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Note on the Production of Cosmic-Ray Mesons

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It is pointed out that the cross sections for the production of mesons in collisions between heavy particles given by Hamilton, Heitler, and Peng are so large that a heavy particle crossing an atomic nucleus must be expected to collide several times inside the same nucleus. This hypothesis accounts for cloud-chamber observations showing the production of several mesons in one point. Anticoincidence experiments of Jánossy and Rochester can also be interpreted easily by the theory of HHP when the occurrence of multiple collisions is assumed.

I. INTRODUCTION

IN a recent publication Hamilton, Heitler, and Peng[1] (quoted as HHP) investigate theoretically fast collisions between neutrons and protons. It is found that in fast collisions between heavy particles mesons are emitted. The cross section for the emission of mesons is found to be of the right order to account for most cosmic-ray phenomena. In the following we attempt to add to one point of the theory of HHP.

Cloud-chamber photographs of penetrating showers obtained by various observers[2–4] frequently show small groups of mesons diverging from a common center. These photographs are most easily interpreted on the assumption that mesons are produced simultaneously in small groups.

A typical photograph of this kind obtained recently by Jánossy, McCusker, and Rochester[4] is reproduced in Fig. 1. The photograph shows three tracks diverging from a point above the chamber. Each of the three tracks is passing through a lead plate, placed across the chamber, but none of the particles starts a cascade while passing through the plate. Thus the tracks cannot be assumed to be electrons. The simplest interpretation of the photograph is to assume that at least two of the three particles are mesons produced simultaneously in one point. The third particle is either a third meson or the primary particle which created the group.

The theory of HHP assumes that a fast heavy particle produces mesons one by one in succession. Multiple processes are mentioned as a possible source for the groups but are not dealt with by HHP. We wish to point out in the following that the groups of mesons observed can be accounted for in a simple way without considering multiple processes in the strict sense.

II. MULTIPLE COLLISIONS

The cross section for a fast neutron or proton to produce a meson with the energy greater than E in a collision with another heavy particle is according to HHP

$$\Phi(E) = 1.5 \times 10^{-24}/E \text{ cm}^2. \quad (1)$$

All energies are measured in units of μc^2, where μ is the mass of the meson.

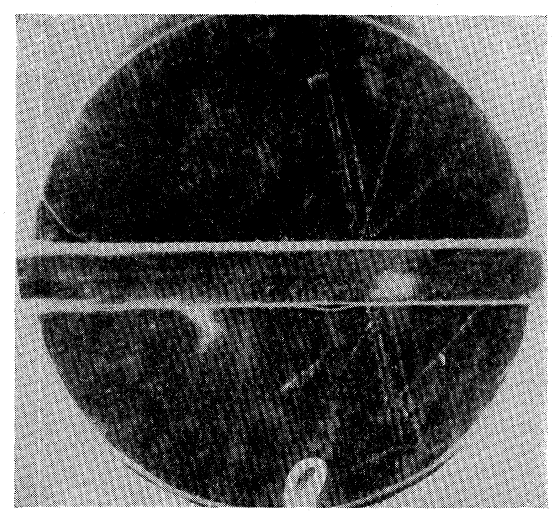

FIG. 1. Meson shower, showing three penetrating particles passing through a lead plate.

[1] Hamilton, Heitler, and Peng, Phys. Rev. **64**, 78 (1943).
[2] Braddick and Hensby, Nature **144**, 1012 (1939); G. Herzog and W. H. Bostick, Phys. Rev. **58**, 218 (1940).
[3] W. M. Powell, Phys. Rev. **58**, 474 (1940); **60**, 413 (1941).
[4] W. H. Bostick, Phys. Rev. **61**, 557 (1942); Jánossy, McCusker, and Rochester, Nature **148**, 660 (1941).

For moderately large values of the energy E the cross section given in (1) is so large that a fast heavy particle passing through a nucleus is likely to collide *several* times during the passage through the nucleus; several mesons may therefore be emitted in a collision with one nucleus. The collision of a fast heavy particle with a nucleus can be considered schematically as follows.

The radius of a nucleus of the weight A can be assumed to be $r_A = 0.53(e^2/mc^2)A^{\frac{1}{3}}$ (compare Heisenberg[5]). The centers of the heavy particles forming the surface of the nucleus thus have an average distance $\bar{r}_A$ from the center of the nucleus given by (2),

$$\bar{r}_A = 0.53(e^2/mc^2)(A^{\frac{1}{3}} - 1). \tag{2}$$

Geometrically a collision between a constituent of the nucleus and the fast particle can take place when the fast particle passes at a distance less than $x = \bar{r}_A + r_E$ from the center of the nucleus, r_E being the radius of a disk with the area $\Phi(E)$ whence $\pi r_E^2 = \Phi(E)$. The heavy particle passing through the nucleus has a chance to pass between the nuclear constituents without a collision. The probability for a passage without collision can be estimated roughly as

$$p = \exp\left[-\Phi(E)/(\pi \bar{r}_A^2/A)\right], \tag{3}$$

and therefore the effective cross section for the emission of at least one meson of the energy E in a collision with a nucleus of the weight A is estimated roughly as

$$\Phi(A, E) = (1-p)\pi(r_E + \bar{r}_A)^2. \tag{4}$$

Inserting numerical values one finds

$$\Phi(A, E) = 1.5\times 10^{-24}/E \times (1 + aE^{\frac{1}{2}})^2 (1 - \exp[-b/E]). \tag{4a}$$

The constants a and b are functions of A only: Some values are given in Table I. Note that $\Phi(A=1, E) = \Phi(E)$ and that for large values of $E\Phi(A, E) \rightarrow A\Phi(E)$ as it must be expected.

TABLE I.

	Pb	Al	O	H
a	1.05	0.43	0.33	0
b	178	140	145	∞

[5] Heisenberg, Leipz. Ber. **89**, 369 (1937).

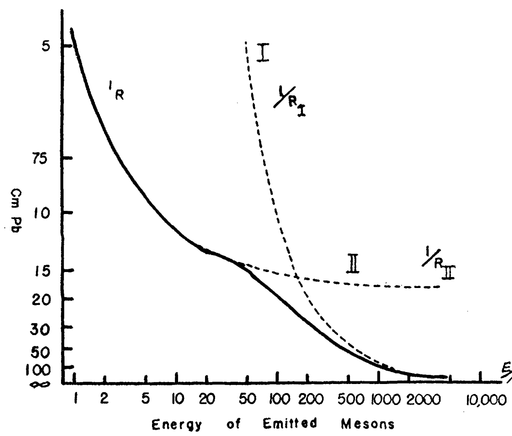

FIG. 2. Mean free path of fast heavy particles in lead. Curve I, $1/R_{\rm I}$, packing neglected. Curve II, $1/R_{\rm II}$, compact nucleus.

The reciprocal mean free path $1/R = N\Phi(A, E)$ as function of E for heavy particles in lead is plotted in Fig. 2 with the full line. N is the number of atoms per cc. The broken line marked I in Fig. 2 represents the reciprocal mean free path, $1/R_{\rm I} = NA\Phi(E)$, one would expect if the packing of the nuclear particles could be neglected. The broken line marked II represents $1/R_{\rm II} = N\pi(r_E + \bar{r}_A)^2$, the reciprocal mean free path one would expect if we neglect the possibility of a fast particle traversing a nucleus without encounter, i.e., regarding the nucleus as compact.

It is seen from Fig. 2 that for the emission of mesons with energies up to 5×10^9 ev ($E=50$), the lead nucleus can be regarded as compact, while for the emission of mesons of energies above 10^{11} ev ($E=1000$), the nuclear particles can be regarded as independent.

The average number n_A of mesons with energies exceeding E emitted by a sufficiently energetic fast particle while traversing a nucleus of weight A is expected to be

$$n_A = A\Phi(E)/\Phi(A, E) = A(1 + aE^{\frac{1}{2}})^{-2}(1 + \exp[-b/E])^{-1}. \tag{5}$$

The multiplicities thus obtained for lead are given in Table II. For lighter nuclei the multiplicities are somewhat smaller. The values obtained for n_A include pseudoscalar and transverse mesons as well as neutrettos.

The argument leading to Eqs. (4) and (5) assumes the nuclear particles to be independent.

This is of course not correct and in the accurate treatment interference would have to be taken into account. In the case of the emission of slow mesons the effect of interference may be serious. In the case of fast mesons, however, the de Broglie wave-lengths of the primary particle and of the emitted mesons are small compared with the average distances of the nuclear particles and the frequencies of both the primary particle and the emitted mesons are large compared with the nuclear frequencies. It is therefore likely that the results obtained on the assumption of independent nuclear particles are at least qualitatively correct for the emission of fast mesons.

We conclude therefore that the theory of HHP leads us to expect that mesons are produced in small groups.

III. COMPARISON WITH EXPERIMENTS

A. Cloud Chamber

The values of the multiplicities n_A given in Table II are, of course, only valid for primaries having sufficient energy to produce the required number of mesons. Primaries having less energy will be stopped completely inside the first nucleus with which they collide closely. The energy required to pass through a nucleus is of the order of 200. The energy required to pass through the atmosphere is according to HHP of the order of 10,000; the average energies of primaries which succeed in traversing the atmosphere must be expected to be of the same order. Thus it is expected that most of the primary particles reaching sea level have sufficient energy to traverse a lead nucleus.

The multiplicities n_A seem, however, to be too large to be compatible with the experimental evidence from cloud-chamber photographs. The predominance of small groups on photographs containing meson showers may be explained by assuming that most of the fast heavy particles near sea level are recoil particles produced by the primaries. The average energy of the recoil particles must be assumed to be small; and most of the recoil particles will have energies only sufficient to produce small groups.

In Fig. 3 a photograph of a big shower obtained by McCusker is reproduced. As the chamber was controlled with a heavy bias towards penetrating showers, it is not unlikely that this photograph represents a penetrating shower produced by a very energetic primary proton or neutron. The tracks seen on the photograph are, however, so numerous that it is impossible to decide whether or not some of the particles are mesons.

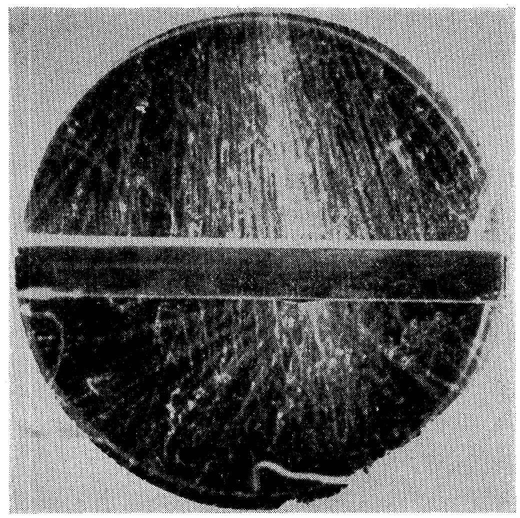

FIG. 3. Large shower obtained with an arrangement giving strong bias towards penetrating showers.

Shower photographs of Blackett and Occialini[6] and of Anderson[7] give evidence for the occurrence of slow heavy particles in showers. Jánossy, McCusker, and Rochester[4] have suggested that the occurrence of slow heavy particles is connected with penetrating showers. We note that the occurrence of slow heavy particles in penetrating showers is well accounted for by the theory of HHP in terms of slow recoil particles.

B. Counter Experiments

1. Transition Effect of Penetrating Showers[8]

Using a counter arrangement as shown in Fig. 4 we have recorded coincidences involving

TABLE II. Number of mesons with energy greater than E emitted by a fast heavy particle crossing a lead nucleus.

E	5	10	100	1000
n_A	18	11	1.7	1

[6] Blackett and Occialini, Proc. Roy. Soc. **A139**, 699 (1933).
[7] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1937).
[8] L. Jánossy and Ingleby, Nature **145**, 511 (1940); L. Jánossy, Proc. Roy. Soc. **A179**, 361 (1941).

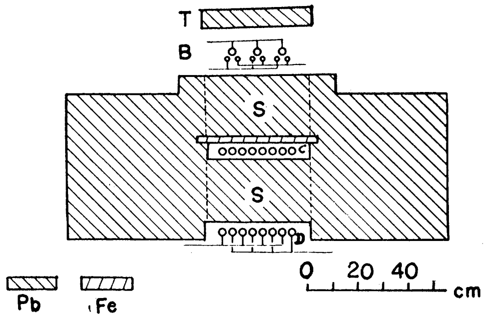

FIG. 4. Arrangement for observing penetrating showers.

the discharges of more than one counter out of each of the counter trays B, C, and D. The counter trays were separated by lead absorbers 15 cm thick, and the whole arrangement was surrounded with an absorber 50 cm thick. It was shown that most of the coincidences were due to penetrating showers. The rate of penetrating showers was found to increase when a lead absorber T was placed close above the top tray B. The increase was considerable for T a few cm thick, while no increase was found for thicknesses larger than five cm of lead. More detailed measurements of the transition effect will be reported shortly by Rochester and Jánossy.

2. *Production of Penetrating Showers by Non-Ionizing Radiation (Jánossy and Rochester*[9]*)*

The arrangement is shown in Fig. 5. The lower part of the arrangement consisted of a coincidence arrangement sensitive to penetrating showers. The absorber T was surrounded with a set of anticoincidence counters A. Anticoincidences A–BCD, that is, coincidences BCD not accompanied by the discharge of any of the counters A, were recorded. These anticoincidences were largely due to penetrating showers started by non-ionizing particles falling on T.

To obtain information about the mean free path of the non-ionizing radiation giving rise to penetrating showers an absorber Σ was placed over the anticoincidence counters. It was found that five cm of lead placed above the counters A did not noticeably affect the anticoincidence rate. However, a lead absorber 35 cm thick placed over the anticoincidence counters cut down the rate of anticoincidences considerably. It was thus concluded that the mean free path of the non-ionizing radiation well exceeded 5 cm of lead. Thus the non-ionizing radiation could not be assumed to consist of photons, and it was suggested that it might consist of neutrons.

To avoid confusion we note that the term mean free path is used in the sense as the average distance a particle has to travel before encountering a collision of some specified kind. This mean free path is in general different from the range of a particle. If a particle is capable of suffering several collisions before being brought to rest, the range exceeds the mean free path considerably.

C. Interpretation of the Counter Experiments

The counter experiments described above were interpreted by HHP in terms of incident protons and neutrons. While we agree with this interpretation, we wish to point out that considerable difficulties are removed by introducing our hypothesis that a heavy particle collides several times in one nucleus.

1. If the collisions of a fast primary were distributed at random along its path and not crowded together into nuclei, then the mean free path for the production of mesons of energies greater than E could be obtained from Eq. (1) as

$$R_{\mathrm{I}} = 1/NA\Phi(E) = E/10 \text{ cm Pb.} \qquad (6)$$

Thus a fast particle traversing a few mm of lead would be expected to give rise to secondaries

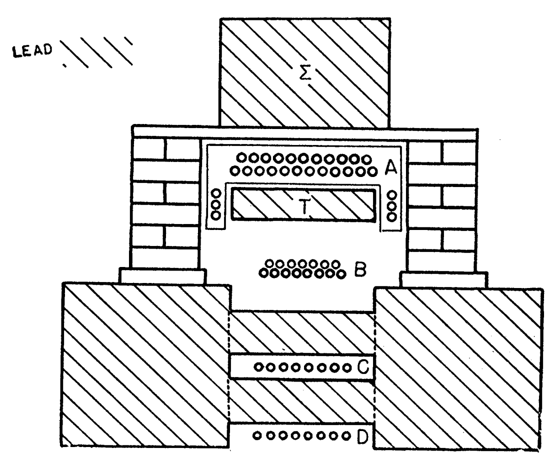

FIG. 5. Anticoincidence arrangement (Jánossy and Rochester).

[9] L. Jánossy and G. D. Rochester, Nature **150**, 633 (1942); Proc. Roy. Soc. **A** (in press); J. G. Wilson, Proc. Roy. Soc. **A174**, 73 (1940).

which would emerge together with the primary. This, however, is clearly incompatible with the interpretation of the anticoincidence experiment in terms of neutrons described in Section III, B2. The anticoincidence experiment shows that the non-ionizing particles have a good chance of penetrating five cm of lead without an encounter leading to ionizing secondaries emerging out of the lead.

Considering, however, the crowding of collisions, the mean free path of a primary has to be obtained by using Eq. (4). One finds

$$R=(1/N)\Phi(A,E). \quad (7)$$

Inserting numerical values one sees that R is much greater than R_{I}. R, however, decreases rapidly with decreasing energy E, and the value R_0 of R corresponding to the mean free path as observed in the anticoincidence experiment is obtained as follows.

Collisions giving rise to mesons of energies so low that they are stopped inside the absorber do not prevent a neutron from giving rise to an anticoincidence.[10] Such collisions can therefore be neglected when considering anticoincidence experiments. Roughly one can neglect all collisions corresponding to values of E smaller than E_0 when the value of E_0 is chosen in such a way that the mean free path $R=R_0$ obtained from (7) for $E=E_0$ is equal to the range of mesons of the energy E_0. For lead one finds

$$E_0\sim 2, \quad R_0\sim 7 \text{ cm Pb} \quad (8)$$

in good agreement with the experiment.

2. The transition effect of penetrating showers described in Section III, B1 can be interpreted in terms of protons and neutrons giving rise to penetrating showers in the absorber T. Saturation is expected for thicknesses somewhat exceeding R_0. This is compatible with the experimental results.

[10] A neutron, however, can be transformed into a proton while suffering a low energy collision, and thus it can be prevented from giving rise to an anticoincidence even if the mesons created in the collision remain inside the absorber. The loss of neutrons due to this process is, however, compensated by the gains of protons which are converted into neutrons in low energy collisions.

Comparing the results of the two experiments described in Section III, B, one finds that five cm of lead put into the path of the non-ionizing radiation has little effect on the anticoincidence rate, and therefore the mean free path of the neutral particles appears to be well above five cm of lead. Regarding the ordinary transition effect (Section III, B1), we note that most of the transition effect is over after five cm of lead. Thus it appears as if the ionizing radiation producing penetrating showers had a shorter mean free path than the non-ionizing radiation. If the two radiations consist of neutrons and protons as we think they do, this may indicate that the mean free path of protons is somewhat less than that of neutrons.

On the other hand the difference between the two experiments can probably be accounted for without assuming different mean free paths for protons and neutrons in the following way.

Penetrating showers are known to be accompanied by extensive air showers. A neutron falling on the anticoincidence arrangement (Fig. 5) may fail to produce an anticoincidence when accompanied by a sufficiently dense air shower as the air shower is likely to discharge some of the anticoincidence counters.

An absorber Σ five cm thick placed above the anticoincidence counters has a twofold effect. First, some of the neutrons which would be recorded without the absorber Σ give rise to mesons while passing through it and thus are not recorded. Secondly, some neutrons originally accompanied by air showers may be stripped of the shower while passing through Σ. Thus neutrons which are stripped of the accompanying cascade and happen to pass through Σ without encounter are recorded additionally because of the presence of Σ. The two effects may compensate each other to some extent, and it is quite likely that this accounts for the small absorption observed in the first five cm of lead.

I am indebted to Professor W. Heitler for valuable comment and for communicating his results, and also to Dr. G. D. Rochester for valuable discussion.

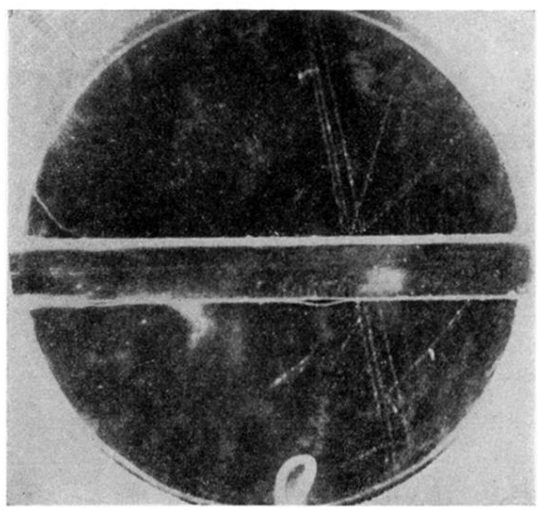

FIG. 1. Meson shower, showing three penetrating particles passing through a lead plate.

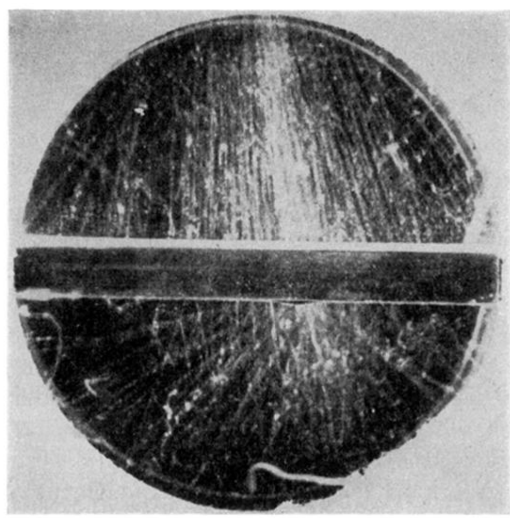

FIG. 3. Large shower obtained with an arrangement giving strong bias towards penetrating showers.