PHYSICAL REVIEW VOLUME 81, NUMBER 4 FEBRUARY 15, 1951

On the Production of Mesons by Primary Cosmic Rays

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(Received January 3, 1950)

The present ideas on the production of π-mesons by the primary cosmic rays and of their decay into μ-mesons lead to differences between the calculated and observed intensities, total energies of the components, and geomagnetic effects, which do not appear resolvable by any plausible adjustment. A consistent explanation of the several effects is found in the assumption of a further intermediate meson, which is identified with the τ-meson of about 900 electron masses. A model which agrees with the available data and is not contradicted by the facts of direct observation, such as in photographic emulsions, consists in the following assumptions:

(1) Production of τ-mesons and π-mesons in a ratio of 5 to 1 by the primary nucleons with a multiplicity 2.7 $P^{0.5}$ (P in Bev/c).

(2) Decay of the τ-mesons into π-mesons with a mean life of 10^{-10} sec.

(3) Decay of the π-mesons into μ-mesons.

I. INTRODUCTION

THE short range of nuclear forces led Yukawa to the assumption that the exchange forces were transmitted by a particle of several hundred electron masses. The identification of this particle with the penetrating component of cosmic rays opened up an avenue of research into nuclear forces at the highest energies.

Experimental investigations have shown that, on the one hand, the most abundant particle in the penetrating component of cosmic rays, the μ-meson, does not interact strongly with the nucleus[1] and on the other, that a particle occurring more rarely in the lower atmosphere, the π-meson, frequently produces nuclear disintegrations.[2] If it is not absorbed the π-meson is known to decay with a mean life[3] of 10^{-8} sec into a μ-meson. Hence it appears to be necessary to assume that the primary cosmic rays, on penetrating into our atmosphere, first produce π-mesons which then decay into μ-mesons. These deductions are based on the experimental study of the behavior of single particles.

In the present paper an attempt is made to apply these concepts to the explanation of observations which result from the superposition of the behavior of single particles. The approach is empirical. By a process of trial and error it is possible to arrive at definite conclusions concerning meson production. It is clear that by the introduction of parameters, such as the multiplicity of production, any single observational fact, such as the latitude effect, may be explained without having necessarily any significance. If the known facts, which previously could not be accounted for, are explained by the introduction of a new essential parameter, in the present case an additional decay, it must be concluded that it has some justification.

The experimental data used for comparison should fulfil two requirements. Firstly, the interpretation of the experimental results should be free from doubt. This is the case for measurements of the penetrating component in the lower part of the atmosphere where it is easily separated from the other cosmic-ray components. These measurements include the different aspects of the geomagnetic effects, the relationship between the momentum spectrum of the primaries and that of the mesons, the intensities at the limit of the atmosphere and at sea level, the total energy of cosmic rays impinging on the earth and of the several components, and, finally, the absorption of the meson component in the lower atmosphere. Secondly, if a model is rejected, the difference between the calculated results and the experimental data should exceed clearly the experimental errors as well as those introduced by approximations in the calculations.

II. THE MODELS WITH EQUIPARTITION OF THE ENERGY OF THE PRIMARY PARTICLE

The equal division of the energy of a primary particle among N μ-mesons is the simplest model. Certain further assumptions and data which we will not discuss further at this stage must be made for the comparison between the model and the observations:

(1) Intensity of primary cosmic rays[4] at the limit of the atmosphere (geomagnetic latitude $\lambda_m = 41°$)

$$I_P = 0.070 \text{ particles cm}^{-2}\text{ sec}^{-1}\text{ sterad}^{-1}.$$

(2) Differential momentum spectrum, subsequently abbreviated DMS, of the form $dp/p^{2.5}$ for $p > 3$ Bev/c of the primary particles.[5]

(3) Deflection of all primary particles in the earth's magnetic field according to Stoermer's theory.[6]

(4) Production of all μ-mesons at an atmospheric depth of 100 mb.

(5) Mean life of 2.15×10^{-6} sec, mass of 216 electron masses, and energy loss independent of energy of 2 Bev for 1000 g cm^{-2} of air.

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[1] Conversi, Pancini, and Piccioni, Phys. Rev. 71, 209 (1947).

[2] C. F. Powell, *Cosmic Radiation* (*Colston Papers*) (Butterworth, London, 1949), p. 83.

[3] P. R. Richardson, Phys. Rev. 74, 1720 (1948).

[4] J. A. Van Allen and J. F. Gangnes, Phys. Rev. 78, 50 (1950).

[5] L. Jánossy, *Cosmic Rays* (Oxford Press, Oxford, 1948), p. 300.

[6] M. S. Vallarta, Phys. Rev. 74, 1837 (1948).

TABLE I. Comparison of calculations and measurements at sea level.

Model	Multiplicity	Geomagnetic latitude of knee	Vertical latitude effect (percent)	Absolute intensity at sea level 10^{-3} part. cm^{-2} sec^{-1} $sterad^{-1}$	Energy of μ-mesons Bev cm^{-2} sec^{-1} $sterad^{-1}$	Exponent of differential momentum spectrum at production
Measured		40 ± 2[a]	18 ± 2[b]	7.7[c]	0.3[d]	3.0[e]
A	$N=1$	46	81	64	0.9	2.5
	$N=4$	34	30		0.9	2.5
	$N=5$	30	17		0.9	2.5
B	$N=3$	38	28	19	0.45	2.5
	$N=3.5$	36	19	17	0.45	2.5
	$N=4$	31	12	16	0.45	2.5

[a] P. S. Gill, Phys. Rev. **55**, 1151 (1939).
[b] See reference 17.
[c] See reference 11.
[d] See reference 13.
[e] J. G. Wilson, Nature **158**, 414 (1946).

(6) The energy of the produced mesons is equal to the energy in the primary beam.

The results obtained on this basis are summarized in Table I. Although the simple μ-meson model A gives a correct value of the latitude effect for a multiplicity $N=5$, it does not do so for the other effects. It has been shown[7] that the correct position of the knee may be obtained in this model by a multiplicity $N=k^3e^{-ck}$, which, however, does not bring the other quantities into agreement.

In model B it is further assumed that:

(7) Each primary produces only π-mesons.

(8) All π-mesons decay into μ-mesons.

(9) The probability of a μ-meson carrying off any momentum between 0 and p/N is constant.

Although this latter assumption is not correct, it is sufficiently accurate for the present purpose.

From Table I it is evident that the new model has decreased the differences between calculation and observation. We will therefore investigate whether further refinements will make the differences vanish.

III. THE MODEL WITH THE PSEUDOSCALAR π-MESON

For the analysis of this model we do not proceed as in the preceding section. Instead of calculating the different effects from the primary DMS we reconstitute the DMS of the π-mesons at production and compare it with that of the mesons produced by the primary nucleons according to the symmetrical pseudoscalar theory.[8] The results of the preceding section make us expect a gap between our results. To eliminate any possibility that this gap may be due to experimental errors we take for the primary DMS the lowest results compatible with the observational facts and for that of the μ-mesons the highest.

The μ-Meson Spectrum at Production

The DMS at production and at the knee of the geomagnetic effect(Fig. 1, curve 2) is calculated from that of particles penetrating 10 cm of lead at sea level and at a geomagnetic latitude $\lambda_m=46°$ (Fig. 1, curve 1)[9,10] after reducing to the known meson intensity[11] at sea level 0.0077 particles cm^{-2} sec^{-1} $sterad^{-1}$. The assumptions are that all observed particles are μ-mesons and that all μ-mesons are produced at the 100-mb level. The error in the μ-meson spectrum at production arising from the second assumption is small.[12]

This DMS, which stops at 2 Bev/c because of the energy loss of 1.8 Bev in 900 mb of the atmosphere and 0.2 Bev in 10 cm Pb, is extended towards lower values in the following way. The DMS, say, at 700 mb, is obtained from that at production by multiplication with the probabilities of arriving at that level. Integration gives the integral spectrum down to a momentum $2(1-0.7+0.1)=0.8$ Bev/c. As the total meson intensity at 700 mb is known[13] the integral spectrum is completed. From this further points on the DMS are obtained.

By repetition of this operation several times to a level of 300 mb the μ-meson DMS at production for momenta >0.4 Bev/c has been determined. This spectrum, which agrees with that found by more direct means,[14] was extended to 0.2 Bev/c with the help of the latter.

As this agreement gives confidence in our method, the μ-meson DMS at production at the equator was derived in the same way using the known values for the latitude effect[15,16] after correction to vertical incidence.[17]

The π-Meson Spectrum at Production

The energy and momentum conservation laws determine the probability $W(p_\mu, p_\pi)$ of production of a

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[7] L. Jánossy and P. Nicholson, Proc. Roy. Soc. (London) **A192**, 98 (1947).

[8] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).

[9] The momentum is measured in Bev/c at production.

[10] Caro, Parry, and Rathgeber, Nature **165**, 688 (1950).

[11] K. Greisen, Phys. Rev. **61**, 212 (1942).

[12] L. Jánossy and J. G. Wilson, Nature **158**, 450 (1946).

[13] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

[14] M. Sands, Phys. Rev. **77**, 180 (1950).

[15] W. C. Barber, Phys. Rev. **75**, 590 (1949).

[16] Biehl, Neher, and Roesch, Phys. Rev. **76**, 914 (1949).

[17] H. D. Rathgeber, Phys. Rev. **77**, 566 (1950).

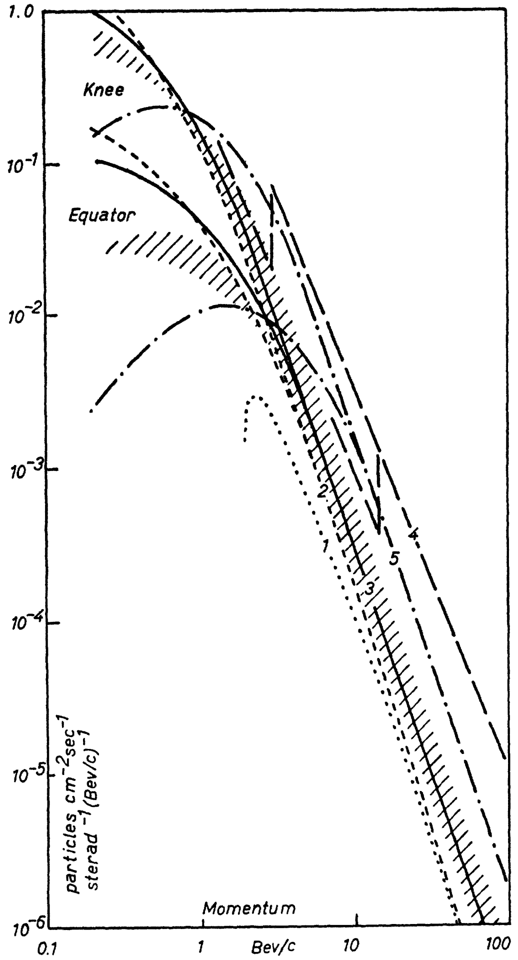

FIG. 1. Differential momentum spectra of: (1) μ-mesons at sea level and geomagnetic latitude 46°, (2) μ-mesons at production, (3) π-mesons at production, (4) primary nucleons, (5) mesons produced by primary nucleons with a multiplicity 1.2 $P^{0.5}$.

μ-meson of momentum p_μ by a π-meson of momentum p_π. Let us consider in the center-of-mass system the general case of the decay of a meson into another meson and a number n of other particles. Then the maximum kinetic energy of the decay meson is:

$$(E_2')_{K\,\mathrm{max}}=c^2([m_1-m_2]^2-n^2m_3^2)/2m_1,$$

in which m_1 is the rest mass of the decaying meson, m_2 that of the decay meson, and m_3 that of one of the other particles. It is found further that the maximum total energy of the decay meson is given by

$$(E_2')_{\mathrm{max}}=c^2(m_1^2+m_2^2-n^2m_3^2)/2m_1$$

and its maximum momentum by

$$(p_2')_{\mathrm{max}}=c\{[(m_1-m_2)^2-n^2m_3^2]\times[(m_1+m_2)^2-n^2m_3^2]\}^{\frac{1}{2}}/2m_1.$$

In the case of $\pi\rightarrow\mu$ decay, in which all μ-mesons emitted by a π-meson at rest have the same range,[18] the last two equations reduce to

$$E_\mu'=c^2(\pi^2+\mu^2)/2\pi, \tag{1}$$

$$p_\mu'=c(\pi^2-\mu^2)/2\pi, \tag{2}$$

in which π and μ are the rest masses of the π- and μ-mesons, respectively.

The transformation to the laboratory system

$$p=[\pm p'+\beta E'/c]/(1-\beta^2)^{\frac{1}{2}} \tag{3}$$

leads, for relativistic particles to

$$(p_\mu)_{\mathrm{min}}=(\mu/\pi)^2p_\pi=gp_\pi, \tag{4}$$

and

$$(p_\mu)_{\mathrm{max}}=p_\pi, \tag{5}$$

introducing the symbol g as a convenient abbreviation.

As the mesons are all emitted with the same momentum and with spherical angular symmetry in the CM-system, the probability $W(p_\mu, p_\pi)$ is constant in the interval from $(p_\mu)_{\mathrm{min}}$ to $(p_\mu)_{\mathrm{max}}$.[19] If $S_\pi(p_\pi)$ is the DMS of the π-mesons, that of the μ-mesons is

$$S_\mu(p_\mu)=\int_{p_\mu}^{p_\mu/g}\left[WS_\pi\Big/\int_{gp_\pi}^{p_\pi}Wdp_\mu\right]dp_\pi \tag{6}$$

for the case in which W is not normalized.

Applying this transformation to a $\pi-$DMS

$$S_\pi=A_\pi p_\pi^{-\gamma}$$

with $W=$constant, gives

$$S_\mu=A_\pi[(1-g^\gamma)\gamma^{-1}/(1-g)]p_\mu^{-\gamma}. \tag{7}$$

As part of the $\mu-$DMS is of the form $p^{-\gamma}$, the generating π-spectra over these ranges are found by multiplication of the μ-spectra by the factor

$$\gamma(1-g)/(1-g^\gamma)=1.57$$

with $\gamma=3.0$ and[20] $\pi/\mu=1.32$.

A correction must be applied to the resulting curve for the nuclear capture of part of the π-meson flux. Only a fraction[21] $R/(R+\rho L)$ of the π-mesons decay into μ-mesons, in which $R=20$ g/cm^2 is the range[21] of the π-mesons for nuclear capture, L is their mean decay path, and ρ is the air density at the 100-mb level. The range, which is smaller than that generally accepted, has been calculated from the density effect in the upper atmosphere[21] using 1×10^{-8} sec as the lifetime of the π-meson. The use of this small range is justified by the program followed in this paper; differences between quantities which are to be compared are made as small as is compatible with the measurements.

The straight part of the π-meson DMS at production has been obtained in this manner. The curved parts were found by assuming several π-meson DMS and

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[18] G. P. S. Occhialini and C. F. Powell, Nature **162**, 168 (1948).

[19] See reference 5, p. 183.

[20] R. E. Marshak, Phys. Rev. **75**, 700 (1949).

[21] A. Duperier, Proc. Phys. Soc. (London) **A62**, 684 (1949).

calculating that of the μ-mesons by numerical methods until a fitting π-spectrum was found.

The Momentum Spectrum of the Primary Particles

The intensity of cosmic rays at the limit of the atmosphere has been measured with Geiger counter telescopes carried by rockets.[4] It was found to be 0.070 particles $\text{cm}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}$ at $\lambda_m=41°$ and 0.028 in the same units at the equator, which corresponds to a DMS of $p^{-1.9}$.

Measurements at $\lambda_m=52°$ in balloon flights[22] with absorber thicknesses up to 6 cm Pb converge towards 0.17 particles $\text{cm}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}$. Correcting for the remaining latitude effect[23] and the absorption in the remaining layer of air this reduces to 0.11 for $\lambda_m=41°$. For the reasons already given we will take 0.070 at $\lambda_m=41°$, that is $p_{\min}=4.5$ Bev/c, as a basis for our calculations.

Assuming that the energy in the primary cosmic rays is proportional to the energy appearing as ionization in the atmosphere their DMS[5] is found to be of the shape $p^{-2.5}$. A DMS with exponent 1.9 extending to infinity would contain an infinite energy. A higher multiplicity of nuclear disintegrations at the equator in the rocket shell may increase the rate at the equator. As we consider the estimate based on the ionization measurements to be more reliable and as we want to take the lowest values we accept $\Gamma=2.5$ as the exponent of the DMS of the primary particles down to the geomagnetic cutoff of 3 Bev/c for $\lambda_m=46°$, the latitude at which we calculated the μ-meson spectrum. This decision is supported by the DMS of the heavy nuclei which follows the same exponent[24] and cannot have been influenced by multiple events.

Burst measurements in the stratosphere indicate that at most only a small proportion of the primaries can be electrons.[25] The east–west effect shows that the majority of the charged particles are positive. Photographic plate measurements[26] reveal that 25 percent of the primaries are stripped nuclei of $Z\geqslant 2$. Hence, we divide the primaries into 75 percent protons and 25 percent α-particles, neglecting the heavier nuclei. Supposing that the nucleons of an α-particle act independently, the number of meson producing nucleons in the α-particles is:

$$0.070\times 25\ \text{percent}\times 4=0.070\ \text{particles}\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}\ \text{at}\ \lambda_m=46°.$$

To obtain the energy spectrum of these it is necessary to find their cut-off momentum. They may be considered as packets of particles of two proton masses and unit charge. As the cut-off momentum is the same for all relativistic particles of unit charge each nucleon will carry a momentum of one-half of the cut-off value for a proton at the same latitude. The DMS of all primary nucleons are traced as curve 4 in Fig. 1 making allowance for the nonrelativistic velocity at the low momentum end.

The Momentum Spectrum of the Mesons Produced by the Primary Nucleons

The symmetrical pseudoscalar theory,[8] which appears to be the most probable from the observations of nuclear physics, gives the probability:

$$W(p,P)\sim N/P\exp\{-N[(p/P)+(1/2Mp)]\} \tag{8}$$

of production of a meson of momentum p by a nucleon of momentum P if $N=KP^r$ is the multiplicity of production. We can estimate K and r from the disappearance of the latitude effect for different absorber thicknesses. Considering that the energy loss in the atmosphere is 2 Bev and that the knee of the latitude effect at sea level[27] occurs at $\lambda_m=40°$, corresponding to a cut-off momentum of 4.5 Bev/c, we conclude that the multiplicity for 4.5 Bev/c nucleons is $N=4.5/2=K(4.5)^r$. Furthermore, it has been observed[28] that the latitude effect disappears at a depth of water of 7 m, which is equivalent to a total energy loss of 3.4 Bev. Since the multiplicity in this case is $N=14/3.4=K(14)^r$, the constants are found to be $K=1.2$ and $r=0.5$.

An approximate transformation can be found by assuming that the probability of production of a meson is constant between the limits 0 and 2 P/N; this satisfies the condition that the energy of the N mesons is equal to that of the primary nucleon. By analogy with Eq. (6) the meson spectrum is then

$$S_p=\int_{2pN}^{\infty}\left[NS_P\Big/\int_0^{2P/N}dp\right]dP.$$

For a primary DMS given by $S_P=A_PP^{-\Gamma}$ this becomes

$$\begin{aligned}S_p&=A_P[2^{\Gamma-2r-1}/(2r-\Gamma)]K^{(2-\Gamma)/(1-r)}p^{(2r-\Gamma)/(1-r)}\\&=A_PK^{-1}p^{-3},\end{aligned} \tag{9}$$

if $r=0.5$ and $\Gamma=2.5$, that is, the exponent of the meson DMS produced by the primaries is the same as that of the μ-meson DMS.

The DMS of the mesons below the cut-off momentum of the primaries, which is curved, and the intensity of its straight portion, which is sensitive to the shape of the probability function at high energies, were found by numerical and graphical methods. The proportionality constant in Eq. (8) was determined in the same manner, the condition being

$$\int_0^P Wdp=KP^r.$$

The DMS of charged mesons at the knee and at the equator, multiplied by a factor 0.67 resulting from the

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[22] M. A. Pomerantz, Phys. Rev. **75**, 1721 (1949).
[23] M. A. Pomerantz, Phys. Rev. **77**, 830 (1950).
[24] M. S. Vallarta, Phys. Rev. **77**, 419 (1950).
[25] R. I. Hulsizer and B. Rossi, Phys. Rev. **73**, 1402 (1948).
[26] H. L. Bradt and B. Peters, Phys. Rev. **77**, 54 (1950).
[27] P. S. Gill, Phys. Rev. **55**, 1151 (1939).
[28] J. Clay, Physica **2**, 299 (1935).

assumed admixture of $\frac{1}{3}$ neutral mesons, are represented in curve 5, Fig. 1.

IV. INTRODUCTION OF A FURTHER DECAY

It is obvious that the DMS of the π-mesons (Fig. 1, curve 3) and that of the mesons produced by the primary nucleons (curve 5) do not agree. We now discuss several conceivable reasons for the difference of a factor 5.2 in the straight portion of the DMS.

(1) Errors in the π-Meson DMS

The experimental errors in this case are certainly below 10 percent for momenta greater than 1 Bev/c. It is known that, contrary to our assumptions, mesons are produced in the lower atmosphere. Their intensity however is much lower than has been estimated previously[29] from assumptions which are now known to be incorrect. The intensity of these mesons will not exceed 10 to 20 percent of the total intensity.

(2) Errors in the Primary DMS

Despite the deductions for showers, the intensity measured with Geiger counter telescopes may have been increased by multiplication processes in the matter surrounding them. This is not the case with heavy nuclei as observed in photographic plates. As any collision will destroy them, the observed rate of heavy nuclei is a minimum rate. The α-particles resulting from a disintegration of heavier nuclei will contribute only a negligible fraction. The consideration of collisions in interstellar space[26] shows that even if cosmic rays should consist exclusively of heavy nuclei at production, a considerable proportion would be separated into protons and neutrons, the latter decaying into protons and electrons. Furthermore, it would be strange if the mechanism which accelerates heavy nuclei did not accelerate protons also. We conclude thus that the proton intensity should be several times that of the heavy nuclei and that the intensity of the primary nucleons cannot be in error by more than 30 percent. Neither can the exponent of the primary DMS be too small. The value we choose is the highest of all the direct observations.

(3) Errors in the Production Process of Mesons

Direct observation of the production of mesons shows that the production process is multiple. The satisfactory agreement of the value for r obtained from the latitude effect and from the change in slope of the primary spectrum in transforming into a meson spectrum [meson decay does not alter the slope, see Eq. (7)] makes it evident that the values used are at least self-consistent. Variations of r within the limits imposed by experimental results will scarcely affect the meson intensity.

As the meson intensity at a momentum higher than the magnetic cutoff is inversely proportional to K [Eq. (7)], an error in K might cause the observed difference. However an increase in K by a factor 5.2 would bring the low momentum part to values exceeding the observed ones. Nevertheless, we shall not reject this explanation since the observed intensities at these momenta might have large errors.

We shall not take into consideration the possibility that the probability function used is altogether wrong. As the probability functions are determined mainly by the relativity transformation from the CM system to the laboratory system all plausible theories will give similar results.

(4) Suggestion of an Additional Intermediate Meson

The effect just discussed, which would be obtained by an increase in K, would also be produced by a decay of the directly produced mesons into π-mesons. As these assumed mesons would be heavier than the π-mesons, we identify them temporarily with the observed τ-mesons of about 900 electron masses, and discuss the effect of this assumption.

The π-mesons are nuclear force mesons, and probably have integral spin. The same considerations apply to the τ-meson. If we assume that in the $\tau \rightarrow \pi$ decay neutral particles are produced, the conservation of spin requires that the sum of their spins be integral. Since it will be shown later that a process which gives a maximum loss of detectable energy fits the experimental results best, we shall consider only the emission of a neutrino pair. In this case the π-meson is not emitted with a single momentum in the CM system, but with an unknown probability distribution between 0 and $(P')_{\max} = c(\tau^2 - \pi^2)/2\tau$ [Eq. (2)]. However, it is possible to use the two limits for the calculation of two spectra which will bracket the true DMS whatever the probability distribution. For $p_\pi' = 0$ the relativity transformation (3) yields for $\beta = 1$

$$p_\pi = (E/\tau c^2) p_\tau = (\pi/\tau) p_\tau = h p_\tau.$$

A DMS of the producing mesons of the form $S_\tau = A_\tau (p_\tau)^{-\gamma}$ is transformed by the foregoing relation into

$$S_\pi = A_\tau h^{\gamma-1} (p_\pi)^{-\gamma}. \tag{10}$$

Using the maximum value for p_π' we find in analogy to Eq. (7)

$$S_\pi = A_\tau [(1 - f^\gamma)/\gamma(1 - f)] (p_\pi)^{-\gamma} \tag{11}$$

in which $f = (\pi/\tau)^2$.

The domain between these limits is shown in Fig. 1 by the hatched areas. As the straight part of the π-meson spectrum falls within the limits, it is seen that this last explanation satisfies the conditions.

An alternative explanation is given by the direct decay of the heavy mesons into μ-mesons. With the

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[29] H. D. Rathgeber, Phys. Rev. 61, 207 (1942).

same reasoning as for the $\pi\rightarrow\mu$ decay [Eq. (7)] the μ-DMS for this case is found to be:

$$S_\mu = A_\tau[(1-j^\gamma)/\gamma(1-j)]p_\mu^{-\gamma}$$

in which $j=(\mu/\tau)^2$. This spectrum is higher by a factor 4 than the observed μ-meson spectrum and is therefore rejected.

V. THE TOTAL ENERGY IN THE PRIMARY COSMIC RAYS AND IN THE SEVERAL COMPONENTS

After the considerations in the preceding section we are left with the explanations that either the production of mesons occurs with a multiplicity 5 times higher than that assumed, or that another heavy meson occurs between the primaries and the π-mesons. The difference between the alternatives will lie in the intensity of the μ-mesons of momenta below 1.5 Bev/c. In the first, all of the energy which disappears in the range above 1.5 Bev/c will reappear as slow mesons; in the second, a major part will disappear completely as neutrinos and the intensity of the slow mesons will be diminished. As no measurements of the intensity of the very slow μ-mesons at their place of production exist we consider the next best quantity, which is the total energy in the μ-meson component. This choice has the further advantage that the analysis is simplified considerably.

The total energies in the μ-meson, the electron, and the nuclear component have been estimated[13] at 0.29, 0.20, and 0.12 Bev cm^{-2} sec^{-1} sterad^{-1}, respectively. Practically the whole of this energy is lost in the atmosphere as ionization. Ionization measurements at several latitudes[30] give the energy lost as ionization at $\lambda_m=46°$ as 2.1 Bev cm^{-2} sec^{-1}. Taking into account that the cosmic rays are incident isotropically[31] on a plane layer we find:

$$2.1/\pi = 0.67 \text{ Bev cm}^{-2}\text{ sec}^{-1}\text{ sterad}^{-1},$$

which is 0.06 higher than the sum of the components in Rossi's estimate. Considering that we want to take the highest possible values, and that the electronic and nuclear components probably have been underestimated, we take 0.31, 0.22, and 0.14 as the respective values.

The total incident energy is found by integration of the spectra of the proton and α-particle components. The minimum incident energy is $0.95+0.28=1.23$ Bev cm^{-2} sec^{-1} sterad^{-1}. It is at once evident that this value is nearly twice the energy lost in ionization.

The energy of the μ-meson component can be calculated in the following manner. Deducting 0.14 Bev cm^{-2} sec^{-1} sterad^{-1}, the energy of the nuclear component, the energy available for meson production is found to be 1.09 Bev cm^{-2} sec^{-1} sterad^{-1}. Assuming again that $\frac{1}{3}$ of this is used in the production of neutral mesons, which decay into the electron component, 0.72 Bev cm^{-2} sec^{-1} sterad^{-1} is left as the energy of all of the charged mesons at production. From Eqs. (4) and (5) we derive that the average momentum of the μ-mesons is $(p_\mu)_{\text{Av}}=[(\mu^2+\pi^2)/2\pi^2]p_\pi=0.79p_\pi$. For relativistic particles the same fraction of the energy will be transferred from the π-meson component to that of the μ-mesons, that is, 0.57 Bev cm^{-2} sec^{-1} sterad^{-1}. This is nearly twice the measured value. In this case we cannot have recourse, as in the intensity analysis, to a higher multiplicity of production for an explanation. The additional meson decay remains as the only proposition consistent with the observations.

The fraction of the energy of the τ-mesons going into the π-meson DMS is $(\pi^2+\tau^2)/2\tau^2=0.55$ for the case of maximum energy transfer. In the case of minimum transfer the fraction reduces to $\pi/\tau=0.33$. According to theory[32] the probability function in the CM system for the type $m_1\rightarrow m_2+2\nu$ of decay has a maximum in the upper half of the momentum range. Experiments[33] on the $\mu\rightarrow e$ decay have confirmed this. Therefore we will take the fraction as 0.45, which makes the energy in the μ-DMS 0.26 Bev cm^{-2} sec^{-1} sterad^{-1}.

Considering the several approximations involved the difference between the latter calculated value and the observed of 0.31 Bev cm^{-2} sec^{-1} sterad^{-1} does not appear significant by itself. It is known however that the π-mesons are nuclear force mesons.[34] We must therefore expect that some of the π-mesons are produced directly. Assuming that 5/6 of the mesons produced by the primary nucleons are τ-mesons and that the rest are π-mesons, the energy of the μ-component becomes:

$$\begin{aligned}&(0.72\times0.17)+(0.72\times0.83\times0.45)\times0.79\\&\qquad=0.31 \text{ Bev cm}^{-2}\text{ sec}^{-1}\text{ sterad}^{-1},\end{aligned}$$

that is the measured value.

Let us consider the π-meson intensity $S_\pi dp_\pi$ for a momentum in the straight part of the DMS as split up into two parts of which the first is produced directly and the second by the intermediary of τ-mesons. If 0.30 is the weighted average of $h^{\gamma-1}=0.11$ [Eq. (10)] and $(1-f^\gamma)\gamma^{-1}/(1-f)=0.37$ obtained by the same reasoning as before, and $S_\tau dp_\tau$ is the intensity of the τ-mesons, $S_\pi dp_\pi=(0.17+0.83\times0.30)S_\tau dp_\tau=0.42\ S_\tau dp_\tau$. The fraction of the π-component which is produced directly is then:

$$0.17/0.42 = 40 \text{ percent.}$$

The π-meson DMS found in this way is lower by a factor $5.2\times0.42=2.2$ than that derived from the primary nucleon DMS. This signifies that, according to Eq. (9), the constant K is too small by the same factor. Our first value for K was derived under the assumption that the energy of one primary particle was shared equally by all mesons. However, the probability distribution used in deriving Eq. (9) is a much better approximation. As the upper limit is 2 P/N instead of

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[33] Leighton, Anderson, and Seriff, Phys. Rev. **75**, 1432 (1948).

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P/N, the constant K is increased by a factor 2. The theoretical distribution [Eq. (8)] having a finite value above 2 P/N brings the factor to a somewhat higher value. For these reasons we use $K=1.2\times 2.25=2.7$, for which value the τ-meson DMS has been recalculated (Fig. 2). The new value of K which has just been derived from considerations about the straight part of the DMS, also brings calculation and observation into satisfactory agreement for the curved parts of the DMS.

The multiplicity $N=KP^r=2.7\times 10^{0.5}=8.5$ for a momentum $P=10$ Bev/c, the average momentum of the primaries, agrees satisfactorily with the observed[35] multiplicity of between 6 and 7, assuming again that $\frac{1}{3}$ of the mesons are neutral.

VI. THE τ-MESON

Several particles with a mass between 700 and 1100 m_e have been reported in the literature.[34] Recently, observation of three more particles of 725±40 m_e has been reported.[36] These are named τ-mesons.

Out of these three heavy mesons coming to rest in a photographic emulsion, one produces a star and two stop without producing tracks. In our model the τ-meson is supposed to decay into a π-meson and two neutrinos. Most frequently the π-meson will carry away more than $\frac{1}{3}$ of the mass difference, i.e., 75 Mev, as kinetic energy. As the maximum energy at which a π-meson is detectable in the Ilford C2 emulsion[37] used is 8.5 Mev practically all π-mesons would escape detection.

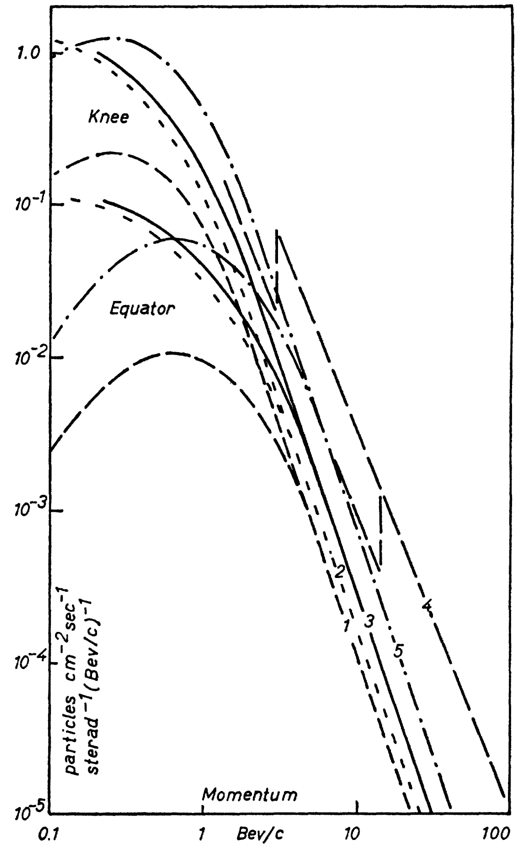

FIG. 2. Differential momentum spectra of: (1) π-mesons produced by primary nucleons, (2) π-mesons produced by τ-mesons, (3) π-mesons at production (observed), (4) primary nucleons, (5) τ-mesons produced by primary nucleons with a multiplicity 2.7 $P^{0.5}$.

Further, if the τ-meson is the main particle of the nuclear force field, it might be expected to occur in penetrating showers. In the region of minimum ionization their tracks would in general not be distinguishable from those of π- or μ-mesons. However, in the lower energy range the tracks of minimum ionization would show occasionally one sharp kink at the point of the τ→π decay. In fact this has been observed under the expected conditions.[38] The fraction of the other observed cases of anomalous scattering of mesons due to this effect cannot be estimated at present.

Assuming that the τ-meson is produced in the wall of the cloud chamber or in the material surrounding it, a proper mean life of the τ-meson between 10^{-10} and 10^{-11} sec is derived. The decay of the neutral heavy meson observed in the same series leads to the same value. This latter observation, as well as other more recent ones[39] of pair production by non-ionizing agents support our assumption of the production of neutral mesons.[40]

These results have been confirmed by the most recent cloud-chamber observations.[41] In 11,000 tracks of penetrating showers 30 pairs produced by neutral particles were found. None of the charged particles showed the properties of electrons on traversing a lead plate. In the same experiment 4 more kinks were photographed. The failure to explain all of the observations by a heavy meson of a single mass is probably due to the production of neutral particles which may be neutrinos. The proper mean life of the neutral heavy meson has been estimated at 3×10^{-10} sec, that of the charged heavy meson is shorter.

The reported observation of the decay of a heavy meson[42] into 3π-mesons only, while supporting the idea of a τ→π decay, would not give the loss of energy derived in this paper if it occurred in a high proportion of the τ→π decays.

Further supporting evidence is found in the study of the π-meson. While there is no doubt that π-mesons interact strongly with nucleons, it appears that their coupling may be too small by a factor 10 or 10^2. In this

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[38] G. D. Rochester and C. C. Butler, Nature **160**, 855 (1947).

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[41] Seriff, Leighton, Hsiao, Cowan, and Anderson, Phys. Rev. **78**, 290 (1950).

[42] Brown, Camerini, Fowler, Muirhead, Powell, and Ritson, Nature **163**, 82 (1949).

case it would be necessary to assume the existence of another meson to account for the nuclear forces.[34]

The artificial production of τ-mesons by existing particle accelerators appears impossible as from 400 to 600 Mev will be required to achieve it.[43]

The frequency of observation of τ-mesons which is estimated as from 1 in 1000 π-mesons to 1 in 10,000, appears to contradict the important part attributed to the τ-meson in our model. However, closer analysis will show that this is not so. The ratio of the observations will be in the ratio of the total track length of the τ- and the π-mesons in the energy range in which they can be distinguished. Curves 2 and 3 in Fig. 2 show that τ-mesons occur only as frequently as π-mesons at these energies. As the ratio of their mean lives is of the order $10^{-8}/10^{-10}=10^2$ the ratio of the track lengths becomes about 10^2.

If, nevertheless, the frequency of observation of the τ-meson should turn out to be too small, there seems to be no objection to considering the τ-meson, like the meson in β-decay, as a virtual particle except where energy conditions are favorable.

In conclusion supporting evidence is found in the scarce direct observational material for the assumption of intermediate τ-mesons of some 900 electron masses with a lifetime of the order 10^{-10} sec.

VII. CONCLUSION

The degradation of energy and the disappearance of energy which have been shown to occur between the primary cosmic rays and the μ-meson component cannot be explained by the direct production of π-mesons alone. On the assumption that there are no fundamental errors in the measurement of the primary intensity we have come to the conclusion that a further meson decay takes place between the primary nucleons and the π-mesons. The particular model for this additional decay is not uniquely determined by the known facts; in fact, the observations quoted in the preceding section make it probable that a combination of several modes occurs.

We shall nevertheless give a general model of the three main cosmic-ray components (Fig. 3). The general genealogy of the μ-meson component has been discussed already. The electron component is presented as arising in the same process as the meson component. The constant relative density of mesons and electrons in extensive showers supports this point of view.[44,45] The electrons might be produced either by photons created in the nuclear collision[46] or by the decay of neutral mesons. The initiation of the electronic component by several of these particles originating in the same collision explains the rapid rise of the electron component in the first tenth of the atmosphere. The production by neutral mesons is made more probable by the observation[47] that the DMS of the particles producing the electron showers follows about the same exponential law as the meson DMS at production.

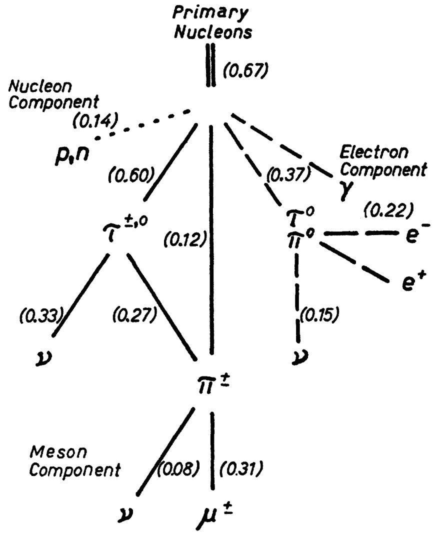

FIG. 3. Transformation model of primary cosmic rays into nucleon, electron, and meson components. The values in parentheses give the energy in Bev cm^{-2} sec^{-1} sterad^{-1}.

Finally, it is interesting to note that about half of the incident energy of cosmic rays disappears into undetectable radiation, according to our model, into neutrinos. It has been shown that the cross section of neutrinos[48] is smaller than 2.5×10^{-37} cm^2. Thus it appears that the entropy of the universe increases not only by the known processes at low energies but also by the production of neutrinos at high energies.

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