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Energy Spectrum of π Mesons Produced by Interaction of Cosmic Radiation with Emulsion Nuclei*

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An analysis of 958 π mesons ejected from stars which terminate their range in G5 emulsion exposed in the stratosphere shows a predominance of negative mesons. The average ratio from all emulsion interactions over a pion kinetic energy $\lesssim 45$ Mev is $\pi^-/\pi^+=5.17\pm0.41$. Further study shows that this ratio varies with the charge of the target nuclei and is strongly dependent on the kinetic energy of the emitted mesons. By classifying the stars on the basis of the sum of the charges on the evaporation tracks a large fraction of the stars can be attributed to the disintegration of heavy (Ag—Br—I) or light (C—N—O) target nuclei. On this basis 537 pions originate from heavy nuclei and 297 from light nuclei. The residual group of 124 mesons arise from peripheral collisions with heavy or light target nuclei, interactions with hydrogen, photomeson production, and fundamental particle decay processes. The variation of the charge ratio with pion kinetic energy is evaluated for both the light and heavy emulsion nuclei and compared with the yield from targets of similar charge employed in cyclotron studies. The energy spectrum of the mesons produced by cosmic ray interactions on emulsion nuclei from 1.5 to 33 Mev shows good agreement with early Bristol measurements of shower particles originating from stars and with more recent studies of ejected mesons by the Russian group. The form of the differential energy spectrum appears to be largely independent of geomagnetic latitude and altitude of the exposure when the meson yield is expressed in units of particles per shower star per Mev.

I. INTRODUCTION

In an earlier publication[1] an analysis of the pion charge ratio was presented on the basis of the observation of 145 σ stars and 26 $\pi-\mu$ events ejected from stars in stratosphere-exposed emulsion. The method of scanning for meson terminations and following back the track to its point of origin appeared to be an efficient method for the detection of heavier fundamental particles decaying with pion emission. This factor and the availability of thicker emulsions, favoring the recording of high-energy mesons, made a continuation of this program desirable both as a means of securing additional information on heavy mesons and to provide adequate statistics for the study of the variation of the charged pion ratio as a function of their kinetic energy and the nature of the target nuclei. Including the events described in the first report a total of 759 σ stars and 199 $\pi-\mu$ events have been observed in the systematic study of 265.7 cc of Ilford G5 emulsion exposed in the stratosphere. In the course of this work a τ meson,[2] a pion-pair probably representing an alternate mode of decay of the θ^0-meson[3] and the mesonic decay of an excited triton carrying a bound Λ^0 particle[4] have been described.

The object of the present report is to evaluate the charged pion ratio as a function of the meson kinetic energy, a phenomenon shown by Mei and Pickup[5] to be strongly energy dependent when all emulsion target nuclei are considered. The complex chemical composition of the emulsion does not permit the assignment of individual nuclear evaporations to a specific target nucleus. Nevertheless, from a study of the total charge on the evaporation tracks associated with the stars it is possible to group the disruptions into heavy (Ag—Br—I) and light (C—N—O) target nuclei groups. This classification and the large number of available events permits a more detailed study of the charged pion production ratio. By correcting geometrically for mesons produced in the emulsion but which failed to terminate their range in the sensitive layers the present data permit the evaluation of the differential energy spectra of the charged pions in the low-energy region where comparable cyclotron data are not available. On the other hand, the complexity of the cosmic radiation producing the disintegrations and the wide angular spread of the mesons limits the utility of the data to only a qualitative understanding of the Coulomb barrier effect on low-energy meson production processes.[6]

II. EXPERIMENTAL

The bulk of the new observations were secured by microscopic examination of G5 plates and unsupported pellicles of 1000- to 1500-microns thickness. An additional smaller volume of emulsion was prepared from Ilford G5 gel in the form of cylindrical castings[7] up to 3280 microns thick. A Leitz 22× oil immersion objective with a working distance of 2300 microns was employed in locating the meson terminations and the tracks were followed back to their points of origin with the aid of a Koristka 55× immersion objective. Re-examination of one 1500-micron thick pellicle with a 40× fluorite

* A preliminary account of this work was presented at the American Physical Society Meeting in Washington, April, 1954 [H. Yagoda, Phys. Rev. 95, 648(A) (1954)].
[1] H. Yagoda, Phys. Rev. 85, 891–900 (1952).
[2] H. Yagoda, Phys. Rev. 95, 648 (1954).
[3] H. Yagoda, Phys. Rev. 98, 103 (1955).
[4] H. Yagoda, Phys. Rev. 98, 153 (1955).
[5] J. Y. Mei and E. Pickup, Can. J. Phys. 30, 430 (1952).
[6] T. Kinoshita, Phys. Rev. 94, 1331 (1954).
[7] H. Yagoda, Can. J. Phys. 34, 122–146 (1956).

TABLE I. Characteristics of stratosphere exposures.

Flight	Date	Atmos depth (g cm^{-2})	λ	Duration (hr)[a]	Emulsion thickness (microns)	Emulsion volume (cc)	No. of σ stars	No. of $\pi-\mu$
	1949–1950[b]		55°N				145	26
449	May, 1951	32 ±2	55°N	11.4	1580	8.72	32	8
532	July, 1951	11 ±1	55°N	8.2	1000	30.0	56	14
916	October, 1952	10 ±1	55°N	4.9	904	3.09	8	3
*W*141	June, 1953	16 ±0.5	55°N	9.0	1500	60.0	330	103
732	March, 1952	9 ±2	41°N	7.6	1500	29.9	75	24
738	May, 1952	15 ±1	41°N	7.9	3280	8.65	17	8
740	May, 1952	13 ±1	41°N	6.4	1000	30.6	75	10
879	August, 1952	13.5±1	41°N	9.5	1000	11.3	21	3

[a] The duration of the exposure is taken as the time spent by the balloon above 60 000-ft elevation.
[b] These flights are described in an earlier publication (see reference 1).

objective indicates that the detection efficiency with the lower power lens is better than 90% for $\pi-\mu$ decays and σ stars with ≥ 1 prong. Although a number of ejected mesons were observed that exhibited only low-energy electrons at the decay point, this category of negative pions was not scanned for systematically owing to their low detection efficiency and the difficulty of differentiating them from $\mu^{\pm}$ mesons. The total number of π^- mesons was evaluated from the σ-star count utilizing a factor of $\pi^-=1.35\sigma$ evaluated by Dudziak[8] from a study of cyclotron-produced mesons. The range-energy tables of Fay, Gottstein, and Hain[9] were employed in estimating the kinetic energy of the ejected mesons from their range in the emulsion.

The characteristics of the stratosphere balloon flights are summarized in Table I. In most flights the balloons achieved a plateau exceeding 95 000-ft elevation. The parcels of emulsion were suspended on the load-line enclosed in air-tight wooden boxes having an equivalent absorber of 0.5 g cm^{-2}. About $\frac{1}{4}$ of the events were recorded in emulsions flown at Pyote, Texas, geomagnetic latitude 41°N, the remainder were observed in preparations exposed above Minneapolis, Minnesota (55°N). The unusually thick emulsion layers employed in this study were developed[10,11] by the use of either an ionic environment hot stage or by a series of isothermal (5°C) amidol developing solutions of successively increasing *p*H.

III. RATIO OF NEGATIVE TO POSITIVE MESONS EJECTED FROM ALL EMULSION INTERACTIONS

The over-all pion charge ratio as a function of meson kinetic energy is summarized in Fig. 1. At the lowest kinetic energy (0–4 Mev) the ratio is about 14 and diminishes to roughly 1.5 in the region of 30 to 40 Mev. This behavior is exhibited by the observations in the Texas as well as the Minnesota flights. The magnitude of the ratio is therefore largely independent of the kinetic energy of the incident radiation over a range of 300 to about 2000 Mev per nucleon, represented by the geomagnetic cutoffs for protons at the two stations. Within the limits of statistical error the present observations are in good agreement with the results of a similar study by Mei and Pickup[5] based on 70 events observed in 600 to 1200 micron thick plates exposed at Minnesota at an elevation of 85 000 ft.

The integral value of the π^-/π^+ ratio for kinetic energies ≤ 40 Mev for all emulsion interactions is 5.17 ± 0.41. This is comparable with an estimate of 5.0 ± 1.9 reported by Bonetti,[12] but larger than the value of 2.9 ± 2.5 observed by Mei and Pickup.[5] That negative mesons predominate at the low kinetic energies under consideration is further demonstrated by our observations on multiple slow-meson production in cosmic-ray stars. In our earlier paper[1] two events of this character have been described, one with two π^- mesons and the other with three π^- mesons. In the current exposures 15 additional events of this character have been observed. The pion charge ejection ratio for this particular group of stars is 4.8 ± 2.2. Of the 17 events, in only one star were both slow mesons of positive sign of charge. A further description of this category of multiple meson ejects will be described elsewhere together with additional observations recorded in emulsions exposed on mountain tops and in rockets.

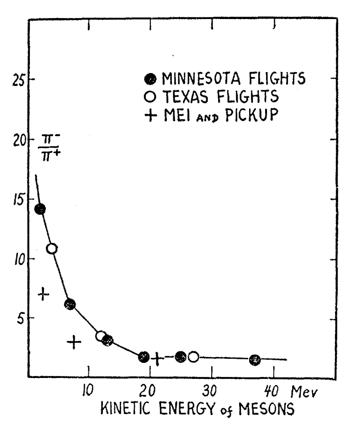

FIG. 1. Variation of pion charge ratio for all emulsion interactions as a function of meson kinetic energy.

[8] W. F. Dudziak, Phys. Rev. **95**, 866 (1954).
[9] Fay, Gottstein, and Hain, Suppl. Nuovo cimento **2**, 234 (1954).
[10] H. Yagoda, Rev. Sci. Instr. **26**, 263 (1955).
[11] H. Yagoda, Science et ind. phot. **29**, 121–125 (1958).
[12] Bonetti, Levi Setti, Panetti, and Tomasini, Proc. Roy. Soc. (London) **A221**, 318 (1954).

IV. PION CHARGE RATIO FROM HEAVY AND LIGHT EMULSION NUCLEI

The number and charges represented by the black and gray evaporation tracks N_h serves as a means for the identification of the disrupted emulsion nucleus. When $N_h \gtrless 8$ the star can be attributed to a heavy silver or bromine nucleus. A sharper discrimination is effected by using as a criterion that the sum of the charges on the evaporation tracks should be $Z>8$. In thick emulsions a large proportion of these tracks terminate in the recording medium thereby facilitating the estimation of the charge of the particle by means of gap-counts, delta-ray density or thindown of heavily charged fragments. When the summation of the charges is $Z \lessgtr 8$ and $N_h \gtrless 3$ the star is attributed to a light nucleus (C—N—O). After this crystallization of the data a residue of complex composition remains whose nature will be discussed in Sec. VI. In terms of this classification the data sort out into 537 pions created in heavy nuclei, 297 pions from light nuclei, and a residual group of 124 mesons (*R*-group).

The variation of the pion charge ratio for the heavy and light groups of emulsion target nuclei is shown in Fig. 2. The statistical uncertainty associated with this ratio is estimated from the number of σ stars x and the number of $\pi-\mu$ events y observed within the energy interval from the relationship:

$$\text{Statistical error} = \pm(y^2P_x{}^2+x^2P_y{}^2)^{\frac{1}{2}}/y^2,$$

where $P_x=\pm x^{\frac{1}{2}}$ and $P_y=\pm y^{\frac{1}{2}}$. The ratios were evaluated on the assumption that the average range of the particles in a fixed energy interval is approximately the same for the members of opposite charge and hence the magnitude is independent of geometric escape correc-

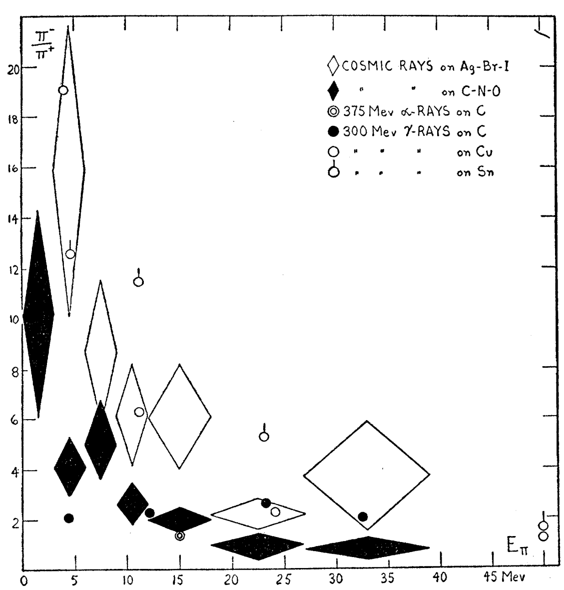

FIG. 2. Variation of pion charge ratio with meson kinetic energy for heavy and light groups of target nuclei.

TABLE II. Classification of mesons ejected from *R*-target nuclei.

Number of nucleon tracks[a]	Number of mesons σ stars	$\pi-\mu$	π^-/π^+
2-tracks	39	16	3.3
1-track	14	11	2.5
V-events	8	1	
0-tracks	15	10	2.0
p-p collisions	3	1	
Meson recoils	0	2	
Tau-decay	1	1	
Pion-pairs	1	1	
Total	81	43	2.6±0.5

[a] In this classification the slow meson is not counted as a nucleon track.

tions. It is evident from Fig. 2 that the charged pion ratio diminishes rapidly with the kinetic energy of the mesons for both the heavy and light groups of target nuclei, and that negatively charged mesons predominate in the disruption of silver and bromine nuclei.

For comparative purposes Fig. 2 also shows the pion charge ratio produced at 120° to a beam of 300-Mev γ rays interacting with copper, tin and carbon targets observed by Voss, Palfrey, and Haxby.[13] The copper and tin targets, which have charges similar to that of bromine and silver, yield pion charge ratios exhibiting a similar meson energy dependence as that produced by cosmic radiation on the heavy emulsion nuclei. Their results from the bombardment of a carbon target, however, indicate a roughly constant yield of positive and negative mesons in contrast with the present observations on the light emulsion nuclei which show a strong energy dependence for this ratio. Wilson and Barkas[14] report a π^-/π^+ ratio of 1.4 for mesons of 11- to 21-Mev kinetic energy produced in a carbon target bombarded by 375-Mev alpha particles, a value consistent with both the cosmic and γ-ray observations.

V. DIFFERENTIAL ENERGY SPECTRA OF COSMIC RAY MESONS

The ranges of the mesons ejected from stars provides an independent method for evaluating the differential energy spectrum of pion production. In order to compare these observations with estimates of the spectrum proposed by the Bristol group[15,16] and Dilworth and Goldsack[17] from their studies of shower particles, all ejected mesons were included except for the last six categories described in Table II in which the mesons obviously originated in processes other than star formation.

To evaluate absolute production rates the number of mesons must be corrected for particles produced in the

[13] Voss, Palfrey, and Haxby, Phys. Rev. **93**, 918 (1954).
[14] H. W. Wilson and W. H. Barkas, Phys. Rev. **89**, 758 (1953).
[15] Camerini, Lock, and Perkins, *Progress in Cosmic-Ray Physics* (Interscience Publishers, Inc., New York, 1952), Vol. 1, p. 24.
[16] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).
[17] C. C. Dilworth and S. H. Goldsack, Nuovo cimento **10**, 926 (1953).

TABLE III. Characteristics of mountain top exposures.

Locality	Exposure initiated	Duration (days)	Emulsion thickness (microns)	Emulsion volume (cc)	No. of σ stars	No. of $\pi-\mu$
Climax, Colorado; $\lambda=48°$N	November, 1950	9	1040	4.58	4	0
	January, 1951	35	1000	9.52	19	1
	March, 1951	25	1250	8.19	6	1
	June, 1951	33	1270	8.30	8	2
	November, 1952	16	1000	19.46	9	0
Mt. Evans, Colorado; $\lambda=48°$N	July, 1951	33	1000	7.49	8	2
	September, 1951	25	1000	11.60	17	1
Chacaltaya, Bolivia; $\lambda=5°$S	December, 1951	40	1500	28.0	16	4

sensitive volume but which failed to terminate their range as a result of escape from the faces or edges of the emulsion. Neglecting edge effects, the probability P that a particle created in an emulsion of thickness t should terminate its range R therein is $P_1=1-R/2t$ when $R<t$, and $P_2=t/2R$ when $R>t$.

In 1500-micron thick emulsions of 58-cm^2 area the correction for escape through the edges becomes appreciable when $R\gtrsim 5$ mm. For long tracks the probability P_3 of the potential trajectory being confined in the sensitive volume $(a\times b\times t)$ when $t\leq R<b$, where b is the smaller side of the emulsion rectangle and $k=t/R$ is expressed by

$$P_3=k/2-[\tfrac{1}{2}-(\cos^{-1}k)/\pi+(k/\pi)(1-k^2)^{\frac{1}{2}}]\times(R/a+R/b)+(2/\pi)[1-(1-k^2)^{\frac{3}{2}}]\times(R^2/3at+R^2/3bt+R^2/6ab)-(Rt/4\pi ab)(2-k^2).$$

For a square pellicle of edge length s, and $R<s$ this simplifies to

$$P_4=k/2-[\tfrac{1}{2}-(\cos^{-1}k)/\pi+(k/\pi)(1-k^2)^{\frac{1}{2}}]\times(2R/s)+(2/\pi)[1-(1-k^2)^{\frac{3}{2}}]\times(2R^2/3st+R^2/6s^2)-(Rt/4\pi s^2)(2-k^2).$$

These geometric escape corrections were derived on the assumption that the meson tracks are perfectly linear and free from large-angle scatterings. During microscopy it can be noted that the large-angle scattering plays a significant role in confining the trajectory within the recording volume. In several instances on approaching an emulsion interface the meson suffered a large-angle scattering which reflected the particle into the detector thereby increasing its potential linear length. It can be assumed, however, that such fortuitous cases are compensated by an equal number of scatterings in an opposite direction which cause the premature escape of the particle.

Mesons will also escape detection which either decay in flight, or escape recognition as a result of nuclear interactions before coming to rest. Calculation of the time interval after which π mesons in motion will have come to rest in their own frame of reference indicate that even for the fastest group of particles in this study only 0.7% will decay in flight. Likewise, using a collision mean free path of 29 cm, as observed by Bernardini[18] in a study of the interaction of 30- to 50-Mev mesons in G5 emulsion, shows that assuming an exponential attenuation, the correction for collision loss is less than 1% at $E\lesssim 10$ Mev. At higher energies the collision loss reaches 5% at 29 Mev and about 10% at 42 Mev. In view of the large statistical error of our observations in the high-energy region, these small collision loss corrections have not been applied.

The geometric escape corrections have been applied to the data secured on stratosphere flights W141, 732 and 740 and for comparative purposes to a series of plates exposed at Climax, Colorado at 3350 meters elevation and Mt. Evans, Colorado (4300 meters) described in Table III. The absolute integral meson production rates ($\pi^{\pm}$ cc^{-1} day^{-1}) for these exposures for the entire kinetic energy range is summarized in Table IV. This comparison indicates a factor of 2 variation in slow-meson production between flights at geomagnetic latitudes 55°N and 41°N. The meson yield on the Colorado mountain tops is about 200-fold less than in the stratosphere at approximately the same geomagnetic latitude. In general, the slow-meson production process shows a similar behavior to the star producing nucleonic component with respect to varia-

TABLE IV. Integral meson production rates.

Exposure	W141	732	740	Colorado
Altitude, km	28.6	32.0	30.0	3.4–4.3
Energy interval, Mev	0–45	0–39	0–27	0–27
No. of $\pi^{\pm}$ ejects	409	93	80	74
Meson production[a] (cc^{-1} day^{-1})	149.9	70.2	60.2	0.45
Total star count, $N_h\gtrsim 3$ prongs (cc^{-1} day^{-1})	1580	950	930	15.7
Shower star estimate[b] $n_s\gtrsim 1$, (cc^{-1} day^{-1})	435	262	256	4.44
Meson production (star^{-1} Mev^{-1})	0.0077 ±0.0004	0.0069 ±0.0007	0.0087 ±0.0010	0.0068 ±0.0008

[a] Corrected for meson escape.
[b] The number of shower stars was deduced from the total star counts using a factor of 0.275 based on the Bristol star prong spectrum (see reference 16) for the stratosphere flights, and a factor of 0.155 observed by Dilworth and Goldsack (see reference 17) at 2800 meters for our Colorado mountain top exposures.

[18] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. 80, 924 (1950).

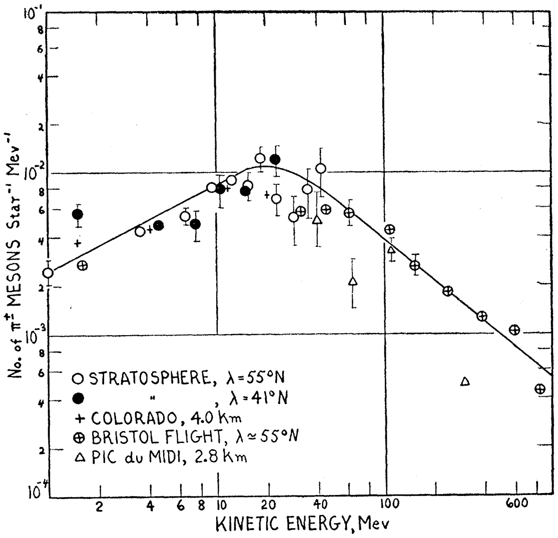

FIG. 3. Energy distribution of combined negative and positive mesons originating from cosmic-ray stars produced in emulsions exposed in the stratosphere and on mountain tops.

tions with geomagnetic latitude and depth in the atmosphere. This is further indicated by the constancy of the meson yield when expressed in units of pions per shower star ($n_s \gtrless 1$) per Mev which averages 0.0075 $\pm$0.0007 for the four independent exposures.

The variation of meson intensity with pion kinetic energy is shown in Fig. 3. The points are differentiated according to the geomagnetic latitude and altitude of the exposures. The points for $\lambda=41°$N represent an average for flights 732 and 740. The absolute meson production rate increases as $E^{0.49\pm0.05}$ from $1<E<15$ Mev kinetic energy and appears to reach a maximum at about 20 Mev. Although our statistics become meager at $E \gtrless 23$ Mev the data are in fair agreement with the measurements of Camerini, Lock, and Perkins[15] in the region of 32 to 46 Mev. In their work the identity and kinetic energy of the particles was established by means of grain density and scattering studies on shower particles originating from stars. The point at 40 Mev deduced by Dilworth and Goldsack[17] by measurements of the magnetic deflection of shower particles recorded in emulsions exposed on the Pic du Midi is also consistent with the spectrum resulting from the present ejected meson study. The Bristol point[16] at 1.6 Mev, also secured by a study of ejected mesons, is in good agreement with our observations at 1.5 Mev.

More recently, Varfolomeev and co-workers[19] have studied the energy spectra of π mesons produced in P-type emulsion of Russian manufacture exposed to cosmic radiation. They employed two cylindrical blocks of this new emulsion,[20] which has a stopping power similar to that of Ilford $G5$, having diameters of 10 cm, one composed of 56 layers 330 microns thick ($t=18.5$ mm) and a second unit made up of 60 layers of 450-microns thickness ($t=27.0$). This improved geometry permitted an extension of the pion energy spectra to 70 Mev, on the basis of the ranges of 195 π^+ and 328 π^- mesons ejected from stars. Their results on the differential energy spectra are summarized in Fig. 4. Our results from Flight $W141$, based on a comparable number of ejected mesons, are exhibited as diamonds normalized to their data at 0–10 Mev. This comparison shows a fair agreement between the two sets of observations, particularly in the low-energy region of $E \lesssim 20$ Mev where the geometric escape corrections and the statistical uncertainties are small. Our data indicate the presence of a sharp maximum at 10–20 Mev in the π^- production spectrum, consistent with a more diffuse maximum at 10–30 Mev reported by the Russian investigators. The statistical spread of the π^+-meson data is too large to permit an estimate of the position of the maximum production rate. However, both sets of data suggest that the maximum is displaced towards a higher energy region than that exhibited by the negative mesons. A relative displacement of this character can be anticipated on the basis of the electrostatic Coulomb forces between the $\pi^{\pm}$ mesons and the positively charged heavy nuclei in which they are produced.

VI. MESONS FROM RESIDUAL TARGET NUCLEI

In the emulsions exposed in the stratosphere 124 ejected mesons could not be assigned to heavy or light target nuclei on the basis of charge summation and prong classification. These events are further analyzed in Table II according to the sign of charge of the meson and the number of associated black and gray tracks. The π^-/π^+ ratio for this group is 2.6$\pm$0.5 which is markedly smaller than the pion charge ratio associated with the multipronged stars. About 50% of the mesons classified in the R group are ejected from 2-prong stars.

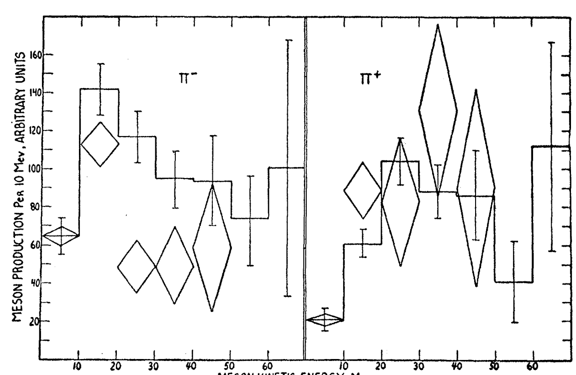

FIG. 4. Differential energy spectra for negative and positive π mesons. The solid line histograms represent the spectra of the Russian group. The diamonds represent our data from stratosphere flight $W141$. Both experiments are normalized to a point at 0–10 Mev kinetic energy.

[19] Varfolomeev, Gerasimova, Zamchalova, Podgoretskii, and Scherbakova, J. Exptl. Theoret. Phys. (U.S.S.R.) **30**, 1164 (1956) [translation: Soviet Phys. JETP **3**, 986–988 (1957)].

[20] Denisenko, Ivanova, Novikova, Perfilov, Prokoffieva, and Shamov, Phys. Rev. **109**, 1779–1784 (1958).

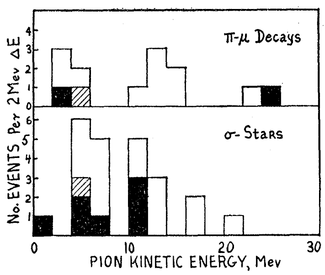

FIG. 5. Histogram showing the energy distribution of positive and negative mesons probably originating from photomeson production processes. The black squares represent events recorded on mountain top exposures, the shaded ones on rocket flights, and the white blocks stratosphere balloon flights.

These and a large fraction of the 1-prong events probably originate as a result of peripheral collisions with emulsion nuclei. Only 4 events were observed which might originate as a result of central collisions with hydrogen nuclei. Of these 3 were slow negative π mesons emitted at wide angles to beams of singly charged minimum ionization tracks without any associated black or gray prongs.

Two events designated "meson-recoils" were observed in which the positive π meson originated at a large angle to the path of a single particle traversing the emulsion. In both cases there was no measurable deviation in the direction of the incident particle or change of ionization after the act of meson production. In one example a 9.0-Mev π^+ particle was produced along the path of a singly charged particle at minimum ionization. The second example consists of an 11-Mev π^+ meson produced along the trajectory of a relativistic alpha particle. These events appear to be similar to an occurrence described by Lord and Schein[21] in which a σ meson of 2.2-Mev kinetic energy is produced along the path of a heavy primary nucleus which they attribute to meson production in a pure nucleon-nucleon interaction.

In retracing the meson tracks to their points of origin a number were observed to originate, well embedded in the emulsion, without any other associated tracks. Occasionally the meson track would appear to start from a heavy grain which might be the track of a recoiling heavy fragment. These particles are probably produced by the interaction of γ rays or neutrons with hydrogen or peripheral neutrons. The energy distribution of 25 zero-prong mesons observed in the stratosphere exposures together with 11 additional events recorded in the mountain top and rocket exposures is shown in Fig. 5. The π^-/π^+ observational ratio for this category of meson production is about 2.

A total of 44 mesons originated in simple interactions in which only one other ionizing particle, besides the meson track, was associated. A part of this group may represent peripheral collisions of nonionizing radiation with emulsion nuclei. The pion charge ratio for these events is 2.5 which suggests the possible occurrence of other production mechanisms. In nine examples the accompanying nucleon track also terminated in the emulsion and could be identified as being produced by a singly charged particle. On the possibility of these representing the decay of Λ^0 particles, the Q-values for 2-body decay were estimated from the momenta of the particles, assuming the associated track to be that of a proton, and the space angle ϕ between the diverging meson-proton tracks. As shown in Table V only event No. 8 gave a Q-value of 35.7 Mev in good agreement with the accepted value for Λ^0 decay of 37.0 Mev. It is difficult to evaluate the significance of the low Q-values of the remaining events. They probably represent peripheral nuclear collisions where the range of the recoil nucleus is too small for resolution. Alternatively, five of the events have a Q-value of 20.8 ± 2.6 Mev suggestive of a grouping which might represent an alternate mode of decay or excited state of the Λ^0 particle. Similar examples where both particles terminate in the emulsion yielding anomalous Q-values of about 20 Mev have been reported by Amaldi,[22] Peters[23] and Friedlander.[24] It is well to note that in restricting the analysis to events in which both tracks terminate their range in comparatively thin media, the data are strongly biased towards the concentration of examples with anomalously small Q-values.

Of some interest is the occurrence a of small group of similar V-events, described in Table V, in which the

TABLE V. Q-values of V-events in which both the meson and the proton terminate their range in emulsion.

Event	Range in microns Proton	Range in microns Meson	Space angle	Q-value (Mev)
	Negative mesons			
V-1	536	1850	74°	7.29
V-2	460	670	130°	8.43
V-3	368	6660	112°	18.10
V-4	1900	4470	137°	24.18
V-5	5	5120	120°	14.62
V-6	89	8500	134°	22.60
V-7	2500	7500	98°	22.39
V-8	3000	10 800	128°	35.7
V-9	6900	1870	102°	16.2
V-10	3.6	6130	180°	16.83
Amaldi[a]	900	1180	120°	20.4
Peters[b]	6243	768	160°	21 ± 0.5
Friedlander[c]	3990	10 910	64°	18.3
	Positive mesons			
V-11	276	2600	134°	14.20
V-12	275	5100	120°	18.04
V-13	25	1120	120°	7.03
V-14	17 100	6900	150°	47.94

[a] See reference 22.
[b] See reference 23.
[c] See reference 24.

[21] J. H. Lord and M. Schein, Science **109**, 114 (1949).

[22] Amaldi, Castognoli, Cortini, and Manfredini, Nuovo cimento **10**, 1351 (1953).

[23] B. Peters, Congrés International sur le Rayonnement Cosmique, Bagnères de Bigorre, France, 1953 (unpublished), p. 174 and 258.

[24] Friedlander, Keefe, Menon, and Merlin, Phil. Mag. **45**, 533 (1954).

meson is of positive charge, as established by the $\pi-\mu$ decay process, and which likewise yield anomalous Q-values if interpreted as arising from a 2-body decay scheme. For three of these occurrences the Q-values of 7 to 14 Mev are similar to that of an event observed in a cloud chamber by Cowan[25] with $Q=11.7\pm4$ Mev. In the 4th example, owing to the long range of the nucleon track accompanying the π^+ meson it was possible to establish that the particle was of protonic mass by constant sagitta-range scattering measurements. At the time of observation, the event suggested the possible existence of an anti Λ^0 particle decaying: $\bar{\Lambda}^0\rightarrow\bar{p}+\pi^+ +Q=47.9$ Mev. The supposed antiproton track came to rest without any evidence of decay or interaction at the terminus. At the time the event was detected it could be rationalized by assuming a γ-ray annihilation process. In view of present day knowledge of the strong interaction of antiprotons coming to rest in the emulsion, this mechanism does not seem a likely explanation of the (p,π^+) V-events. If these rare oddities originate from nuclear interactions, it also implies that the (p,π^-) V-tracks giving low Q-values may well be of similar origin.†

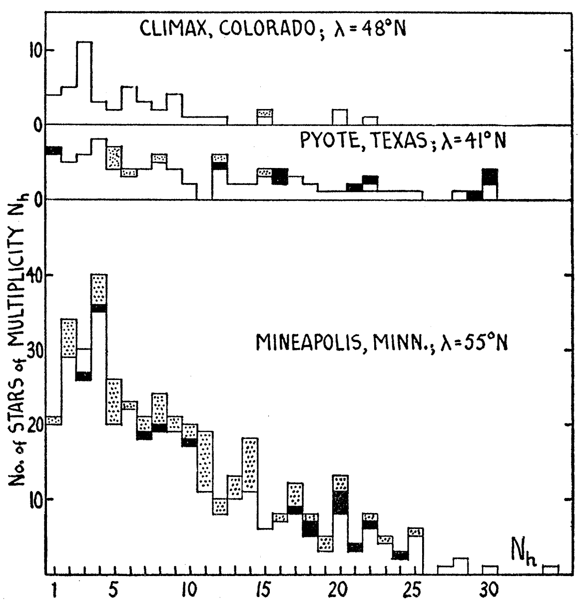

FIG. 6. Histograms showing the distribution of black and gray prongs N_h from stars associated with slow mesons. The shaded areas indicate events initiated by singly charged relativistic particles, the black blocks represent stars produced by multiply charged primaries of $Z\geqslant2$.

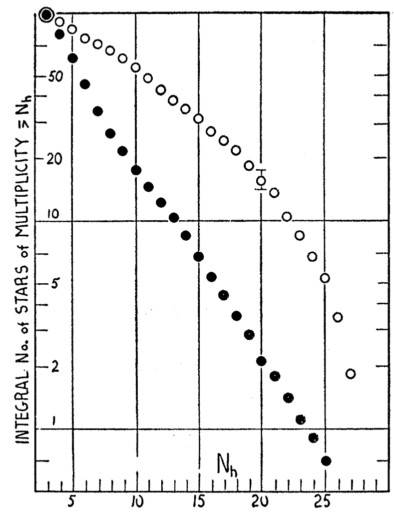

FIG. 7. Comparison of integral star prong distribution from ejected meson study at $\lambda=55°$N (upper curve) with that from a normal distribution (Bristol data) in which all stars of $N_h\geqslant3$ are tallied. Since the slow terminating mesons fall in the category of black or gray prongs our N_h values of Fig. 6 must be augmented by one prong for normalization purposes with the Bristol star spectrum.

VII. THE INCIDENT STAR-PRODUCING RADIATION

The star size distributions, classified according to the number of black and gray evaporation prongs N_h, are compared in Fig. 6 for several levels of exposure in the atmosphere. The distributions at geomagnetic latitudes 41° and 55°N are similar, suggesting that the disruptions were initiated chiefly by secondary rather than primary radiation, and on both exposures about 17% of the stars are initiated by charged particles. This estimate is to be regarded as a lower limit, as at high elevations radiation reaches the emulsions at large zenith angles and such fast charged particles may be identified as emergent shower particles unless the event is accompanied by a pronounced narrow-angle shower. At mountain top elevations the stars appear to be produced largely by uncharged particles. In general, the data suggest that in exposures near the top of the atmosphere about 80% of the stars associated with slow mesons are initiated by nonionizing radiation. Since it is well established[26] that the peak of the γ-ray production occurs at 75 Mev, an energy inadequate for meson production, in most all instances the events must be attributed to neutrons.

The star size distributions also suggest a pronounced preponderance of large stars. The deviation of the integral N_h distribution from a normal star distribution at stratosphere elevations, shown in Fig. 7, indicates

[25] E. W. Cowan, Phys. Rev. 94, 161 (1954).

† *Note added in proof.*—Since the preparation of this manuscript G. M. Frye, Jr. [Phys. Rev. Letters 1, 14 (1958)] has observed an example of an antiproton annihilation event in which only neutral pions are produced. This event was detected by the presence of an electron pair at the rest point of the antiproton, attributed to the alternate minor mode of decay of the neutral pion $\pi^0\rightarrow e^++e^-+\gamma$. Since this phenomenological mode of decay occurs very infrequently (1.2% of all π^0 decays) it suggests that the annihilation of antiprotons without the production of charged particles may be an appreciable process. Thus the possibility still exists that event Y-14 of Table V may represent the decay of an antilambda particle. However, D. J. Prowse and M. Baldo-Ceolin [Phys. Rev. Letters 1, 179 (1958)] have presented evidence for the existence of an antilambda hyperon decaying $\overline{\Lambda^0}\rightarrow p^-+\pi^+$ for which they estimate a Q value of $35_{-0.9}^{+2.6}$ Mev in good agreement with that of the normal Λ^0 particle. The Q value of event Y-14 is about 10 Mev too high to be reconcilable with this process.

[26] Carlson, Hooper, and King, Phil. Mag. 41, 701 (1950).

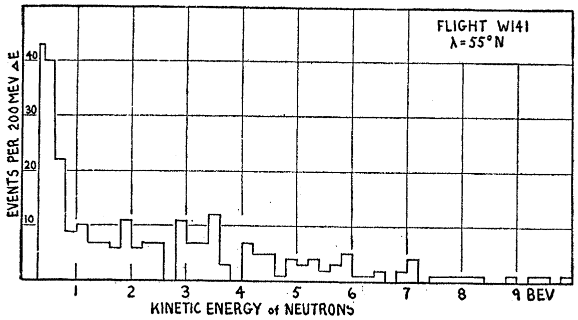

FIG. 8. Differential energy spectrum of neutral radiation producing stars of $N_h > 3$ accompanied by an ejected meson.

that for $N_h > 10$ large stars are concentrated threefold by the slow-meson scanning mechanism. The present study therefore provides added information on the relative abundance of high-energy neutrons in the upper atmosphere. The kinetic energy of the particles initiating this special group of disruptions can be estimated from the following considerations:

(a) For stars of $N_h > 3$ constituted exclusively of black and gray tracks, $E_a = 37N_h + 4N_h^2 + (E_\pi + 140)$ Mev. This empirical relationship[27] allows for the kinetic energy of the undetectable secondary neutrons on the assumption that their energy is 1.25 that of the proton prongs. The additive term $(E_\pi + 140)$ represents the total energy of the associated slow meson.

(b) In disruptions accompanied by shower particles of $N_s > 1$, the energy of the incident particle can be approximated, as shown by Roederer,[28] from $E_b = 1500N_s + 155N_h - 100 + (E_\pi + 140)$ Mev in stars where $N_s < 4$. When $N_s > 2$ the energy contributed by the slow meson is negligibly small and $E_b \approx 150(10N_s + N_h)$ Mev.

The resultant neutron energy distribution (Fig. 8) indicates that about 40% of the disruptions are initiated by particles of 300- to 800-Mev kinetic energy and that the spectrum extends up to 10 Bev. Owing to the strong bias introduced in the selection of the stars by the stopping meson criterion, the spectrum should be viewed chiefly as characteristic of the neutral radiation producing this particular category of events, rather than as being entirely representative of the over-all neutron energy distribution in the upper atmosphere. With this reservation, the integral neutron energy spectrum shown in Fig. 9 indicates that for total energies $E_t < 4$ Bev the distribution follows a power law $N(>E_t) = kE_t^{-\gamma}$ with $\gamma = 1.0 \pm 0.15$. The neutron energy distribution at 16 g cm^{-2} of air appears to be similar to that of the primary protons at the top of the atmosphere which varies as $E_t^{-1.15}$ as deduced from the latitude effect on the primary proton flux.[29] The frequency of neutron-initiated stars, when corrected for meson escape, provides an estimate of the omnidirectional neutron flux of 1400 (sec m^2 sterad)$^{-1}$ when one employs a geometric collision cross section for all emulsion nuclei of charge $Z > 1$ capable of forming stars with $N_h > 3$.

The data on the variation of slow-meson production with altitude (Table IV) permit the evaluation of the range in air of the radiation responsible for the special category of stars under consideration. Using our balloon and mountain top observations from geomagnetic latitudes $>48°$N and assuming an exponential collision process yields a mean free path for the high-energy nucleonic component $L_c \simeq 110$ g cm^{-2}. This is in good agreement with an analysis of the upper limit for $L_c = 110$ g cm^{-2} of air deduced by Rossi[30] from diverse cosmic-ray measurements of the nucleonic component in the atmosphere.

VIII. DISCUSSION OF RESULTS

The preponderance of negative π mesons in our cosmic-ray observations is largely understandable in terms of the high frequency of interactions produced by neutrons. Thus, Bradner[31] observed a π^-/π^+ ratio of 9.1 for the mesons produced by the bombardment of a carbon target with 270-Mev neutrons, a value consistent with our pion ratio of 10 at very low meson kinetic energies from C–N–O-target nuclei. Likewise, the good over-all agreement between the cosmic-ray pion ratios and that observed by Voss[13] using 300-Mev γ rays is in a large measure attributable to the large proportion of the disruptions being initiated by non-ionizing radiation.

While the differential energy spectra deduced from the present study display the accelerative effect of the Coulomb barrier in shifting the maximum for π^+ pro-

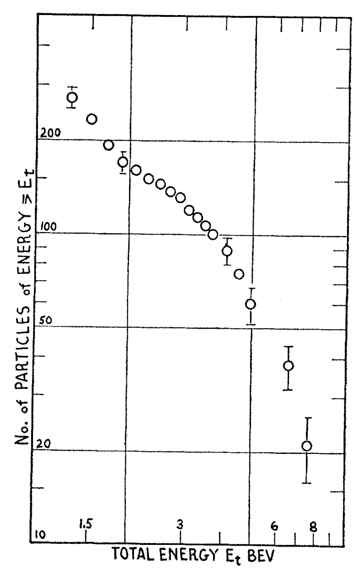

FIG. 9. Integral energy spectrum of high-energy neutrons deduced from stars accompanied by slow mesons.

[27] Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. **40**, 862 (1949).
[28] J. G. Roederer, Z. Naturforsch. **7a**, 765 (1952).
[29] S. F. Singer, *Progress in Cosmic-Ray Physics* (Interscience Publishers, Inc., New York, 1957), Vol. 4, Chap. 4, p. 272.
[30] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), p. 496.
[31] Bradner, O'Connell, and Rankin, Phys. Rev. **79**, 720 (1950).

duction towards higher energies, it is worth noting an anomalous behavior at very low kinetic energies. Positive mesons created in the nucleus with an initial kinetic energy E_0, after crossing a Coulomb barrier V_c would be observed with an energy $E=E_0+V_c$, and hence $E\gtrsim V_c$. As shown in Fig. 10, however, an appreciable number of mesons have been observed with E considerably less than $V_c=Z_1Z_2e^2/r$ Mev if the nuclear radius r is taken as $1.2\times10^{-13}A^{\frac{1}{3}}$ cm.

The effect is particularly pronounced in the heavy Ag—Br target nuclei, about 40% of the observations having values of $E\lesssim 10$ Mev, whereas $V_c=11.8$ and 9.7 Mev for Ag and Br nuclei, respectively. The meson track selection criteria favor the observation of very low-energy mesons. Applying geometric escape corrections to the data with the aid of eqP_4 indicates that about 10% of the π^+ mesons of $E\lesssim 40$ Mev produced in the disruption of heavy nuclei emerge with energies considerably less than V_c. This effect is less pronounced for the C—N—O-target nuclei, only 2% of the mesons having kinetic energies $\lesssim 3$ Mev. This low-energy tail of the π^+ production spectrum may originate from the escape of mesons after and during the evaporation of the nucleus. In many instances the slow meson occurs as a wide-angle member of a large shower suggesting an origin from secondary intranuclear collisions. This would be more probable in heavy target nuclei than in ones composed of relatively few nucleons which is in accordance with the present observations.

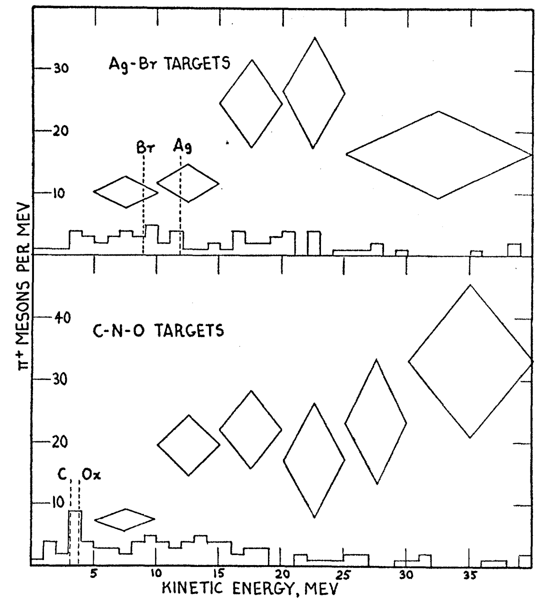

FIG. 10. Differential energy distribution of π^+ mesons produced in heavy and light nuclei. The arrows indicate the extent of forbidden regions on the basis of the Coulomb barrier. The diamonds represent an estimate of the geometrically corrected mesons produced per 1-Mev interval of kinetic energy averaged over 5-Mev regions of the spectrum.

ACKNOWLEDGMENTS

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