# Cosmic-Ray Meson Spectra

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In a recent paper[1] (denoted hereafter as I), Hamilton, Heitler, and Peng have proposed a comprehensive theory of the origin of cosmic-ray mesons, which appears to provide at least a qualitative interpretation of a large number of observations on cosmic-ray penetrating particles. These authors aim at giving a connected account of cosmic-ray and nuclear phenomena, and have selected that form of the meson theory which gives the best account of nuclear forces, *viz.*, that proposed by Møller and Rosenfeld.[2] According to Heitler *et al.*,[3] the meson field of a fast proton of energy $E \gg \mu c^2$ when scattered in the field of a stationary nucleon, radiates an amount of meson energy $\epsilon \lesssim E$. We take the meson mass energy $\mu c^2$ to be $10^8$ ev. The released energy $\epsilon$ may (1) result in a single meson of energy $\epsilon$ which in the process of being scattered in the field of the stationary nucleon gives rise to a single or a multiple of $n$ mesons. The cross section $\gamma_n$ for each multiplicity $n$ has a maximum at some energy $\epsilon_n$ which increases with $n$. After the maximum, $\gamma_n$ decreases rapidly, and the asymptotic expressions are

$$\gamma_1 \sim \epsilon^{-2}; \quad \gamma_n \sim \epsilon^{-2n-4} \quad \text{for} \quad n \neq 1. \tag{1}$$

Alternately (2) it may also happen that only a part $\epsilon'$ of the radiated energy is used up in meson production, and the balance is taken up by the recoiling nucleon; the latter can then produce fresh mesons by nuclear collisions. This process is analogous to cascade production of electrons.

On the assumption of a suitable primary proton energy spectrum incident on the top of the atmosphere, an expression is deduced for the energy distribution in the single-meson spectra $f(\epsilon, x)$, where $x$ is the depth from the top of the atmosphere. It is shown that the function $f(\epsilon, x)$ for a given value of $x$ has a maximum value for $\epsilon \sim 3\mu c^2$ below which it falls rapidly to zero. These critical values of $\epsilon \sim 1/f$ where $f = f' \sim \frac{1}{3}$ are the coupling constants between a nucleon and the vector and pseudoscalar components of its meson field. The decay constants of the corresponding mesons are taken to be $10^{-8}$ and $10^{-6}$ sec., respectively.

Given below are some of the results we obtained which are in agreement with the predictions of the theory.

## MESON SPECTRA

Several investigators have used Wilson chamber photographs of penetrating particles in magnetic fields to measure the meson energy spectra. The most reliable measurements for the low energy spectra appear to be those of D. J. Hughes.[4] His energy distribution curve shows a maximum near $\epsilon \sim 8 \times 10^8$ ev, and the number of penetrating particles of lower energy diminish rapidly. This is not in agreement with the distribution $f(\epsilon, x)$ in which the maximum occurs for $\epsilon \sim 3 \times 10^8$ ev.

Photographic plates exposed to cosmic rays at high altitudes are found to contain single and multiple star-like tracks. A detailed account of the results will be published by one of us (B.C.) elsewhere. In Table I are given our findings on the total frequency of multiple track distribution observed in photographic plates, kept at altitudes varying from 7000 ft. to 14,500 ft., under (1) air, (2) absorbers like water, paraffin, and wood, and (3) under lead. In every case the frequency distribution has a principal maximum at $n=1$, a second maximum at $n=3$; and in no plate was any multiple track with $n>7$ observed. The first

TABLE I. Frequency of multiple tracks.

| Absorber | Frequency of tracks | | | | | | |
|---|---|---|---|---|---|---|---|
| $n=$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Air | 192 | 30 | 87 | 63 | 38 | 5 | 3 |
| Hydrogeneous substances | 86 | 14 | 22 | 20 | 20 | 0 | 0 |
| Lead 0.5 cm to 5 cm | 69 | 19.6 | 42.3 | 34.2 | 12.9 | 2.2 | 0 |

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[1] Hamilton, Heitler, and Peng, Phys. Rev. **64**, 78 (1943).

[2] Møller and Rosenfeld, Kgl. Danske Vid. Sels. Math.-Fys. Medd. **17** (1940).

[3] Heitler and Peng, Proc. Camb. Phil. Soc. **38**, 296 (1942).

[4] D. J. Hughes, Phys. Rev. **57**, 592 (1940).

maximum is not significant, as it contains mainly tracks of ionizing particles originating outside the photographic emulsion. In a paper[5] on meson spectra, reasons were given for the conclusions that (1) the star-like tracks on photographic plates are mainly due to multiple meson production, the energy associated with each multiple $n$ is $\epsilon_n = n \cdot \mu c^2 + k$, where $k \sim 10^7$ ev represents the kinetic energy of the particles; (2) protons (neutrons) are primarily responsible for such multiple production, (3) a transition effect is observed in lead, with a maximum under 1.5 cm Pb; in this case photons directly or indirectly are responsible for the additional multiples produced. The occurrence of a maximum at $n=3$ was noticed, but no satisfactory explanation for it could be suggested.

According to I, the frequency distribution curve for the occurrence of multiples of $n$ mesons is approximately given by

$$f(\epsilon, x) \cdot (\gamma_n/\gamma_1). \tag{2}$$

The asymptotic expression for $\gamma_n/\gamma_1$ is $\epsilon^{-2n-2}$, which shows that within the energy interval for which the values of $\gamma$ have been calculated, the ratio diminishes exponentially, i.e., the expectation of occurrence of high multiplicity becomes vanishingly small with increasing $n$. According to our findings (2) has a maximum for $n=3$ corresponding to $\epsilon \sim 3\mu c^2$, and this may be taken as a qualitative verification of the occurrence of the maximum predicted according to I. Further it appears to us to be more than a mere coincidence that the region of maximum occurrence of single mesons, $\epsilon \sim 8 \times 10^8$ ev, should also coincide with the region where the production of multiple mesons cease (i.e., $> 7\mu c^2$).

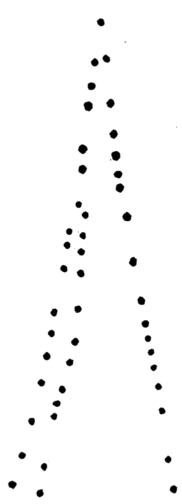

FIG. 1. Track in photographic emulsion traced by use of a camera lucida. Magnification ×760.

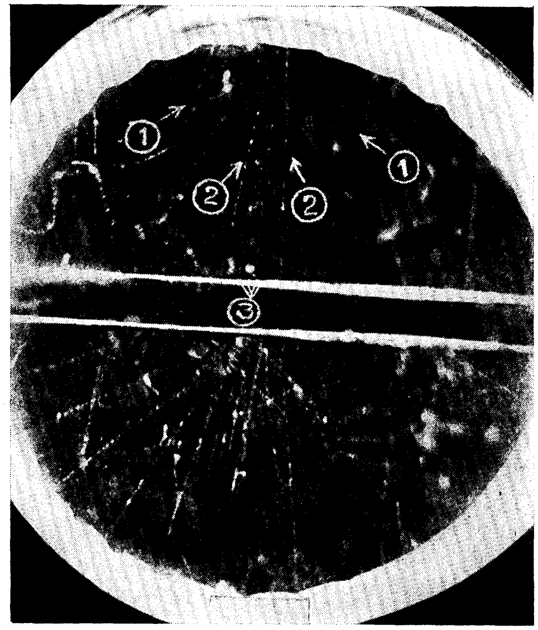


FIG. 2. Wilson cloud-chamber photograph showing production of mesons by a cascade process.

## CASCADE PRODUCTION OF MESONS

According to I a cascade production of mesons can also be expected. Hazen[6] finds no evidence of their occurrence in his high altitude Wilson chamber photographs. On the photographic plates referred to in the previous paragraph, records of at least six such events have been found. A camera lucida tracing of one of them is given in Fig. 1. Since photographic plates are exposed to cosmic rays for at least six months, it is difficult to adduce conclusive evidence that all the tracks on a plate which are considered to be due to cascade meson production have been traversed by the mesons at the same instant of time. A Wilson chamber photograph obtained by one of us (M.S.) is given in Fig. 2. It shows the

[5] D. M. Bose, Trans. Bose Research Inst. **15**, 55 (1942).

[6] W. E. Hazen, Phys. Rev. **64**, 257 (1943).

production of mesons by a cascade process. All the tracks appear to be of the same age. The tracks in Group 1 have originated outside the chamber; the other two groups have originated within the chamber. The left-hand track of group 2 is absorbed in the lead plate (2.2 cm), and its energy is $<4\times10^7$ ev. The four tracks in group 3 appear to start as a pair which is doubled again. These tracks are not appreciably scattered during their traversal through the lead plate, but they have produced knock-on electrons.

### BURST PRODUCTION

One of us (M.S.)[7] has recently published a photograph of a burst originating in the gaseous volume of a Wilson chamber. It appears to start as a number of ionization strands, diverging from a small region, which subsequently broaden and merge into a dense volume of ionization. A possible interpretation of the burst according to I is as follows: A high energy proton has by a process of nuclear collision given rise to a cascade production of fast vector mesons. The latter have within a short length disintegrated into high energy electrons, from which several cascade showers have started.

The above theory enables us to correlate and interpret many findings on penetrating particles obtained from Wilson chamber photographs and from tracks on photographic plates. A detailed comparison between the predictions of the theory and our findings will be given elsewhere.

[7] M. Sinha, Phys. Rev. **64**, 248 (1943).

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# Letter to the Editor

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## On the Maximal Energy Attainable in a Betatron

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BY means of a recently constructed induction accelerator-betatron, Kerst succeeded in obtaining electrons up to 20 Mev.[1] The principle of operation of the betatron is the acceleration of electrons by a tangential electric field produced by a changing magnetic flux, which is connected with the magnetic field keeping electrons on the orbit by a simple relation. In contrast to a cyclotron, whose applicability is essentially limited to the non-relativistic region on the ground of defocusing of orbits due to the change of mass at high energies, there is no such limitation for the betatron.

We may point out, however, that quite another circumstance would lead as well to the existence of a limitation for maximal energy attainable in a betatron. This is the radiation of electrons in the magnetic field. Indeed, electrons moving in a magnetic field will be accelerated and must radiate in accordance with the classical electrodynamics. One can easily see that quantum effects do not play here any important role as the dimension of the orbit is very great. As was shown by one of us[2] an electron moving in a magnetic field $\mathbf{H}$ radiates per unit of path the energy

$$-(dE/dX)=2/3(e^2/mc^2)^2(E/mc^2)^2[(\mathbf{V}/c)\mathbf{H}]^2 \qquad (1)$$

where $e$ is the charge, $m$ the mass, $\mathbf{V}$ the velocity, and $E$ the energy of the electron; $E$ is assumed much greater than $mc^2$.

In the betatron $\mathbf{V}$ is normal to $H$ and practically for the whole path equal to $c$. Then we have

$$-(dE/dX)=2/3(e^2/mc^2)^2(EH/mc^2)^2. \qquad (2)$$

The limiting value of energy $E_0$ is to be determined from the condition that the radiated energy (2) will be equal to energy gained by the electron in the electric field produced by magnetic flux per unit of path:[3]

$$\frac{2}{3}r_0^2\left(\frac{E_0H}{mc^2}\right)^2=\frac{e|d\phi/dt|}{2\pi R_0c}=\frac{e}{c}R_0|\dot{H}| \qquad (3)$$

$$\dot{H}=dH/dt \qquad r_0=e^2/mc^2.$$

Here $R_0$ is the radius of the orbit, $\phi$ is the induction flux.[1]

Hence:

$$\frac{E_0}{mc^2}=\left(\frac{3eR_0}{2r_0^2c}\frac{\dot{H}}{H^2}\right)^{\frac{1}{2}}. \qquad (4)$$

Taking for $H$ and $E$ the values now being in use we get $E_0\approx5\times10^8$ ev, which is only five times as great as the energy which one expects to obtain in the betatron now under construction. From (4) one sees that $E_0$ is inversely proportional to the magnetic field applied and proportional to the square root of energy gained in the rotation electric field per unit of path. All this requires the using of smaller $H$ or of higher frequencies with the purpose of getting higher limiting values of $E_0$.

The radiative dissipation of energy of electrons moving in a magnetic field must be also of importance for the discussion of the focusing of the electronic beam, as the energy of particles being accelerated will grow more slowly with the growth of $H$ if the radiation is taken into account. This latter question may deserve a separate discussion.

[1] D. W. Kerst, Phys. Rev. **61**, 93 (1942).
[2] I. Pomeranchuk, J. Phys. **2**, 65 (1940).
[3] D. W. Kerst and R. Serber, Phys. Rev. **60**, 53 (1941).

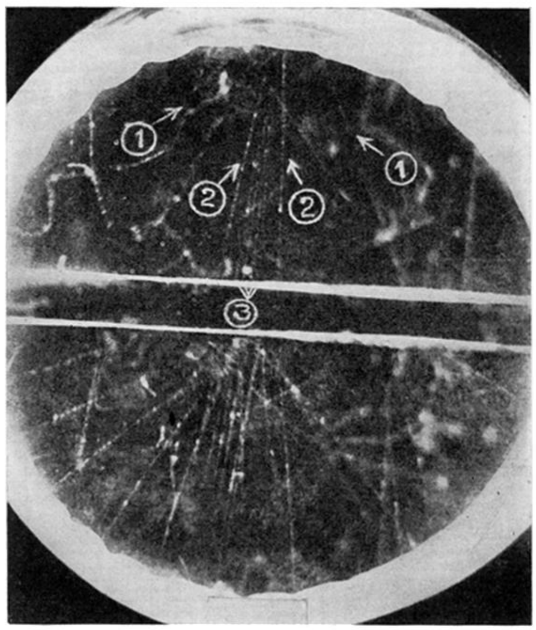


FIG. 2. Wilson cloud-chamber photograph showing production of mesons by a cascade process.