

responsible for more than a small fraction of the observed difference.

Similarly, it does not seem possible to account for this difference by a difference in the energy loss of mesotrons in air and in carbon.

Consequently our results strongly support the hypothesis of the instability of the mesotrons which form the hard component of the cosmic radiation.

The apparent lack of dependence of the average range upon atmospheric depth does not seem serious at the present because there is no definite knowledge about the variation of the mesotron energy spectrum with altitude and

because the statistical fluctuations in the experimental values of the average range L are still large.

The writers acknowledge with thanks the helpful discussions and the support given to this work by Professor A. H. Compton. They are greatly indebted to Dr. J. C. Stearns for the facilities made available in Colorado and to Mr. O. E. Polk and Mr. W. Bostick for their generous assistance throughout the experiments. Finally, they wish to express their appreciation to the National Carbon Company for facilitating these experiments by lending them the large amount of graphite required.

MARCH 15, 1940

PHYSICAL REVIEW

VOLUME 57

Electrons Arising from the Disintegration of Cosmic-Ray Mesotrons

BRUNO ROSSI

Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois

(Received January 22, 1940)

A simple theoretical expression is deduced for the ionization produced by the electrons arising from the disintegration of cosmic-ray mesotrons.

SEVERAL experimental facts indicate that the mesotrons which form the hard component of cosmic rays are unstable and that a considerable number of them actually disintegrate as they come down in the atmosphere. In each disintegration process an electron is supposed to be produced which carries the electric charge of the mesotron, while, in order to fulfill the requirements of the conservation laws, the emission of a neutrino is also postulated. The electron gets, on the average, half of the total energy of the mesotron and it then multiplies according to the cascade theory. Thus, the decay should increase the number of electrons which accompany the mesotron beam in the atmosphere, as compared with the number of those present in a condensed material. In the latter, of course, the disintegration practically does not occur until the mesotrons are stopped by ordinary energy loss and then the decay electrons have only a relatively small energy (half of the rest energy of the mesotrons, i.e., about 40 million ev).

The number of electrons arising from the decay has been estimated by Ferretti and by Euler.¹ The calculations involve the multiplication theory and are accurate to the same extent as the multiplication theory itself. This theory gives reliable results only for electrons with energies sufficiently larger than the critical energy E_c ($E_c = 1.5 \times 10^8$ ev in air), while most of the observed electrons have energies of the same order or smaller than E_c .

I wish to show that more definite conclusions can be reached by computing directly the amount of ionization produced by the decay electrons without recourse to the multiplication theory. The method is very obvious, but it may be of some interest since it provides a fairly accurate relation between measurable quantities, thus suggesting a further experimental test of the disintegration hypothesis.

¹ B. Ferretti, *Nuovo Cimento* **15**, 421 (1938); H. Euler, *Zeits. f. Physik* **110**, 692 (1938). See also H. Euler and W. Heisenberg, *Ergebn. d. Exakt. Naturwiss.* **17**, 1 (1938).

Let c be the velocity of light, m_0 the rest mass of the mesotrons, τ_0 their lifetime, βc the velocity, $p = \beta/(1 - \beta^2)^{1/2}$ the momentum measured in the $m_0 c$ unit, $E = m_0 c^2(1 + p^2)^{1/2}$ the energy (including the rest energy), $-(1/m_0 c^2)(dE/dx) = a/\beta^2$ the ionization loss in air (measured in $m_0 c^2$ per g/cm²). The experiments, by which we measure the so-called intensity of the hard component, generally give the number N of the mesotrons above a certain momentum p_0 , which is determined by the thickness x_0 of the absorber used to cut off the soft component. With a lead absorber of 14 cm, for instance ($x_0 = 160$ g/cm²), p_0 is about 4. Let $f(p)$ be the differential spectrum of the mesotrons. Then

$$N = \int_{p_0}^{\infty} f(p) dp. \quad (1)$$

Let W be the total energy removed by the decay from the mesotron beam in a layer of 1 g/cm² of air. We may put $W = W_1 + W_2 + W_3$, where W_1 represents the contribution of the mesotrons above p_0 , W_2 that of the mesotrons below p_0 and W_3 that of the mesotrons which are brought to rest before disintegrating. The probability of decay in a layer of 1 g/cm² of air for a mesotron with momentum p is $1/(\rho c \tau_0 p)$, ρ being the density of the air. Then

$$W_1 = \frac{m_0 c^2}{\rho c \tau_0} \int_{p_0}^{\infty} f(p) \frac{(1 + p^2)^{1/2}}{p} dp.$$

Since for $p > p_0$ we may assume $(1 + p^2)^{1/2}/p = 1$ (the error is smaller than 3 percent for $p > 4$),

$$W_1 = \frac{m_0 c^2}{\rho c \tau_0} \int_{p_0}^{\infty} f(p) dp = \frac{m_0 c^2}{\rho c \tau_0} N. \quad (2)$$

W_2 turns out to be small as compared with W_1 , due to the small number of mesotrons with momentum smaller than p_0 . Hence, it is only necessary to estimate W_2 approximately and a quite sufficient approximation is reached by calculating the momentum spectrum for $p < p_0$ on the assumption that the absorption curve of the mesotron beam in a dense absorber has a constant slope between 0 and x_0 . It follows that

$$\frac{f(p)}{f(p_0)} = \frac{-(dp/dx)_{x=x_0}}{-(dp/dx)_{x=x}},$$

where $-dp/dx$ is the "momentum loss" per g/cm² due to ionization and is given by

$$\frac{dp}{dx} = \frac{-(dE/dx)}{(dE/dp)} = \text{const} \frac{(1 + p^2)^{1/2}}{p^3}.$$

Since we may assume $(1 + p_0^2)^{1/2}/p_0^3 = 1$, it is

$$f(p) = f(p_0) p^3 / (1 + p^2)^{3/2}$$

and

$$W_2 = \frac{m_0 c^2}{\rho c \tau_0} f(p_0) \int_0^{p_0} \frac{p^2}{1 + p^2} dp = \frac{m_0 c^2}{\rho c \tau_0} f(p_0) (p_0 - \text{arc tg } p_0). \quad (3)$$

Finally, on our assumption, the number of mesotrons which are brought to rest in 1 g/cm² of air is $af(p_0)$, and the energy released by the subsequent decay of these mesotrons is

$$W_3 = m_0 c^2 af(p_0). \quad (4)$$

The absorption coefficient μ of the mesotron beam, as given by the absorption curve in a dense material at $x = x_0$, is $af(p_0)/N$. Accordingly, (3) and (4) can be written as follows

$$W_2 = \frac{m_0 c^2}{\rho c \tau_0} (p_0 - \text{arc tg } p_0) \frac{N}{a} \mu, \quad (3')$$

$$W_3 = m_0 c^2 N \mu. \quad (4')$$

Assuming $m_0 c^2 = 8 \times 10^7$ ev, $\tau_0 = 2 \times 10^{-6}$ sec., $a = 0.025$ $m_0 c^2$ per g/cm², $p_0 = 4$, $\rho = 1.29 \times 10^{-3}$ g/cm³, $\mu = 0.6 \times 10^{-3}$ cm²/g (sea level values), we compute

$$\begin{aligned} W_1/N &= 1 \times 10^6 \text{ ev per g/cm}^2, \\ W_2/N &= 0.065 \times 10^6 \text{ ev per g/cm}^2, \\ W_3/N &= 0.05 \times 10^6 \text{ ev per g/cm}^2. \end{aligned}$$

As already mentioned, half of the energy $W_1 + W_2 + W_3$ released by the decay goes into electrons, which then multiply giving rise to more or less complex showers. In any case, however, this energy is finally dissipated in the ionization produced either by the decay electrons themselves or by their secondary shower electrons. Since the average energy V_0 required to produce an ion is nearly a constant ($V_0 \approx 32$ ev), we are in a position to calculate immediately the amount of ionization due to the secondary electrons arising from the decay. If we further

assume the penetrating power of the showers to be small as compared with that of the mesotron beam, formulae (2), (3') and (4') enable us to express the above ionization as a function of the local mesotron intensity N . We may state, indeed, that, as a result of the decay, each mesotron with momentum above p_0 coming down from the atmosphere is accompanied by an electron radiation which gives rise to

$$\left. \begin{aligned} J_d &= (W_1 + W_2 + W_3) / (2V_0N), \text{ or, at sea level,} \\ J_d &= 1.7 \times 10^4 \text{ ions per g/cm}^2 \text{ of air.} \end{aligned} \right\} (5)$$

In order to estimate the relative magnitude of J_d , we may note that, at sea level, the ionization is mainly due to the mesotrons and to the secondary electrons to which they give rise either by close collisions with atomic electrons or by disintegration. Showers generated by primary electrons contribute only a small fraction. The total number of mesotrons is $N(1 + \mu x_0) = 1.1N$. Their average energy loss may be taken as equal to 2×10^6 ev per g/cm², hence the total number of ions which they produce in 1 g/cm² is $7 \times 10^4 N$. This figure includes the ions generated directly as well as those produced by the electrons arising from close collisions. It follows that J_d amounts to $(1.7 \times 10^4) / (7 \times 10^4) = 0.24$ times the ionization produced directly and indirectly by the mesotrons themselves.

It should, therefore, be comparatively easy to test the existence of the decay electrons by ionization chamber measurements performed with and without a lead absorber in order to separate the electron from the mesotron component. Measurements at high altitude under a layer of some dense material should be compared with measurements at lower altitude without this layer, the amount of matter above the apparatus being the same in both cases. Under the dense layer electrons from primary showers

or from close collisions are still present, while the decay electrons are reduced to a negligible fraction of those observed under air.

No such experiments with and without lead have been performed so far. Bernardini and his collaborators, however, carried out recently some counter measurements which failed to detect the decay electrons.² Unfortunately, it is difficult to compute exactly the number of counts to which the decay electrons should give rise in an experiment like Bernardini's, as the number of electrons recorded with a given counter set depends rather critically upon the experimental arrangement. A rough estimate may be obtained remembering that the intensity measurements on cosmic rays with ionization chambers and with counters can be brought into agreement by ascribing to the cosmic-ray particles a specific ionization equal to about 100 ions per cm of standard air, i.e., 7.75×10^4 ions per g/cm². It then follows from (5) that about 22 decay electrons from every 100 mesotrons above p_0 should be expected at sea level. This number is large enough as to let Bernardini's negative result appear as an argument against the hypothesis that the mesotrons may disintegrate with a lifetime as small as 2×10^{-6} sec. Since, however, a large arbitrariness is connected with the above choice of the specific ionization, it is not yet possible to decide whether or not a real disagreement exists between the results of Bernardini and those which support the hypothesis of the disintegration of mesotrons.

The writer expresses his appreciation to Professor A. H. Compton and to Professor C. Eckart for reading and discussing the manuscript of this paper.

²G. Bernardini, B. N. Cacciapuoti and O. Piccioni, *Ricerca Scient.* **10**, 809 (1939).