Mesotron Production in the Atmosphere

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With Geiger-Müller tubes arranged for fourfold vertical coincidence, a Rossi-Hsiung type of experiment was performed in an aeroplane up to an altitude of 25,000 feet. A sheet of lead 8.1 cm thick placed between the counter tubes and another lead plate of 2.2 cm thickness was alternately changed from the position above all the tubes to a position between the second and third tubes. From the difference between the counting rates in the two cases, it was found that at an altitude of 25,000 feet an average of 2 ionizing penetrating particles (mesotrons) per minute were ejected in the forward direction from a lead plate (38 cm×5.2 cm×2.2 cm) by the action of non-ionizing rays (photons). This value leads to a cross section for the production of mesotrons by photons which is in at least rough agreement with the theory.

IT is now generally recognized that most of the penetrating cosmic-ray particles at sea level are mesotrons. Bowen, Millikan and Neher[1] concluded from their high altitude cosmic-ray measurements that the great majority of the penetrating cosmic-ray particles found at sea level are secondaries produced by the soft component of cosmic radiation in the upper atmosphere. A similar suggestion was made by A. H. Compton[2] in 1935. Counter experiments performed by Rossi,[3] Hsiung,[4] and Maass[5] at sea level and Shonka[6] at 14,200 feet altitude do not show any definite evidence for the production of penetrating particles by non-ionizing soft rays.[7] The same conclusion has been reached by Anderson from cloud-chamber studies concerning mesotron production by electrons. We should therefore conclude that at least at sea level no significant part of the mesotrons is being produced as secondaries from soft cosmic radiation. However, higher in the atmosphere such production of mesotrons might nevertheless occur because of the rapid increase in the intensity of the soft component with altitude.

To obtain more definite evidence concerning the production of mesotrons in the atmosphere, Professor A. H. Compton suggested that a Rossi-Hsiung type of experiment should be performed in an aeroplane up to an altitude of 25,000 feet.

APPARATUS

For the present experiment, four Geiger-Müller tubes were arranged for fourfold vertical coincidence according to Fig. 1. The tubes were

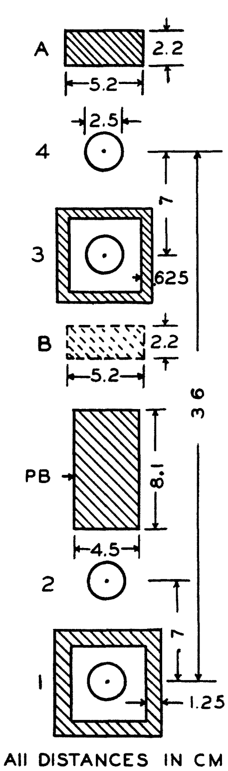

FIG. 1. Arrangement of the counter tubes.

[1] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **46**, 653 (1934).
[2] A. H. Compton, Proc. Phys. Soc. London **47**, 747 (1935).
[3] B. Rossi, Zeits. f. Physik **68**, 64 (1931); **82**, 151 (1933).
[4] D. S. Hsiung, Phys. Rev. **46**, 653 (1934).
[5] H. Maass, Ann. d. Physik **27**, 507 (1936).
[6] F. Shonka, Phys. Rev. **55**, 24 (1939).
[7] B. Rossi informed us that in collaboration with L. Jánossy he recently found a very small but distinct effect showing the production of mesotrons by photons at sea level. Cf. paper by P. M. S. Blackett and B. Rossi in this issue.

made of a copper cylinder 2.54 cm in diameter and 30 cm long, sealed in glass. The central electrode was a tungsten wire of 0.075 mm diameter. All four tubes had plateaus of 150–300 volts. We are indebted to Mr. F. Shonka for these tubes.

Between the tubes 2 and 3 was placed a lead block of 8.1 cm thickness to absorb the soft component of cosmic radiation, thus only penetrating particles were recorded by the counter telescope. The Geiger-Müller tube number 1 was surrounded by 1.25 cm of lead to shield the tube from softer shower particles. Another lead shield of 0.625 cm thickness was placed about tube number 3 to absorb Compton recoil electrons produced in the lead below this tube. A lead plate of 2.2 cm thickness was alternately moved from above the counter tube 4 (position A) to a place between the tubes 3 and 2 (position B).

When the lead plate was placed in position B only penetrating ionizing rays passing through all four counter tubes were recorded. Any penetrating ionizing rays produced in the lead between the counters by a non-ionizing incident ray was not recorded since the tubes 4 and 3 were not activated. On the other hand, when the lead plate was moved to position A, penetrating ionizing rays produced in this lead were recorded if they traversed all four counter tubes. Therefore, by alternately recording fourfold coincidences with the lead plate in position A and in position B, one could determine the relative number of penetrating rays which were produced in this lead plate.

The counting circuit used was of the Neher-Harper[8] type. RCA 34 tubes with a filament current of 0.06 ampere were employed for quenching the discharge in the Geiger-Müller tubes. The coincidences were recorded by a Cenco impulse counter. The high voltage source for the counter tubes (1150 volts) consisted of a Burgess battery of dry cells. All parts of the circuits were mounted together rigidly to avoid any changes in capacity due to the shaking and vibration of the aeroplane.

The time constants t of the coincidence circuit were determined by measuring the double accidental coincidence rates. The values for the 4 different counter tube circuits were the following: $t_1 = 2.2\times10^{-4}$ sec., $t_2 = 1.8\times10^{-4}$ sec., $t_3 = 2.0\times10^{-4}$ sec., and $t_4 = 1.6\times10^{-4}$ sec.

An important factor was to test the efficiency of the counter telescope as a function of the counting rate of the individual Geiger-Müller tubes. As the single counting rate of each counter tube increases rapidly with altitude, a decrease in efficiency of the apparatus was to be expected. Let us call W the probability of recording an individual ray in the Geiger-Müller tubes, n the number of single rays, and t the resolving time of each counter tube. M. Curie[9] showed that the probability for recording a single count is given by $W = e^{-nt}$ and the probability for recording a fourfold coincidence is therefore $W_4 = e^{-4nt}$.

It is obvious that to obtain a high efficiency for recording fourfold coincidences it is necessary to have a sufficiently high resolving time t for each individual counter tube. In the present case $t \sim 10^{-4}$ second and the estimated single counting rate at 25,000 feet altitude $n \sim 20$ per second. Hence $W_4 = e^{-0.008} \sim 1$. We should therefore expect no appreciable change in efficiency carrying the counters from sea level to an altitude of 25,000 feet. This conclusion was directly tested with a radium source placed at such a distance from the apparatus that the individual counting rate was about the same (20 per second) as that estimated for the altitude of 25,000 feet. The fourfold coincidences were counted alternately with and without the radium source and we found that the average number of fourfold coincidences per minute was with radium: 0.49 ± 0.03; without radium: 0.48 ± 0.03. This result shows that for recording fourfold coincidences there was no change in the efficiency of the apparatus within the experimental error.

Results and Discussion

Readings were taken with the counting tubes in a vertical position at three-minute intervals between altitudes of 13,000 and 25,000 feet. The results obtained are shown in Table I. Up to 20,000 feet no appreciable differences between A and B were observed. From 20,000 to 25,000 feet, the excess with the lead above is quite apparent, and at 25,000 feet the ratio $A/B = 2.1$.

[8] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).

[9] M. Curie, J. de phys. et rad. **1**, 20 (1920).

TABLE I. *Results of measurements.*

ALTITUDE	13,000 FT. TO 20,000 FT.		20,000 FT. TO 25,000 FT.		25,000 FT.	
Position of Lead...... See (Fig. 1)	A	B	A	B	A	B
Number of Fourfold Coinci- dences in 3-min. Intervals.	7	5	8	4	11	2
	4	5	9	7	10	4
	6	4	9	5	10	11
	6	7	11	9	10	2
	1			9	10	6
					15	6
Average	4.8 ± 0.7	5.2 ± 0.7	9.2 ± 1.0	6.0 ± 0.7	11.0 ± 0.9	5.2 ± 0.6
	Ratio $A/B=0.9$		Ratio $A/B=1.5$		Ratio $A/B=2.1$	

The statistical errors are appreciable, but the difference in the coincidence counting rate between the positions A and B is well outside the maximum error.

To obtain a better statistical accuracy we took all the measurements together which were taken above the altitude of 20,000 feet and calculated the average number of fourfold coincidences in positions A and B. We obtained the following results: Position A: $K_A=10.3\pm0.7$; Position B: $K_B=5.5\pm0.5$; $K_A/K_B=1.9\pm0.2$. Thus the experiment shows a distinct excess in the number of registered penetrating cosmic-ray particles when the lead plate is placed above all the counter tubes.

There are different possibilities which can be considered in the interpretation of the results of the present experiment: (a) The scattering of mesotrons, (b) multiple processes, (c) the changing over of a fast neutron into a proton, (d) creation of a mesotron by a neutretto, and (e) creation of a mesotron by a photon.

(a) The scattering of mesotrons in dense materials was studied in the cloud chamber by Blackett and Wilson.[10] With the lead plate in position A the number of scattered mesotrons capable of traversing the counter telescope is greater than in position B. The observed effects of Blackett and Wilson, however, are much too small to account for the great excess of penetrating particles which was observed at high altitudes. This is also in agreement with the theoretical calculations carried out by Williams,[11] who found that for lead thicknesses of 2 cm a small effect has to be expected. It is, however, possible that some of the positive results (excess of mesotrons in position A) observed at sea level can be interpreted as due to the scattering of mesotrons in lead and iron.

(b) Nordheim pointed out that a possible explanation for the excess of mesotrons in position A can be given in terms of multiple processes which take place in the lead. The existence of multiple processes was discussed formerly by Nordheim and Hebb[12] and recently by Heisenberg,[13] but sufficient experimental evidence has not yet been obtained for calculating the order of magnitude of the expected effects. Therefore it seems rather difficult to make any quantitative estimates as to whether or not the magnitude of this effect is sufficient to account for the observed excess of mesotrons in position A at high altitudes.

(c) E. Fermi suggested[14] that a fast neutron when interacting with a nucleus can change into a fast proton. If the primary neutron striking the lead plate in position A has energies greater than about 3×10^8 ev, then the emitted proton will be able to traverse the lead shield of 10 cm thickness and give rise to a fourfold coincidence in the counter telescope. On the other hand, for position B the ejected proton cannot be recorded, because the primary neutron would not activate tubes 3 and 4. Such an effect can explain the observations provided high energy neutrons are sufficiently abundant at high altitudes. Experiments from Halban[15] and Korff[16] show that the neutron intensity in the cosmic radiation is very great at high altitudes, but it is not known what fraction of these, if any, consist of fast neutrons.

(d) The creation of a mesotron by a neutretto was first discussed by Arley and Heitler.[17] In view of the fact that there is not at present sufficient experimental evidence for the existence of the neutretto, this point will not be discussed any further.

(e) The creation of a mesotron by a photon

[10] P. M. S. Blackett and J. G. Wilson, Proc. Roy. Soc. **A168**, 159 (1938).
[11] E. J. Williams, Proc. Roy. Soc. **A169**, 531 (1939).

[12] L. W. Nordheim and M. H. Hebb, Phys. Rev. **55**, 111 (1939).
[13] W. Heisenberg, Zeits. f. Physik **113**, 61 (1939).
[14] This suggestion of Fermi's concerning the exchange of a fast neutron into a fast proton was mentioned by B. Rossi in a Chicago Cosmic-Ray Seminar.
[15] H. v. Halban, L. Kowarski and M. Magat, Comptes rendus **208**, 572 (1939).
[16] S. A. Korff, paper in this issue.
[17] N. Arley and W. Heitler, Nature **142**, 158 (1938).

was proposed by Bhabha[18] and Heitler[19] and later discussed by others.[20] Heitler calculated the cross section for processes of the following type:

$$h\nu + P = N + Y^{+}$$
$$h\nu + N = P + Y^{-}.$$

(P = proton, N = neutron, Y^{+} = positive mesotron, Y^{-} = negative mesotron.) He found that the cross section per proton for mesotron energies of about 10^8 ev is given by the expression

$$\Phi_P \simeq 1/(50\lambda^2).$$

($1/\lambda = r_0 = c^2/me^2$ is the classical electronic radius.) For higher energies the cross section increases and seems to approach a constant value of about 10^{-26} cm^2 as estimated by Nordheim.[21] If we assume that the observed excess of mesotrons for position A is due to the creation of mesotrons by photons in the lead, then we can estimate the experimental cross section of a process of this kind and compare it with the theoretical value of 10^{-26} cm^2.

The experimental value for the cross section was obtained in the following way. The altitude dependence of the intensity of the soft component of the cosmic radiation was recently measured by Regener and Ehmert.[22] Knowing the number of electrons incident on the lead plate A at sea level, we can calculate the corresponding number of electrons at 25,000 feet altitude from the altitude curve of Regener and Ehmert. The number of photons incident on the lead plate A is twice as great as that of the electrons. On the basis of this we find that about 2000 photons are incident from all directions on the lead plate A at 25,000 feet altitude. Assuming that the created mesotron will be emitted in the direction of the incident photon we can estimate that about 100 of these photons have a chance to create mesotrons which will traverse the counter telescope. The number of these mesotrons was actually observed to be about 2 per minute. Hence the probability for the creation of a mesotron by a photon in 2 cm of lead thickness is given by

$$W \simeq \frac{2}{100}.$$

Since there are 82 protons in a lead nucleus and there are 3.4×10^{22} lead atoms per cc, the cross section per proton for the creation of a mesotron by a photon is given by

$$\Phi_P \simeq \frac{2}{100} \times \frac{1}{6.8 \times 10^{22}} \times \frac{1}{82} \simeq 3 \times 10^{-27}\ \text{cm}^2.$$

This value of the cross section agrees as well as can be expected with the theoretical value given by Nordheim in view of the uncertainties which are present both in the theory and in the estimated intensity of the incident photons.

It seems then probable that the creation of mesotrons by photons must be considered as a possible mechanism for the mesotron production in the upper atmosphere. On the other hand, there is still the possibility that there exist other more efficient processes for the production of mesotrons. On the basis of directional experiments carried out at sea level and high altitudes, Johnson[23] suggested that mesotrons might be produced by positively charged primary particles, presumably protons. However, an appreciable number of primary protons is not observed at sea level and there is no direct experimental evidence that they are present at high altitudes.

We might also mention that a recent analysis by Euler and Wergeland[24] of the ratio of penetrating to soft particles in the big air showers of Auger leads to the conclusion that there is an appreciable number of mesotrons present in these showers and further that these mesotrons must be created by soft shower particles with a cross section of about 2×10^{-26} cm^2 per proton. This finding is in accord with the experimental results of the present investigation that part of the mesotrons are created by photons.

The writers are greatly indebted to Professor A. H. Compton for helpful suggestions and for his continued support.

[18] H. J. Bhabha, Proc. Roy. Soc. **A164**, 257 (1938).
[19] W. Heitler, Proc. Roy. Soc. **A166**, 529 (1938).
[20] H. Yukawa, S. Sakata, M. Kobayasi and M. Taketani, Proc. Phys.-Math. Soc. Japan **20**, 720 (1938); M. Kobayasi and T. Okayama, Proc. Phys.-Math. Soc. Japan **21**, 1 (1939); L. W. Nordheim and G. Nordheim, Phys. Rev. **54**, 254 (1938); W. Heisenberg, Zeits. f. Physik **113**, 61 (1939).
[21] L. W. Nordheim, J. Frank. Inst. **226**, 575 (1938).
[22] E. Regener and A. Ehmert, Zeits. f. Physik **111**, 501 (1939).
[23] T. H. Johnson, Phys. Rev. **55**, 111 (1939).
[24] H. Euler and H. Wergeland, Naturwiss. **27**, 484 (1939).