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The Mesotron Component of Cosmic Rays

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From experimental and theoretical results a complete qualitative picture of the mesotron component is evolved. The intensity, the production, the decay-coefficient of the mesotrons in the whole atmosphere as well as the origin of the mesotrons at sea level are obtained in the form of curves. It is further shown that this picture gives a satisfactory interpretation of the anomalous absorption, the atmospheric effects and the latitude effect at sea level.

INTRODUCTION

THE cascade theory of electron showers which is based on relativistic quantum mechanics has been successfully applied to the results of cosmic-ray experiments. The observed intensity of cosmic rays in the high atmosphere as well as the latitude effect at high altitudes have been explained by the same primary energy spectrum.

The cascade theory, however, cannot give an interpretation of cosmic-ray intensity at sea level consistent with the latitude effect at the same height. It is known that nearly all the cosmic-ray particles at sea level are not electrons but particles of higher penetrating power which must, at least partly, be of secondary origin on account of their decay.[1,2]

Although all the measurements of the absorption of the mesotron component give a real radioactive decay, they are not in quantitative agreement. In the present paper it is attempted to give an explanation of these differences as well as a consistent picture of the formation and decay of the mesotrons in the whole atmosphere.

THE MESOTRON INTENSITY IN THE ATMOSPHERE

The total number of cosmic particles which travel in a vertical direction has been known for some time from sea level to a height of 30 km[3] (curve 1, Fig. 1). Recently the number of particles penetrating 4 to 18 cm of lead has been measured.[4–7] At sea level this number is about 80 percent of the total intensity[8] (point A). The relative intensity of the hard component in the whole atmosphere (curve 2) is obtained by tracing the curve of the penetrating particles through this point. Thus an upper limit for the mesotron intensity which itself is assumed identical with the penetrating particles only up to a height of 8 km is found. This assumption might not be completely correct even at low

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[3] G. Pfotzer, Zeits. f. Physik **102**, 23 (1936).
[4] E. G. Dymont, Nature **144**, 782 (1939).
[5] A. Ehmert, Zeits. f. Physik **115**, 326 (1940).
[6] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **57**, 847 (1940).
[7] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 615 (1941).
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altitudes as shown by the relative occurrence of slow mesotron and proton tracks at 4300-m altitude which contain about 70 percent mesotrons and 30 percent protons.[9]

Further the number of mesotrons at the limit of the atmosphere must be zero on account of their decay. A third value for the construction of the mesotron curve is the position of its maximum which must be below the height of the maximum production of mesotrons. As is found later the difference in height of the two maxima should be small because of the high decay-coefficient at that height which is independent of the mesotron intensity within wide limits. The precise shape of the curve (curve 3) found in this way is not important for the present purpose.

THE PRODUCTION OF MESOTRONS IN THE ATMOSPHERE

The production of mesotrons in a block of 2-cm lead has been measured between pressures of 30 and 5 cm Hg.[6] In order to extrapolate the results to the whole atmosphere the following assumptions are made:

(1) The mesotrons are produced in pairs by photons which must have at least an energy of twice the rest mass of a mesotron. The minimum energy is set at 4×10^8 ev.[4] The number of these photons is proportional to that of the electrons of the same energy.

(2) The production of mesotrons is independent of the energy of the photon provided it is above the minimum.

A curve representing the number of electrons in the atmosphere with an energy $>4\times10^8$ ev is calculated by making use of the cascade theory[10] and the primary energy spectrum.[11] A curve (curve 4) parallel to this is traced through the measured points *B*, *C*, *D*, *E* the position of which is given by the experiment[6] in relation to the intensity of the penetrating particles (curve 2). The good fit of the points and the curve is a justification of the assumptions. The second of these is not necessarily correct because the relative energy spectrum of the mesotron producing rays does not change considerably below the maximum of the total intensity at 8 cm Hg. A further point lies considerably below the curve, but as it has been measured in a thicker block (5 cm Pb), the producing radiation is absorbed in it to a greater extent. The original point lies, when expressed in radiation units, at a depth $l=17$. The additional absorber is $l=2/0.4=5$ which brings the total depth to 22

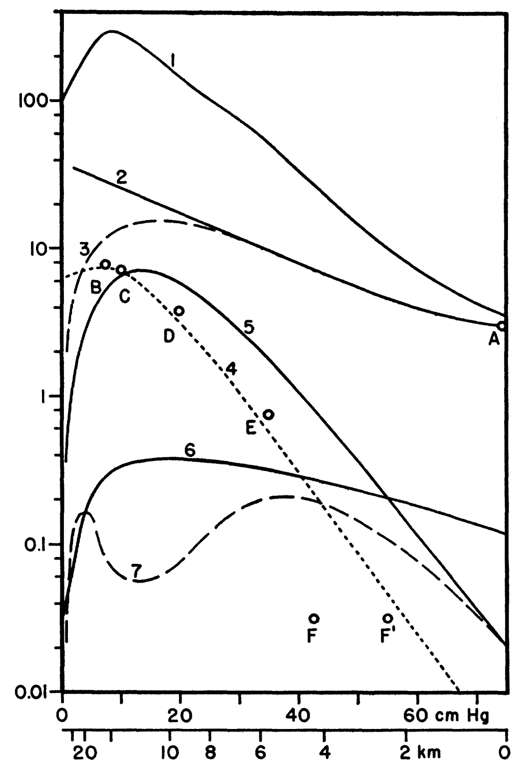

FIG. 1. Curve 1: Total number of cosmic-ray particles at latitude 50° North; curve 2: number of penetrating particles; curve 3: number of mesotrons; curve 4: number of mesotrons produced in 2-cm lead; curve 5: number of mesotrons produced in a column of air 1 km high; curve 6: decay coefficient per km of mesotrons; curve 7: contribution of layers 1 km thick to number of mesotrons at sea level.

and the point to position F'. Thus the agreement becomes satisfactory.

A transformation from lead to air is necessary for obtaining the production in the atmosphere itself. In the absence of an adequate theory this transformation is assumed to be proportional to the number of protons and neutrons in a nucleus or to the mass. Thus multiplying the production per gram and per cm^2 with the air mass in a

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[10] H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **A159**, 432 (1937).

[11] W. Heitler, Proc. Roy. Soc. **A161**, 261 (1937).

column of 1-km height and of 1-cm^2 section one obtains the production of mesotrons per km (curve 5).

Because of the decrease of the production of mesotrons and the increase of the density of air with increasing pressure, the production in air goes through a maximum at a height of 12 km (15 cm Hg), i.e., considerably below the maximum of total intensity.

THE DECAY OF THE MESOTRONS

In certain radioactive decay experiments the production of the radioactive elements continues during the measurement of the decay rate. Similar conditions apply to the present problem for which the decay equation is:

$$(\alpha+\beta)N=(dN/dH)+P.$$

In this α is the absorption coefficient, β the decay coefficient, N the number of particles, H the height above sea level, P the production of mesotrons, and dN/dH the differential of the intensity-height curve (curve 3). With the exception of the decay coefficient all other quantities are known either from experiments or from the present paper. Thus it is possible to calculate β for the whole atmosphere (curve 6).

As the average momentum of the mesotrons is proportional to its decay path L or inversely proportional to β

$$L=1/\beta=p\tau_M/\mu_M$$

(τ_M and μ_M decay time and mass of mesotron at rest), this curve gives the average energy of the mesotrons as a function of altitude.

This fact together with the cascade theory of electron and photon absorption explains the shape of the curve A. At the top of the atmosphere the average energy of the mesotrons will be equal, on account of their production in pairs, to half the average energy of the photons, which in turn equals that of the primary particles. This latter is estimated[12] at about 5×10^9 ev at the latitude under consideration. Comparing this with $L=13$ km for $E=1.5\times10^9$ ev, one finds that the decay-coefficient becomes $\beta=0.025$/km. This value agrees well with the present results which give $\beta=0.03$/km.

With increasing depth of the atmosphere the energy of the mesotron producing rays decreases rapidly through the mechanism of shower production; i.e. the decay coefficient increases.

At still greater depths of the atmosphere (below 10 km) the production of mesotrons in air falls off. As the mesotrons of the lower energy ranges disappear preferentially through decay and absorption the mean energy increases and consequently the decay coefficient decreases. The same difference in the energy spectra of the mesotrons at sea level and at 6 km has also been directly observed.[13] A further check is found in the coinciding of the maximum decay, which is equal to βN and takes place at a pressure of 20–30 cm Hg, and of the hump in the absorption curve which is due to the decay electrons.

The decay time at sea level which is calculated by taking the different values of mean energy at sea level as well as of the mesotron rest mass, lies between 1 and 3 μsec.

THE ORIGIN OF THE MESOTRONS AT SEA LEVEL

A fraction $e^{-(\alpha+\beta)H}$ of the mesotrons which originate in a layer H km high will reach sea level. The contribution to the intensity at sea level of the different layers is obtained by multiplying the number of mesotrons formed in each layer by the above factor.

Down to sea level the production of mesotrons per decay path is of the same order as their intensity. Therefore the decay coefficient of all mesotrons (curve 6) at the height H can be taken as that of the mesotrons produced at the same height.

If this approximation is sufficient, the sum of all contributions which were calculated in the described way (curve 7) must be equal to the number of mesotrons found at sea level, which is approximately the case.

The important result is that the mesotrons at sea level come in about equal parts from two definite layers; the first has a maximum at 6 km and the second at 22 km. The mesotrons from the stratosphere are of higher energy than those

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[13] M. Schein, E. O. Wollan, and G. Groetzinger, Phys. Rev. **58**, 1027 (1940).

from the troposphere. It is not possible to decide whether the difference in their mean energy is sufficient to identify them with components found in absorption experiments at sea level.[14] It is further to be noticed that practically nothing is contributed from layers between 10 and 15 km.

THE ANOMALOUS ABSORPTION OF THE MESOTRONS

Even if in measurements of cosmic-ray absorption at altitudes of a few kilometers the air mass between this point and sea level is replaced by a much denser absorber of the same atomic weight, the intensity at the higher altitude is still greater than at sea level.

A density effect which was calculated recently[15] was found insufficient to account for this difference. The radioactive decay of the mesotrons however gives a decay path L of 6 to 10 km.[16,17] These results were calculated under the assumption that no mesotrons are produced below the highest measuring point.

Thus in comparing these values with the present results which give $L=8$ km at sea level, $L=5$ at 2 km and $L=4$ at 4 km, it must not be forgotten that mesotrons are produced below 4 km in sufficient quantity to account for the difference.

THE ATMOSPHERIC EFFECTS

Taking into account the results of the present paper one expects to find the cosmic-ray intensity at sea level I_{76}, which consists mainly of mesotrons, to be a function of the form:

$$I_{76}=G[F(E),\ T(H),\ P].$$

In the atmosphere the number of mesotrons produced at a certain pressure is only a function of the primary energy spectrum at the limit of the atmosphere $F(E)$. But the number reaching sea level is determined by the height of the layer in which they are produced. This height is a function of the pressure at sea level P and of the temperature distribution $T(H)$.

As all these quantities are functions of time, the intensity is a function of time also.

Simultaneous registration at stations distributed over the whole earth and correlation of series of observations extending over long periods enables one to separate three effects: variation of primary energy spectrum, barometric effect, and temperature effect. The latter, which is usually only correlated to ground-level temperature, varies of course with geographic situation and meteorologic conditions.[18]

It is known from balloon ascents that variations of atmospheric pressure at sea level are accompanied by such temperature changes in the stratosphere that the pressure at a fixed height in the upper stratosphere does not change. Thus the barometric effect as far as it is due to decay is only caused by changes in height of the lower mesotron contributing layer. In this case the decay coefficient obtained from the barometric effect[19,20] must be slightly smaller than the decay coefficient at sea level, because the high energy contribution does not vary with changes in barometric pressure. As the decay path calculated from the barometric effect under the assumption of adiabatic pressure changes is $L=4$ km or about half the true $L_{76}=1/\beta=8$ km, the changes in height of the contributing lower layer must be about twice those for an adiabatic pressure change. In fact a factor 3.5 is found by comparing the observed pressure change at a height of 9 km δP_9, which is equal to 1.5 times the pressure change δP_S at sea level,[21] with the calculated adiabatic change $\delta P_{9A}=0.42\delta P_S$.[22] In consideration of the large possible error in all values, the agreement is satisfactory.

In other experiments, which confirm also the present deductions, the cosmic-ray variations have been measured at a depth of 40 m of water.[23] All the mesotrons from the lower layer are absorbed in the water and in fact no barometric effect has been observed. The remaining half-diurnal period of 0.2 percent amplitude whose maxima coincide with those of the half-diurnal

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[19] H. D. Rathgeber, Naturwiss. **26**, 842 (1938).
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[21] W. H. Dynes, M. O. Geophysical Memoirs No. 2 (1912).
[22] B. Haurwitz, Ver. Geophys. Inst. Leipzig [2] **3** (No. 5).
[23] E. Regener and W. Rau, Naturwiss. **27**, 803 (1939).

pressure oscillation of the atmosphere, must be due to effects taking place in the upper layer.

An observed seasonal effect has been attributed to changes in the mean air temperature and has given a decay path $L=32$ km.[24] The seasonal changes in temperature extend through the whole atmosphere, but in summer the temperature in the stratosphere is much lower than in winter and probably causes a descent of the high mesotron contributing layer. Thus the decrease in mesotron intensity due to a rise in the lower layer is partially compensated by an increase due to the upper contributing layer and explains the high value found.

The intensity variations which remain after barometric correction, on passage of warm or cold air fronts, are obviously due to changes in the normal temperature distribution.[25]

Further it is to be expected that changes in the primary energy spectrum which for example are caused by magnetic storms, should be accompanied not only by intensity variations but also by changes in the coefficient of the barometric effect.

THE LATITUDE EFFECT AT SEA LEVEL

Any acceptable picture of the mesotron component must give a satisfactory interpretation of the latitude effect at sea level. The present results combined with the cascade theory are able to give this in a qualitative manner.

Below a height of 8 km (in radiation units $l=10$) the number of secondary electrons produced by electrons with energy $<y=4$ falls off rapidly. Therefore primary electrons $<4\times10^8$ ev $\times e^y=2\times10^{10}$ ev (the critical energy for mesotron production is assumed to be 4×10^8 ev) cannot produce mesotrons below that height. As electrons of an energy superior to 2×10^{10} ev are not influenced by the earth's magnetic field, the contribution from the lower mesotron producing layer is not subjected to the latitude effect.

Thus the latitude effect for the upper layer is twice the observed effect, i.e., 30 percent. Because only the mesotrons produced by the higher energy electrons in the upper layer will reach sea level it is possible to estimate the latitude effect of this layer to be inferior to 50 percent.

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SUMMARY

A possible curve of the mesotron intensity in the whole atmosphere has been obtained.

The mean decay coefficient of these mesotrons rises from 0.03/km at the limit of the atmosphere to a maximum of 0.4/km at a height of 10 to 12 km and falls off again to 0.1/km at sea level. The corresponding average mesotron energies are: 3×10^9, 2×10^8 and 1×10^9 ev.

The mesotrons which reach sea level originate in about equal parts in two distinct layers, one around a height of 6 km and the other above 17 km. The latter is composed of mesotrons of high energy and the former of mesotrons of lower energy.

Further it is shown that these results explain the differences in the experimental determinations of the decay path and give a consistent qualitative picture of the mesotron component.