On the Production of the Hard Component of the Cosmic Radiation

I. The Photon Hypothesis*

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The number of quanta (and electrons) of energy k within dk times their range in units of radiation theory (photon lengths) produced in matter by a primary electron of energy E is calculated from the theory of showers to be $Z(k)dk=\alpha(E/k^2)dk$, where $\alpha=0.57$ for quanta and 0.44 for electrons. With the help of the known energy distribution of the electrons coming from the outside, the energy distribution of photon lengths in the higher atmosphere is obtained. A comparison with the number and energy distribution of mesons (obtained from data near sea level and underground) leads to the following consequences of the hypothesis that the mesons are created by photons. The production process must be of moderate multiplicity and its cross section must increase from about 1/100 of the cross section for pair production by photons in air at moderate energy (7 to 10 Bev) to about 1/10 at higher energy (over 18 Bev). These high cross sections required for the production of energetic mesons seem to imply correspondingly large cross sections for absorption and constitute a serious difficulty for the understanding of their great penetrating power.

1. THE SECONDARY NATURE OF THE HARD COMPONENT

It can hardly be doubted that the mesons forming the hard component of the cosmic radiation do not come from outside but are created within the atmosphere itself by primaries of a different nature. This follows at once if the instability of the mesons is admitted and the evidence on this point now seems quite convincing.[1] A comparison of the energy distribution of the mesons and of their observed geomagnetic effect with the energies necessary to reach points of various geomagnetic latitudes leads to the same conclusion.[2] A direct proof of the production of mesons in higher strata of the atmosphere has been recently obtained by Schein and Wilson.[3] Interesting indirect evidence for the production of mesons is provided by the new observations of S. A. Korff[4] who finds a high concentration of neutrons in the upper atmosphere. Any meson production process should according to Yukawa's theory be accompanied by fairly large recoils of nuclear particles and should therefore constitute an effective neutron source. With respect to the nature of the primaries and the details of the production mechanism, however, no satisfactory experimental evidence is yet available.

The theory of mesons as developed by Yukawa[5] and others in its present form can be applied only in a qualitative way, as it is not yet possible to treat high energy phenomena satisfactorily owing to divergence difficulties. One might use this theory, however, to obtain a classification of possible processes. Among them are the production of mesons by a kind of photoelectric effect and their production by protons in analogy to the emission of quanta by electrons.[6]

Most authors seem to be inclined to the opinion that the hard component is created by the soft component as the simplest possible assumption. We have therefore investigated the consequences of this hypothesis by comparing all

* A preliminary report of this paper was given at the Washington Meeting of the American Physical Society, Phys. Rev. **55**, 1111 (1939).

[1] See for example H. Euler and W. Heisenberg, Ergebn. d. exact. Naturwiss. **17**, 1 (1938).

[2] L. W. Nordheim, Phys. Rev. **53**, 694 (1938). In this paper an attempt was made to account for the behavior of the hard component by assuming that the primaries are of the same nature as the secondaries they produce. This hypothesis is, of course, not compatible with the supposed instability of the mesons, and further it would lead to the conclusion that every primary has to be accompanied by a large number (of order 10) of slow secondaries even at great depths in contradiction to recent experiments, reference 21.

[3] M. Schein and V. C. Wilson, Phys. Rev. **54**, 304 (1938).

[4] S. A. Korff, Phys. Rev. **56**, 210(A) (1939).

[5] H. Yukawa and others, I–IV, Proc. Phys. Math. Soc. Japan **17**, 58 (1935); **19**, 1084 (1937); **20**, 319, 720 (1938). H. Fröhlich, W. Heitler and N. Kemmer, Proc. Roy. Soc. **A166**, 154 (1938).

[6] W. Heitler, Proc. Roy. Soc. **A166**, 529 (1938), L. W. Nordheim and G. Nordheim, Phys. Rev. **54**, 254 (1938), M. Kobayasi and T. Okayama, Proc. Phys. Math. Soc. Japan **21**, 1 (1939).

available data regarding the number and energy distribution of electrons, photons* and mesons. It is possible to arrive in this way at a rather complete description of the features of the production process. It has to be of moderate multiplicity (i.e., a single photon has to be converted into more than one but not too many mesons in one single act) and the cross section for this conversion but not the multiplicity must increase with energy reaching values of the order $\frac{1}{10}$ of the cross section for pair production in air at energies of some 10 Bev.

This latter result leads, however, to a serious difficulty for the photon hypothesis. From general principles one has to conclude that the inverse of the production process should have a cross section of the same order of magnitude as the direct process; this means, as will be discussed in Section 5, that a high efficiency of production has as a consequence also a high rate of absorption or, at least, a rapid rate of degradation of energy. It is then hardly possible to account for the high penetrating power and hardening of the cosmic radiation at greater depths underground.[7] Though it might not be absolutely impossible to circumvent this difficulty, it seems that this could be effected only by rather artificial means. A discussion of alternative hypotheses regarding the origin of the hard component is given in the following paper.

2. The Number of Photons Produced by One Primary Electron

When a primary electron of energy E enters the atmosphere it starts at once to build up a shower, i.e., it multiplies into many electrons and photons of correspondingly lower energy. As long as the cross section for meson production is small compared to the cross section for radiative processes, the former effect will not disturb the course of the shower. The quantity which determines the rate of meson production will then be the total number of photons per energy interval dk multiplied with the average range, i.e.,

$$Z_\gamma(k)dk = dk\int N_\gamma(k,\, x)dx,$$

where $N_\gamma(k, x)$ is the distribution function for quanta of energy k as a function of depth x. The number of mesons of energy ϵ produced by the primary electron will then be

$$F(\epsilon) = \int Z_\gamma(k)\sigma(k,\, \epsilon)dk,$$

where $\sigma(k, \epsilon)$ is the cross section for creating one meson ϵ by a quantum k.

This quantity $Z_\gamma(k)$ can be obtained from the theory of showers[8] in the following way. Let $N_e(k, x)$ be the distribution function for particles (electrons and positrons) corresponding to the distribution $N_\gamma(k, x)$ of photons. At $x=0$ there is one particle of energy E and no photons so that we have $N_e(k, 0)=\delta(E-k)$ and $N_\gamma(k, 0)=0$. We introduce the moments

$$\begin{aligned} n_e(s,\, x) &= \int_0^E dk(k/E)^s N_e(k,\, x), \\ n_\gamma(s,\, x) &= \int_0^E dk(k/E)^s N_\gamma(k,\, x). \end{aligned} \tag{1}$$

Then if x is measured in units of the shower theory, n_e and n_γ satisfy[9]

$$\begin{aligned} \frac{d}{dx}n_e(s,\, x) &= -A(s)n_e(s,\, x) + B(s)n_\gamma(s,\, x) \\ \frac{d}{dx}n_\gamma(s,\, x) &= C(s)n_e(s,\, x) - Dn_\gamma(s,\, x), \end{aligned} \tag{2}$$

* We shall always speak of photons and not electrons as the part of the soft component which is effective for the meson production, as this is suggested by Yukawa's theory. As we shall see later the assumption that electrons are the active agent or that both electrons and photons contribute, would lead to practically the same results as the photon hypothesis.

[7] This difficulty was pointed out by L. W. Nordheim, J. Frank. Inst. **226**, 575 (1938), but the state of affairs can now be much more precisely shown.

[8] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937); H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **A159**, 432 (1937); L. Landau and G. Rumer, Proc. Roy. Soc. **A166**, 213 (1938); D. Iwanenko and A. Sokolow, Phys. Rev. **53**, 910 (1938).

[9] L. Landau and G. Rumer, reference 8, Eq. (17). Our $N_e(k, x)$, $N_\gamma(k, x)$ are the same as their $\Pi(E, t)$, $\Gamma(E, t)$ and n_e, n_γ differ only by a factor from Π_s, Γ_s.

where

$$A(s)=\frac{4}{3}[\psi(s+1)+\gamma]-\frac{s(5s+7)}{6(s+1)(s+2)},$$
$$B(s)=\frac{2}{3}\cdot\frac{3s^2+11s+14}{(s+1)(s+2)(s+3)},$$
$$C(s)=\frac{3s^2+7s+8}{3s(s+1)(s+2)},\qquad (3)$$
$$D=7/9$$

with $\psi(s+1)=(d/ds)\log\Gamma(s+1)$ and γ equal to Euler's constant. Eqs. (2), (3) are derived with the exact expressions at high energies for the cross sections for pair production and radiation by electrons. They do not include, however, the loss of energy due to ionization nor the Compton effect. This omission is of no importance for our application since in the production of mesons by quanta we are concerned only with high energies where these two effects are negligible.

If we integrate $n_e(k, x)$, $n_\gamma(k, x)$ over x, letting

$$z_e(s)=\int_0^\infty dx n_e(s, x),\quad z_\gamma(s)=\int_0^\infty dx n_\gamma(s, x),\qquad (4)$$

we find from (2)

$$n_e(s,\infty)-n_e(s,0)=-A(s)z_e(s)+B(s)z_\gamma(s),$$
$$n_\gamma(s,\infty)-n_\gamma(s,0)=C(s)z_e(s)-Dz_\gamma(s).$$

The initial conditions on N_e, N_γ, with the definitions (1) and for $s>1$ lead to

$$n_e(s,0)=1,\quad n_e(s,\infty)=0,$$
$$n_\gamma(s,0)=0,\quad n_\gamma(s,\infty)=0,$$

so that we have

$$-A(s)z_e(s)+B(s)z_\gamma(s)=-1,$$
$$C(s)z_e(s)-Dz_\gamma(s)=0.$$

Hence

$$z_e(s)=D/[A(s)D-B(s)C(s)],$$
$$z_\gamma(s)=C(s)/[A(s)D-B(s)C(s)].\qquad (5)$$

Now inversion of the Laplace-Mellin[10] transformation (1) gives with the help of (4)

$$Z_e(k)=\int_0^\infty dx N_e(k, x)=\frac{1}{2\pi ik}\int_{\delta-i\infty}^{\delta+i\infty} ds(E/k)^s z_e(s),\qquad (6)$$
$$Z_\gamma(k)=\int_0^\infty dx N_\gamma(k, x)=\frac{1}{2\pi ik}\int_{\delta-i\infty}^{\delta+i\infty} ds(E/k)^s z_\gamma(s).$$

The contour is a line running parallel to the imaginary axis and passing to the right of $s=1$, corresponding to the condition on Eqs. (5). Both $z_e(s)$ and $z_\gamma(s)$ have simple poles at this point. Since we are primarily interested in $Z_\gamma(k)$ we consider it in some detail. In addition to the pole at $s=1$, $z_\gamma(s)$ has simple poles on the real axis[11] in the intervals between $s=-2, -3, -4\cdots$. We can evaluate the integral by deforming the contour to the left and finding the residues of the integrand at each of these poles. Thus if the residue of $z_\gamma(s)$ at $s=1$ is R_1 and the residues at the points $s=-a_n$ $(n<a_{-n}<n+1, n\geq 2)$ are R_{-n}, then

$$Z_\gamma(k)=(1/k)\{(E/k)R_1+(k/E)^{a-2}R_{-2}+(k/E)^{a-3}R_{-3}+\cdots\}.\qquad (7)$$

One easily finds that $R_1=0.57$, $R_{-2}\simeq 0.06$, $a_{-2}\simeq 2.6$. The second term is therefore smaller than the first by a factor $(0.06/0.57)(k/E)^{3.6}$ and for our purposes it is sufficient to write

$$Z_\gamma(k)=0.57E/k^2.\qquad (8)$$

The case for electrons is essentially the same, only the residues are different. Corresponding to Eq. (8) we have

$$Z_e(k)=0.44E/k^2.\qquad (9)$$

The formulas (8), (9) will break down in the immediate neighborhood of the point $k=E$. One can show that the function $Z_\gamma(k)$ actually goes to zero at this point but with a vertical tangent, so that the error committed in using (8) right up to this point will be quite insignificant.

[10] Courant and Hilbert, *Methoden der Mathematischen Physik I* (Springer, second edition, 1930), p. 87. The results (6) can be obtained in a slightly different manner by integrating the Laplace-Mellin integrals for N_e and N_γ. The order of the integrations is interchanged and the integration over x performed first.

[11] There seem to be no poles off the real axis. We made a numerical search for such poles in the vicinity of $s=1$. The presence of poles off the real axis would not influence the result greatly. They would introduce oscillatory terms into (7) which would not be expected with the smooth dependence on energy of the cross sections for pair production and radiation.

TABLE I. *Energy flux.*

Energy Interval Bev	Flux Bev cm^{-2} sec.$^{-1}$
1–3	0.11
3–7	0.44
7–18	0.87
>18	0.94

3. The Total Number of Quanta in the Atmosphere

The number of photon lengths as produced by one primary electron of energy E was determined in Section 2 as

$$Z(E, k)dk = 0.57Edk/k^2, \quad k \leqslant E \qquad (10)$$

where the length is measured in the units of radiation theory, i.e., for air 0.39 m water equivalent or about 1/25 of the whole atmosphere. The corresponding electron distribution is obtained simply by multiplying (10) with 7/9 giving a numerical factor of 0.44 (electrons and photons together give a factor very nearly one.) Except for this insignificant difference in the numerical factor it will make no difference whether the photons or electrons or both are held responsible for the meson production.

To obtain the total number of photon lengths in the cosmic radiation we have to integrate $Z(E, k)$ over the distribution of the primary electrons. This distribution has been obtained with sufficient accuracy by Bowen, Millikan and Neher[12] by integrating the ionization *versus* depth curves over depth at various geomagnetic latitudes. Their result is reproduced in Table I showing the total energy per second and cm^2 brought in at various energy intervals. The greater part of this intensity must consist of electrons and positrons only, as shown by the good agreement between the soft intensity in the higher atmosphere as calculated from the above primary distribution and as actually observed.[13] The tolerance for an extra nonelectronic component would depend on the accuracy of the shower theory which we believe to be within about 30 percent, an uncertainty which is irrelevant for our purpose. Also our present discussion is based explicitly on the hypothesis that the hard component is generated by the soft one so that no other primaries than electrons are considered.

Regarding the distribution in the high energy tail (>18 Bev) (i.e., not influenced by the geomagnetic field) no absolutely definite statements can be made. It seems, however, fairly certain that it actually consists of electrons and not of photons of lower energies. This is shown by the shift of the maximum and slower decrease at increasing depth of the cosmic-ray intensity at the equator as compared to the difference between the curves for higher latitudes. The actual shape of the absorption curve suggests a power law,[14] $E^{-(s+1)}dE$ with s between 1 and 2 and most probably about 1.8. This law also agrees well with the observed number of multiplicative showers

The above distribution refers to the total incoming radiation with all around incidence. To convert the flux $S(E)$ corresponding to this condition into the number of rays $j(E)$ coming in per unit solid angle we have the obvious relation (θ = angle to vertical)

$$S(E) = Ej(E)\int_0^{2\pi} d\varphi \int_0^{\pi/2} \cos^2\theta \sin\theta d\theta = \frac{2\pi}{3}Ej(E), \qquad (11)$$

$$j(E) = \frac{3}{2\pi}\cdot\frac{S(E)}{E}.$$

To obtain convenient formulas we note that the flux per energy interval in the range from 3 to 18 Bev is nearly constant. If we make this approximation and assume a power law for higher energies the absolute number of ionizing primary electrons per unit solid angle and cm^{-2} sec.$^{-1}$ will be

$$\begin{aligned} j(E)dE &= 0.042dE/E, \quad 3 < E < 18 \\ &\left.\begin{aligned} &= 0.0014(s-1)(18/E)^{s+1}dE \\ &= 3.6dE/E^{2.8} \end{aligned}\right\} 18 < E \end{aligned} \qquad (12)$$

with E in Bev, $s = 1.8$. This distribution shows of

[12] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **53**, 855 (1938).

[13] L. W. Nordheim, reference 7; R. Serber, Phys. Rev. **54**, 317 (1938).

[14] L. W. Nordheim, Phys. Rev. **51**, 1110 (1937), W. Heitler, Proc. Roy. Soc. **A161**, 261 (1937), H. Euler and W. Heisenberg, reference 1.

course a slight discontinuity and a change of slope at $E=18$.

For the absolute number of photon lengths $X(k)=\int Z(E, k)j(E)dE$ also per unit solid angle, cm^{-2}, $sec.^{-1}$ and Bev energy range, one finds from (10) and (12):

(a) due to primaries over 18 Bev (field insensitive)

$$\begin{aligned} X_a(k)dk &= 2.65dk/k^{2.8}, \quad k>18 \\ &= 0.27dk/k^2. \quad k<18 \end{aligned} \tag{13a}$$

(b) field sensitive part due to all primaries between E and 18 Bev.

$$\begin{aligned} X_b(E, k)dk &= (0.43-0.024E)dk/k^2, \\ & \qquad k<E<18 \\ &= (0.43-0.024k)dk/k^2. \\ & \qquad E<k<18 \end{aligned} \tag{13b}$$

The sum of X_a+X_b gives the total number of photon lengths as a function of the minimum energy E which itself is determined by the geomagnetic latitude. The field sensitive part is represented by X_b alone. All this distribution will be found near the intensity maximum of the cosmic radiation in the atmosphere at about 1 m H_2O equivalent, and it will introduce no appreciable error, if for the discussion of meson production, we assume that it is entirely concentrated there.

4. Comparison with the Number of Mesons

Unfortunately not much is known regarding the number, energy distribution, and geomagnetic effect of the hard component in the upper atmosphere. Near sea level and underground, however, more complete data are available. It seems safe to extrapolate from sea level upwards, as the mesons seem to exhibit fairly definitely a range type absorption, as shown by the comparison of energy distribution and absorption measurements. Furthermore they apparently do not multiply to a great extent once they have been created.[15]

The total number of cosmic rays per unit solid angle cm^{-2} $sec.^{-1}$ near the vertical[16] is at sea level about $j=0.015$. The number of hard rays is about 70 percent of this, i.e., $j=0.0105$. The geomagnetic effect for the hard component is of the order 12 to 15 percent, i.e., about $j=0.009$ rays must have been produced by primaries of an energy greater than ~ 18 Bev. The total number of the latter as determined from (12) is 0.011 which means that there is nearly one meson at sea level per primary high energy electron.

The energy distribution of the mesons has been studied by Anderson and Neddermeyer and by Blackett.[17] The chief result of these measurements is, that the individual energies of the mesons, though large, are comparatively small compared to the energies of the primaries to which they are due in the last instance (as shown by the geomagnetic effect). The average energy at sea level is about 3 or 4 Bev. It has been remarked by Blackett that the total energy carried by the mesons at sea level is about 1/20 of the total incoming energy or about $\frac{1}{10}$ of the energy incoming at the equator, while the number of rays there is of the same order of magnitude as the number of incoming rays.

This low average energy of the mesons leads to an important conclusion. From (13a) and (13b) one finds that the field-sensitive part of the cosmic radiation produces more quanta of energy below 6 or 7 Bev than the high energy part.[18] The total energy loss by a meson in the atmosphere from ionization is around 2 Bev, i.e., mesons created with 7 Bev will arrive at sea level with around 5 Bev. The fraction of mesons over 5 Bev at sea level is about 20 percent only (in Blackett's series 169 out of 829). If, therefore, the mesons were created by photons of the same energy, i.e., the photon energy transferred to a single meson, the geomagnetic effect would be of the order of 40 to 50 percent instead of 15 percent. Therefore mesons of a given energy below 7 Bev must have been created by photons of considerably higher energy. The most reasonable interpretation of

[15] A production of low energy meson secondaries for which there is some evidence and an additional real absorption by production of showers (compare Euler and Heisenberg, reference 1) will make no appreciable difference in the following comparison as long as the cross sections for these processes are as small as they seem to be, or as long as these effects are restricted to low energies.

[16] T. H. Johnson, Rev. Mod. Phys. **10**, 208 (1938).

[17] C. D. Anderson and S. Neddermeyer, Int. Conf. Nuclear Physics, London, 1934; P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937).

[18] This result is independent of any finer details of the primary distribution, as according to (10) the number of quanta k is proportional simply to the total energy brought in by electrons of energy higher than k.

this fact is that a photon divides its energy over several mesons, i.e., it produces them in multiples so that each meson receives only a fraction of the primary energy. The alternative hypothesis that a photon gives only a fraction of its energy to single mesons while continuing to exist with reduced energy seems less likely from the point of view of Yukawa's theory and would require correspondingly higher cross sections for the production process.

More detailed information regarding this behavior can be obtained from the analysis of the geomagnetic effect by Compton and Turner.[19] Primaries below 7 or 8 Bev give only an insignificant contribution to the cosmic radiation at sea level. As only 2 Bev are required by a meson to traverse the atmosphere the above threshold can be explained by assuming a multiplicity of 3 or 4 in the average.

We can also estimate the absolute value of the cross section for meson production. According to Compton and Turner the contribution of primaries between 7.5 and 15 Bev is about 1.3 percent per Bev energy range, i.e., in absolute numbers for the hard radiation $0.013\times 0.011 \cong 1.5\times 10^{-4}$ ray per unit solid angle cm^{-2} $\mathrm{sec.}^{-1}$. From (10) and (12) we calculate on the other hand for the total number of photon lengths with energies larger than k_0 created by electrons of energy less than E_0

$$Q(E_0, k_0)=\int_{k_0}^{E_0} dE \int_{k_0}^{E} dk Z(E, k) j(E)$$

$$=0.024\left(\frac{E_0}{k_0}-1-\log\frac{E_0}{k_0}\right)$$

and therefore for the number produced per Bev energy interval

$$\frac{dQ(E_0, k_0)}{dE_0}=0.024\left(\frac{1}{k_0}-\frac{1}{E_0}\right). \qquad (14)$$

If the minimum energy for a meson to reach sea level is ϵ Bev and the multiplicity of the production process r, then $k_0=\epsilon r$ and the probability that a photon is converted into r mesons in one unit length (39 cm H_2O) is

$$w(k)=\frac{1.5\times 10^{-4}}{0.024r[(1/\epsilon r)-(1/E_0)]}, \qquad (15)$$

which is not quite a constant but nearly so in the region of 8 to 15 Bev and of the order of magnitude 1.2×10^{-2} for $\epsilon \cong 2$ Bev. Thus the cross section has to be of the order 1/80 to 1/50 of the cross section for pair production of quanta in air, or ~ 0.5 to 1×10^{-27} cm^2 per nuclear particle. This estimate is, of course, rather rough and could be refined only with a more accurate knowledge regarding the laws of distribution of the energy of the photon over the mesons produced, but it should give a fair idea of the order of magnitude. The latter seems to be entirely reasonable from the point of view of Yukawa's theory.

The situation is, however, rather different for mesons of very high energy. An estimate of their number and distribution can be made from the absorption measurements underground,[20] if we assume that they lose energy only by ionization (or more generally that they show a specific energy loss independent of energy). If we then extrapolate backwards to the top of the atmosphere we obtain a lower limit for the number of mesons there since one would have to have a larger number to start with in case there were any additional mechanisms for absorption or degradation of energy.

If the energy distribution of mesons at the place of their generation is $M(E)dE$ then the total intensity at depth x is

$$I(x)=\int_0^\infty M(E+\beta x)dE=\int_{\beta x}^\infty M(E)dE,$$

where β is the specific energy loss. The observed x^{-s} law for the absorption ($s=1.8$ between 30 and 300 m H_2O, $s=2.4$ between 300 and ~ 1000 m H_2) results then from

$$M(E)dE=(C/E^{s+1})dE,$$
$$I(x)=C/s(\beta x)^s, \quad s=1.8 \qquad (16)$$

To determine the constant C we notice from the data of Wilson[20] that the intensity at 50 m below

[19] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937). The authors are indebted to Professor Compton for the following remark in the text.

[20] V. C. Wilson, Phys. Rev. **53**, 337 (1938); P. H. Clay, A. van Gemert and J. Clay, Physica **6**, 184 (1939).

sea level, i.e., 60 m H_2O below the top of the atmosphere is 0.073 of the intensity of 0.015 at sea level. Of this around 80 percent are mesons. Taking $\beta=0.2$ Bev per m H_2O we obtain

$$\begin{aligned} M(E)dE &= 0.14dE/E^{2.8}, \quad 6<E<60 \\ &= 1.6dE/E^{3.4}. \quad 60<E \end{aligned} \tag{17}$$

In case a different value for β is assumed the first line has to be multiplied by $(\beta/0.2)^{1.8}$ with a corresponding change in the second line.

The most important feature to be deduced from the absorption measurements is the very high penetrating power of fast mesons which corresponds to a distribution extending to very high energies. That the charged particles themselves are responsible for carrying the cosmic radiation underground has been proved by the measurements of Nielsen and Morgan and of Wilson[21] which show that the true absorption coefficient as measured by absorbing material between counters is actually as small as demanded by the power absorption law.

Comparing now the meson distribution (17) with the primary electron distribution (12) and the photon distribution (13a) we find that we have for every 26 primary electrons or every 19 photon lengths one meson of the *same* energy. If we again make the assumption that the production process is a multiple process of average multiplicity r and that the photon energy is in the average about equally distributed over the r mesons created, we obtain for the probability of such a process in one unit length

$$w(k)=\frac{0.14}{2.65}[r(k)]^{s-1}=\frac{1}{19}r^{0.8}. \tag{18}$$

With $r\simeq 3$ this is $0.13\simeq\frac{1}{8}$. If the multiplicity varies with energy the cross section has to change correspondingly. As a general result we find that the cross sections at these high energies are considerably greater than at lower energies, namely by about a factor 10, if the multiplicity of ~ 3 is conserved.

The same result regarding the efficiency of high energy quanta in producing mesons follows also from a comparison of the energy carried downward by mesons, with the total energy coming in at the equator. It follows also from the total number of photon lengths compared to the total number of mesons.

5. Difficulties of the Photon Hypothesis

We have arrived at a well-defined picture of the meson production on the photon hypothesis. There are, however, two serious objections which have to be considered in detail. From a comparison between the geomagnetic latitude and east-west asymmetry effect Johnson[22] concluded that the field-sensitive part of the cosmic radiation near sea level must be due practically entirely to positive primaries. In his new asymmetry measurements at high altitudes near the equator he found, on the other hand, that the east-west effect is rather small near the intensity maximum in the upper atmosphere. As at this location the soft component predominates[23] by far, Johnson concluded that the hard rays near sea level must be due to primaries different from electrons. There seems to be, however, a possibility of getting around this argument. The minimum energies for positives to be able to reach the equator under an angle of 60° to the vertical in the east and west directions are very far apart, *viz.*, around 32 and 11 Bev (Stoermer's limits) while the latitude effect at greater depths is determined in the main by the radiation which comes in near the vertical and is due to a much smaller energy range for the primaries. The above mentioned behavior might possibly be explained therefore by assuming that there is a large excess of positive primaries in a fairly narrow energy band near the threshold for the vertical of 15 to 18 Bev which is compensated partly or entirely by negative primaries still within the energy limits for the east-west effect.

The other difficulty is of a more intrinsic nature. The production process discussed here consists in the conversion of a photon into one or more mesons upon collision with an atomic

[21] W. M. Nielsen and K. Z. Morgan, Phys. Rev. **54**, 245 (1938); V. C. Wilson, Phys. Rev. **53**, 908 (1938).

[22] T. H. Johnson, reference 16, p. 232; T. H. Johnson and J. G. Barry, Phys. Rev. **55**, 503 (1939).

[23] The multiplication in the region of maximum intensity of a primary electron in air is of the order 1 for every Bev energy, i.e., near the equator of the order 30 (average energy for the electrons coming in at the equator). Any noticeable east-west effect observed there can then only be due either to the electrons themselves or to a radiation which also multiplies considerably in 1–2 m H_2O.

nucleus. Necessarily then the inverse processes must also be possible, i.e., processes in which the same number of photons and mesons are involved and only one meson and the photon exchange their role in initiating the process. In the case of a single process, namely the production of one meson by one photon, the inverse process is simply the one of reversed direction; in case of multiple production the inverse process is the creation by one meson of a photon and several other mesons, which all share the available energy. Such a process means either a complete absorption for the single process or for the multiple process an appreciable energy loss and degradation of the initial energy. Furthermore, as long as all individual energies are large compared to the rest energies of the involved "particles" (photons and mesons) the cross section for the inverse processes should be of the same order of magnitude as the direct processes, and in particular should show the same asymptotic behavior at high energies. This relationship between direct and inverse processes is well illustrated by the example of the normal radiative processes of electrons. The production of mesons is the analog of the pair production by quanta. The inverse process is the radiation by electrons, which, as is well known, is similarly effective in dissipating their energy as the absorption of quanta by pair production.

To the high efficiency of the production process at high energies then must also correspond a considerable rate of energy dissipation for the meson. From the value 1/19 for the probability of one process per unit length (from (18) and the assumption of single processes which is actually too favorable), one would have an average free path of around 19 times the unit length or 7 m H_2O or an absorption coefficient of 0.0011 g^{-1} cm^2. The observed integral absorption coefficient for the hard component (which includes the loss of particles by normal stopping in addition to any true absorption) is at sea level 0.0006 g^{-1} cm^2, which is already lower than the expected one, and at 100 m H_2O is as low as 1.8×10^{-4} (calculated from the power law $x^{-1.8}$ for the absorption). The discrepancy is actually more serious than would appear from the above figures. Even if one did accept the last low value (1.8×10^{-4}) which would mean a reduction of the absorption cross section by a factor 8 to 10, it would mean that one would have to increase the number of mesons created with energies sufficient to reach a depth of 100 m, by a factor e, so that the ratio of production to absorption cross section would have to be of the order 30, going to still higher values at still lower depths. The difficulty coming from the inverse processes is in fact already of a grossly qualitative nature, as the apparent constancy of the production cross section at high energies (following from the asymptotic behavior of the meson distribution as shown by the absorption underground) is incompatible with the continuous hardening of the hard component when going to greater depths, i.e., to higher energies.

It might not be absolutely impossible to overcome this difficulty by varying the primary distribution or introducing numerical factors or the like, or by inventing a mechanism which excludes the inverse processes. The situation seems, however, to be such that the burden of proof lies now on the opposite side. That is, the feasibility of the photon hypothesis (or at least the assumption of the exclusive photonic origin of the hard component) has to be demonstrated before it can be accepted.

It seems important, therefore, to discuss other possibilities, a preliminary survey of which will be presented in the following paper.