of protons.

(3) As observed in Sec. III.3, the few K-mesons found are of relatively low energies, as in the work of Fowler and Perkins. Thus, although the statistics are poor, there may be a tendency for the K-mesons to be produced preferentially at low energies when compared

[7] B. Judek and E. Pickup (to be published).

with pions. If so, this could indicate a mode of production for heavy mesons different from that for pions. It may be noted, however, that heavy mesons of greater energy have been observed in cloud chamber work, but little is known about the energy spectrum at present. Powell[4] conjectures that the hyperons and heavy mesons may often originate from secondary interactions of pions (produced in nucleon-nucleon collisions) with other nucleons in the same nucleus. Evidence that hyperons and K-mesons are created in the interaction of pions with hydrogen nuclei has been obtained in work with the Brookhaven Cosmotron.[8] Recent work on a very high-energy nuclear shower by Koshiba and Kaplon[9] gives a production ratio of neutral mesons to charged shower particles of 0.50 ± 0.11 indicating little, if any, production of heavy mesons in such an event as opposed to what might be expected from the statistical theories of multiple-meson production. This apparent lack of an abundant production of heavy mesons at high energies could also be in accordance with a secondary mode of production for the heavy mesons.

(4) We are indebted to the office of Naval Research for enabling our emulsions to be exposed on "Skyhook" balloon flights, to Miss Margaret Stott for some scanning of the emulsion used, and to Miss Jacqueline Dazé for the drawings.

[8] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953).

[9] M. Koshiba and M. F. Kaplon, Phys. Rev. **97**, 193 (1955).

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Spin Polarization of the Deuteron*†

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Methods of specifying the state of polarization of a particle of spin 1 are discussed. Selection rules for polarization effects in simple nuclear reactions are derived; in general four parameters are needed to describe the deuteron polarization due to such reactions. Methods of determining these parameters include the use of magnetic deflection. A rough analysis is made of the polarization of deuterons scattered by carbon.

INTRODUCTION

Recently many successful experiments have been done with polarized beams of protons and neutrons. The present paper deals with the theoretical possibilities of extending such experiments to spin 1 particles, in particular, the deuteron. Considerable care must be taken in defining the state of polarization of a spin 1 particle, and this is discussed in Sec. 1. Sections 2 and 3 present general theorems applicable to experiments involving polarized spin 1 particles, whereas Sec. 4 presents a rough analysis of polarization effects for the special case of scattering of deuterons by a nucleus with zero spin and zero isotopic spin, such as carbon. The first three sections apply to any particle of spin 1 and may be of interest in considering the possibility that some of the heavy mesons have spin 1.

1. POLARIZATION STATES OF THE DEUTERON

The spin state of a particle (or nucleus) taking part in a nuclear reaction in general must be described as a statistical mixture of the pure spin states in which the particle may be found. If the description consists of weighting equally all members of any basis set of mutually orthogonal spin functions, the mixture is spatially isotropic and describes *unpolarized particles*. Any different distribution will describe anisotropic states and refers to *polarized particles*.[1] States which may be described by a single wave function will be called *completely polarized*. In the case of particles of spin $\frac{1}{2}$ the most general spin state may be described as a mixture of a completely polarized state with statistical weight P and an unpolarized state with weight $(1-P)$, where P is the percentage polarization. No such simple picture exists for particles of spin greater than $\frac{1}{2}$.

The von Neumann density matrix ρ is a convenient starting point in discussing polarization.[2] It may be expressed as a linear combination of independent Hermitian matrices, whose number equals the square of

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† Aided in part by the Office of Naval Research. A brief report of some of this work was given in Phys. Rev. **90**, 365 (1953).
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[1] The term polarization as we use it includes both "polarization" and "alignment" in the sense of Bleaney: B. Bleaney, Proc. Phys. Soc. (London) **A64**, 315 (1951); Simon, Rose, and Jauch, Phys. Rev. **84**, 1155 (1951). *Alignment* may be considered as special cases of the *tensor* type of polarization discussed later, whereas *polarization* corresponds to the *vector* type.

[2] L. Wolfenstein and J. Ashkin, Phys. Rev. **85**, 947 (1952); R. H. Dalitz, Proc. Phys. Soc. (London) **A65**, 175 (1952). Our methods and notation generally follow those of the former paper.