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Intensity and Rate of Production of Mesotrons in the Stratosphere

MARCEL SCHEIN, WILLIAM P. JESSE AND E. O. WOLLAN
The University of Chicago, Chicago, Illinois

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Two free balloon flights have been made with a coincidence-counter apparatus designed to record the vertical mesotron intensity and also the number of mesotrons produced in a 2-cm lead block by a non-ionizing radiation. The results show that the mesotron intensity at first increases with elevation and reaches a maximum at a pressure at about 6.6 cm Hg where the intensity is about 11 times that at sea level. Above this altitude the intensity falls off until at the lowest pressure reached (3.6 cm Hg) the intensity has decreased to about 8 times the sea-level value. Between $p=8$ cm and 50 cm Hg the mesotron intensity decreases almost exponentially with the mass of air traversed from which we obtain a constant "absorption coefficient" $\mu=1.2\times10^{-3}$ g^{-1} cm^{-2} for the mesotrons in this range. The production of mesotrons in the lead block becomes noticeable at about 35 cm pressure and increases with altitude at about the same rate as does the soft component. This is evidence that the photons are the agents responsible for a large part of the observed creation in the lead and on this assumption we calculate a cross section for the creation process $\sigma_{ph}=0.7\times10^{-27}$ cm^{-2} per nuclear particle in lead.

INTRODUCTION

DURING the past six months two free-balloon flights have been made for the purpose of determining the intensity and rate of production of mesotrons as a function of altitude. A counter train for threefold coincidences was used to measure the vertical intensity with 8 cm of lead inserted in the path of the particles to eliminate any soft radiation. Simultaneously measurements were made of the rate of production of mesotrons by non-ionizing radiation in a lead block of 2 cm thickness. Similar attempts to obtain penetrating secondaries from a non-ionizing soft radiation have been made by Rossi[1] and by Hsiung[2] at sea level and by Shonka[3] at an elevation 4300 meters with negative results. Positive evidence of such mesotron production was obtained by Schein and Wilson[4] in an airplane flight at an altitude of 7600 meters. A bibliography of previous work is given in the last named paper.

APPARATUS

The detailed arrangement of the counter set is shown in Fig. 1. Counters 1, 2 and 3 represent one coincidence set, and counters 2, 3 and 4 constitute another set. Since a particle which passes through either set of counters must penetrate at least 8 cm of lead, the coincidences registered here must be due to penetrating particles, i.e., to mesotrons. The top set of counters can be actuated only by mesotrons which have originated outside the apparatus, whereas the lower set can be set off either by a mesotron entering from the outside or by one

[1] B. Rossi, Zeits. f. Physik **82**, 151 (1933).
[2] D. S. Hsiung, Phys. Rev. **46**, 653 (1934).
[3] F. Shonka, Phys. Rev. **55**, 24 (1939).
[4] M. Schein and V. C. Wilson, Rev. Mod. Phys. **11**, 292 (1939).

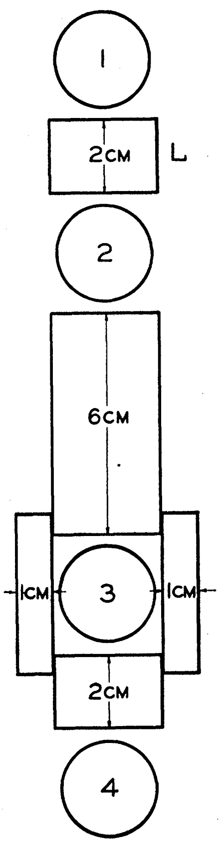

FIG. 1. Arrangement of counter apparatus.

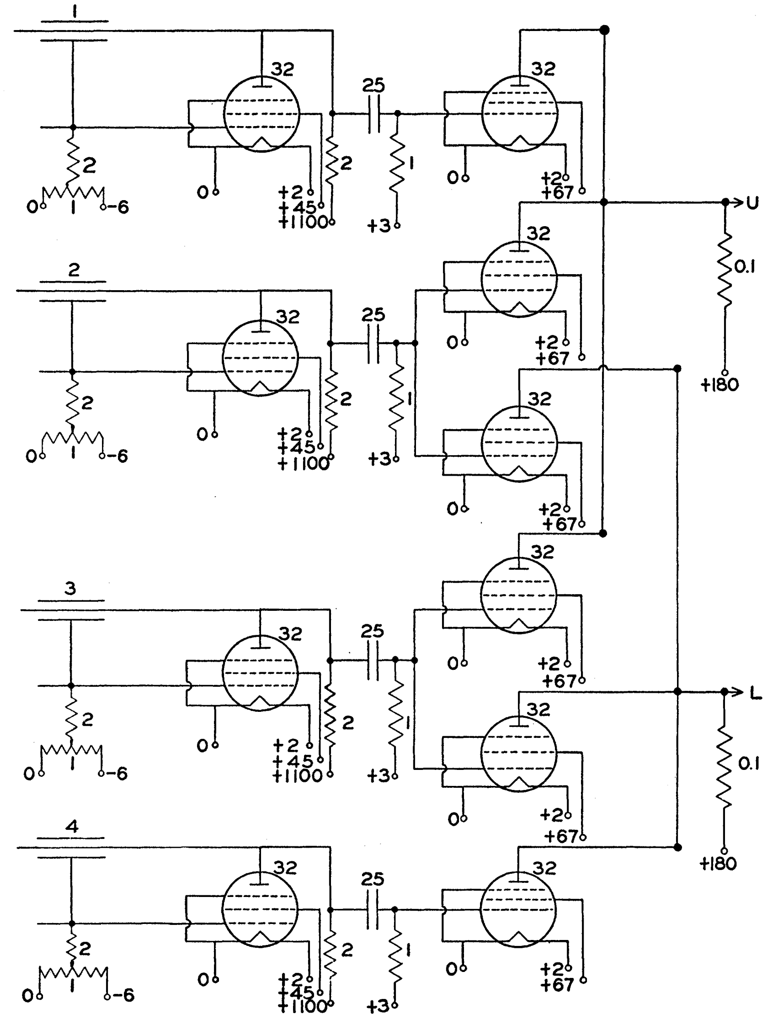

FIG. 2. Diagram of connections for the first two stages in the two threefold coincidence circuits. Capacities are given in microfarads, resistances in megohms and potentials in volts.

which is produced in the lead block L. If there is such a production of mesotrons in the lead block L by a non-ionizing radiation, one should observe a greater number of counts in the lower set of counters than in the upper set. Thus the difference in the counting rate between the two sets represents the rate of production of mesotrons in the 2-cm lead block.[5] In order to reduce the effect of softer particles originating from horizontal air showers, a shield of 1 cm of lead was placed on the sides of counter 3.

Each Geiger-Mueller tube was 10 cm in length and 2.5 cm in diameter, and was made according to the technique of Shonka.[3] The cut-off voltage for each of these tubes was approximately the same (about 850 volts) and the plateau for constant counting rate extended over a range of several hundred volts. The actual voltage used on all counter tubes was the same and was approximately 1100 volts.

The arrangement of the coincidence circuits is shown in Fig. 2. The discharges in each counter

[5] Because of the absorption of the incident mesotron in the last 2-cm block of lead, a correction amounting to about one percent of the rate for the upper coincidence train is to be added to the production rate as thus calculated. A similar minor correction has to be made for those mesotrons which are produced in different parts of the 2-cm lead block and which have not sufficient energy to traverse the lower counter train.

tube are quenched by an RCA 32 tube in a Neher-Harper circuit.[6] Since counter tubes 2 and 3 are common to both coincidence sets (Fig. 1), the pulse from each tube was divided at the output of the Neher-Harper tube and fitted into two different mixing circuits (U and L) by means of two 32 tubes. Careful tests by means of chance coincidences proved the complete independence of these two coincidence circuits. In each mixing circuit the pulse was first lengthened and then used to operate a Western Electric B 1003 relay which actuated a shutter for a light beam. The mesotron counts were thus registered on a photographic film. This film was wound on a cylinder which was rotated by clock work at the rate of one rotation per hour. By means of a helical screw the cylinder was also advanced in the direction of its axis by a distance equal to one millimeter per hour. Such a recorder gives a very compact record. On a film $30\times 2\frac{1}{2}$ cm a record for a ten-hour flight was obtained with complete data from the two counter sets. A portion of the film from one of the flights which gives only the data from the lower counter set is shown in Fig. 3. The number of spots per cm, which is proportional to mesotron intensity, is observed to increase rapidly on passing from row to row, then to remain constant for a long period, and finally to decline slowly. This corresponds to the rapid rise of the apparatus, to the final equilibrium position, and considerably later to the initial stages of the descent.

A continuous record of the barometric pressure was obtained throughout the flight on a second drum which was driven at a slower rate by the same clock. The barometric capsule consisted of an evacuated metallic bellows inside which was placed a very stiff steel spring. Such an arrangement practically eliminates all hysteresis effects. Ground tests of the pressure device gave an average random error of about 1 mm of mercury. This barometric device has been in use in this laboratory for over a year and has given satisfactory results in some fifteen balloon flights. The temperature in the apparatus was also recorded throughout the flight by a device consisting essentially of a bimetallic strip.

The total weight of the equipment was 17 kilograms, the lead alone weighing $5\frac{1}{2}$ kilograms. Two flights were made with this apparatus, the first on August 14 and the second on October 20, 1939. The length of each flight was about twelve hours. In the first flight, 15 balloons were used and the minimum pressure reached was 6.6 cm of mercury. In the second flight with twenty-one balloons the minimum pressure was 3.5 cm. Altitude-time curves for both flights are given[7] in Fig. 4. It is interesting to note that in both cases the balloons reach an equilibrium position in the stratosphere where they remain at a constant altitude for four or five hours. Under these conditions the mesotron intensity can be determined for the corresponding pressure with very good accuracy.

Because of the rapid increase of the soft component of cosmic rays with altitude, the counting rate of each individual G-M tube also increases rapidly. This will result in a decreased efficiency in recording coincidences unless the resolving

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

[7] Where, for convenience, altitudes have been given in this paper they have been taken from conversion tables in Humphreys' *Physics of the Air* (McGraw-Hill, 1929).

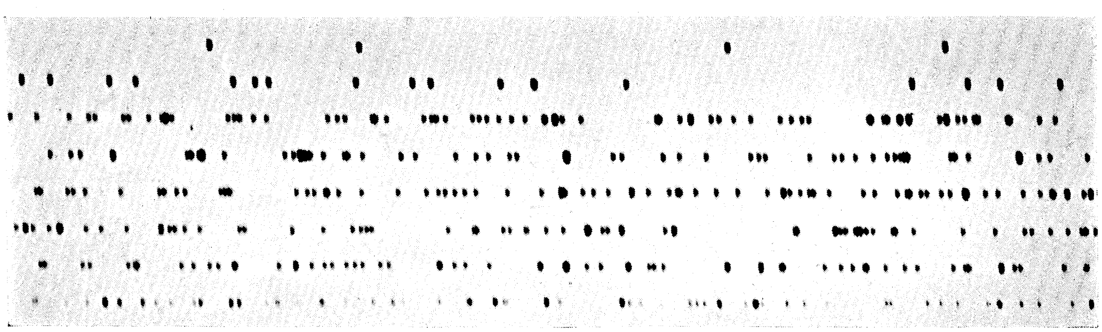

FIG. 3. A reproduction of part of the film showing a portion of each hour's record for threefold coincidence counts.

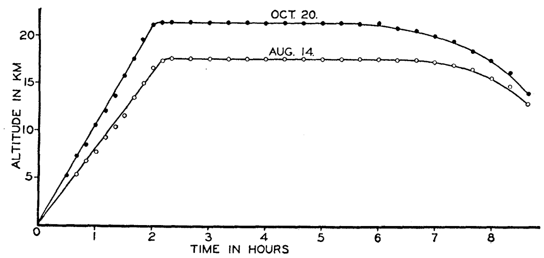

FIG. 4. Altitude time curves for the two flights. The balloons descended after nightfall and the cooling of the gas in the balloons accounts for the nonlinear character of the descent curve.

power of the tubes and circuits involved is sufficiently high.[4] Therefore the resolving time of each G-M tube alone and also the resolving time of each tube with its corresponding circuit was determined with a cathode-ray oscillograph. By this method and also by the method of chance coincidences the resolving time of each of the four different counter-tube circuits was found to be between 1 and 2×10^{-4} second. A further test was made by bringing a radium source near the apparatus while the coincidence set was counting vertical mesotrons. Even when the radium was brought so near that the counting rate in each individual G-M tube was greater than that expected in the stratosphere, no decrease in the efficiency of recording threefold coincidence counts was observed.

Experimental Results

The combined results from the two flights are represented by the curve in Fig. 5. Curve B, which gives the number of coincidences recorded in the upper counter set (G-M tubes 1, 2 and 3), and yields directly the number of mesotrons as a function of the barometric pressure or of the altitude. Curve A, which corresponds to the number of coincidences recorded in the lower counter set (G-M tubes 2, 3 and 4), gives in addition to the number of mesotrons present at each altitude those which are produced by a non-ionizing radiation in the 2-cm lead block below the first G-M tube. Curve C, which is the difference between curves A and B, represents as a function of altitude the number of those mesotrons which are produced in the lead block by a non-ionizing radiation.

From curve B one sees that the mesotron intensity increases with altitude and reaches a maximum value at about 17.6 km (6.6 cm Hg). The intensity at the maximum is about 11 times that at sea level and, although from this point on, the intensity decreases with altitude, it is still about 8 times[8] the sea level value at 21.3 km (3.6 cm Hg). The vertical lines at the measured points represent the probable errors. At low altitudes the percentage errors are rather large, but they become less at higher altitudes where the counting rate is greater and where the equipment remained for a longer time. The top point from the first flight (at 6.6 cm Hg) represents the point at which the apparatus leveled off and remained for several hours with the result that several thousand counts were recorded. So few coincidences were recorded at altitudes below 4.5 km that reliable results could not be obtained with our equipment. Therefore, for this part of the curve we have used data obtained by Rossi, Hilberry and Hoag,[9] who have made a more extensive study of the mesotron intensity with about the same lead shield at points between sea level and the top of Mt. Evans.

From curve C, which gives as a function of altitude the number of mesotrons produced in

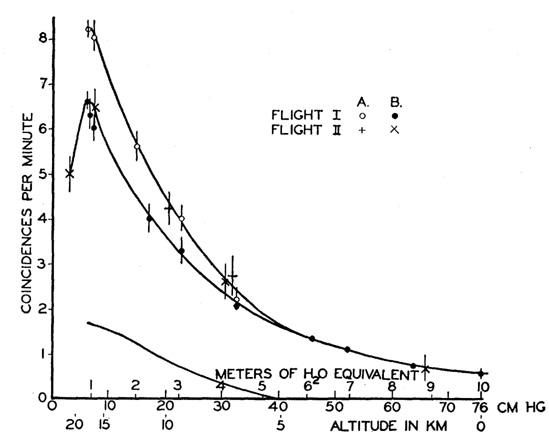

FIG. 5. The plot represents, (A—upper curve) coincidence altitude curve for lower counter set, (B—center curve) same for upper counter set (mesotron intensity as a function of altitude), (C—lower curve) difference between A and B (created mesotrons as a function of altitude).

[8] The point at 3.6 cm Hg was obtained on the second flight, for which part of the record was damaged and for this reason the accuracy is not as good as for the top point from the first flight.

[9] B. Rossi, H. Van N. Hilberry and J. B. Hoag, Phys. Rev. **56**, 837 (1939).

the 2-cm lead block, one sees that the production begins noticeably at about 6 km and increases with altitude attaining a value of about 25 percent of the total mesotron intensity at the maximum. Since our second flight did not give a complete record for the lower counter set our production curve extends to only 17.6 km which corresponds to the maximum altitude reached in the first flight.

In Fig. 6 is plotted the log of the intensity *vs.* the pressure. The fact that this curve is approximately a straight line between a pressure of 8 cm Hg and about 50 cm Hg shows that the mesotron intensity decreases in this range almost exponentially with the mass of air traversed. From this curve we obtain a constant absorption coefficient $\mu=1.2\times10^{-3}$ g^{-1} cm^{-2} in the range $p=8$ cm Hg to 50 cm Hg. From $p=50$ cm Hg to sea level the absorption coefficient changes from the above value to a value $\mu=0.7\times10^{-3}$ g^{-1} cm^{-2} at sea level as given by Wilson.[10]

Discussion

Variation of mesotron intensity with altitude

The first measurements of cosmic rays in the stratosphere with shielded equipment were made by Compton and Stephenson[11] in the "Century of Progress" balloon flight manned by Commander T. G. W. Settle and Lieutenant C. L. Fordney. They used an ionization chamber shielded with 6 cm lead and they reached an altitude corresponding to a pressure of about 5 cm Hg. Their results can be compared with those obtained by a vertical counter arrangement only after they have been reduced by a Gross transformation. If we should consider their reduced measurements as giving a mesotron curve to be directly comparable with ours, we find that the ratio of the intensity at the altitude of 17 km to that at sea level is much larger in their case than in ours. For comparison we have plotted their reduced curve together with ours

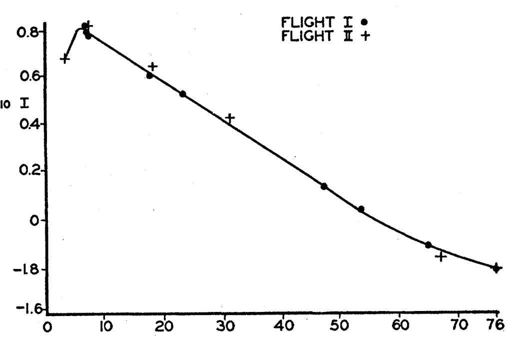

FIG. 6. The plot gives the logarithm of mesotron intensity as a function of pressure.

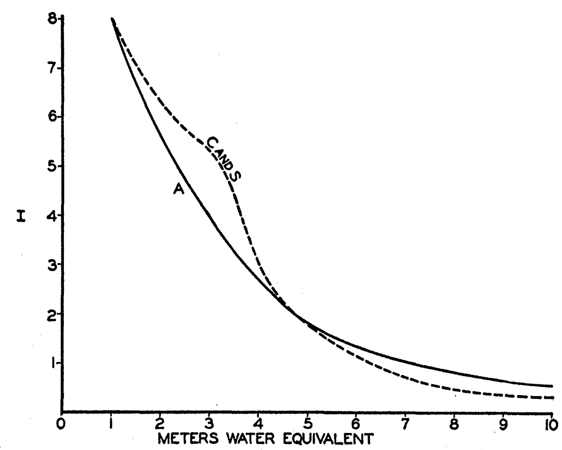

FIG. 7. Comparison of curve *A* of Fig. 5 with the shielded ionization chamber measurements of Compton and Stephenson reduced by means of the Gross transformation.

in Fig. 7. We have arbitrarily fitted their curve to the top of our curve *A* of Fig. 5. We have considered their data more comparable with curve *A* than with curve *B* since their equipment would also be expected to record mesotrons which are produced in the lead shield. When their curve *C* and *S* and our curve *A* are fitted at the top one sees that except for a large hump in their curve the two give the same increase in intensity over the upper half of the atmosphere. In the lower half of the atmosphere ionization measurements with lead shields in general give a more rapid increase of intensity than is obtained with vertical counter arrangements, a fact which may be due to the inadequacy of the Gross transformation.[12]

It is possible that at least part of the large hump in the *C* and *S* curve at an altitude of

[10] V. C. Wilson, Phys. Rev. **53**, 337 (1938).

[11] A. H. Compton and R. J. Stephenson, Phys. Rev. **45**, 441 (1934).

[12] Also, since *C* and *S* used 6 cm of lead whereas in curve *A* 10 cm were used, *C* and *S* will observe more slow mesotrons, which are relatively abundant at higher altitudes.

about 9 km arises from large showers which are known to increase rapidly with altitude.[13]

It seems that a more reliable measurement of the vertical mesotron intensity can be obtained with coincidence counters than with a shielded ionization chamber since in the latter case large showers will contribute much to the total ionization while with counters a large shower appears as a single coincidence. In our counter set such showers will be most effective from the sides which are not sufficiently shielded.[14]

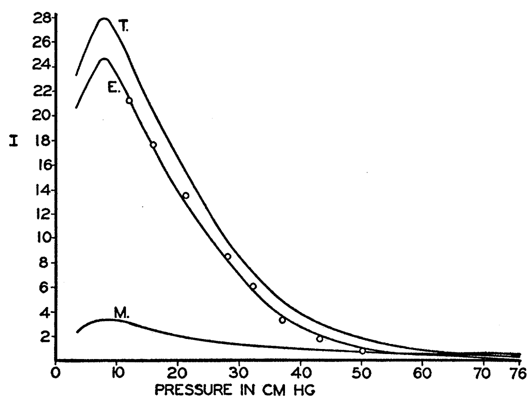

FIG. 8. The plot represents as a function of pressure, (T) the total vertical intensity as measured by Pfotzer, (M) vertical mesotron intensity from present experiments, (E) the difference between curves T and M which should give the vertical electron intensity. The open circles which represent the shower intensity as measured by Regener and Ehmert are seen to follow very closely curve E.

Since the appearance of our first paper[15] on this subject a preliminary report of measurements of the intensity of the penetrating component by means of a vertical coincidence counter arrangement shielded by 10 cm of lead has been published by Dymond.[16] From three flights in which he used the radio method of transmitting the counts he finds that the mesotron intensity reaches a maximum at about 16 km at which altitude the intensity is about 9 times that at sea level. In this respect his measurements are in qualitative agreement with ours, but since he gives no curve for the dependence of mesotron intensity on altitude no exact comparison between his results and ours can be made. Dymond carried out his measurements at a geomagnetic latitude of about 59°N whereas ours were made at 52.5°N. The above-mentioned agreement between the two measurements indicates that, as is the case for the total intensity,[17] no appreciable latitude effect of the mesotron intensity in the stratosphere can be expected between 52.5°N and 59°N.

It is interesting to note the relative proportion of the soft and penetrating components of the cosmic rays as a function of altitude. A direct measurement of the total vertical intensity has been made by Pfotzer[18] with coincidence counters. His results for the total vertical intensity (curve T) are plotted together with our curve for the penetrating component (curve M) in Fig. 8. The difference between these two curves (curve E) should give the vertical electron intensity (soft component).

The shower intensity as a function of altitude has been measured by Regener and Ehmert[19] down to a pressure of 12.3 cm Hg and more accurately at lower altitudes by Johnson.[20] Their measurements are represented by the circles fitted to the soft component curve at the top point. One sees that the shower intensity curve follows very closely that of the soft component.

At the maximum of curve T(p = 8 cm Hg) the mesotrons represent about 12 percent and the electrons about 88 percent of the total vertical intensity, while at sea level about 75 percent of the total vertical intensity consists of mesotrons and only the remaining 25 percent of electrons. The area under the mesotron curve from the top of the atmosphere down to sea level is about 10 percent of the area under the total vertical intensity curve.

[13] P. Auger and collaborators, Rev. Mod. Phys. **11**, 288 (1939).

[14] In a recent counter experiment carried out in an aeroplane up to an altitude of 8.5 km, measurements of the effect of lateral showers have been made with an arrangement similar to the one described above but in which one of the counters was moved out of line. A correction at this altitude for the effect of lateral showers was found to be not more than about three percent. A note on this experiment will be published in the near future by Schein, Wollan and Groetzinger. See also T. H. Johnson and J. G. Barry, Phys. Rev. **57**, 245 (1940).

[15] M. Schein, W. P. Jesse and E. O. Wollan, Phys. Rev. **56**, 613 (1939).

[16] E. G. Dymond, Nature **144**, 782 (1939).

[17] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **53**, 855 (1938); H. Carmicheal and E. G. Dymond, Proc. Roy. Soc. **A171**, 321 (1939).

[18] G. Pfotzer, Zeits. f. Physik **102**, 23 (1936).

[19] E. Regener and A. Ehmert, Zeits. f. Physik **111**, 501 (1939).

[20] T. H. Johnson, Phys. Rev. **47**, 318 (1935).

Created Mesotrons

Curve C (Fig. 5), as we have mentioned above, gives as a function of altitude the number of mesotrons which are created by a non-ionizing radiation in the 2-cm lead block. Any mesotrons which are created with energies less than 1.2×10^8 ev would not be recorded by our apparatus since they would not be able to penetrate the 8-cm lead shield. Also, if mesotrons are created in multiples,[21] the number recorded would be less than those created in the lead block since each multiple process would be recorded as a single event.

Since we are dealing here with mesotrons created by a non-ionizing radiation, it is reasonable as a first assumption to associate the production in the 2-cm lead block with photons, which we know are present in large quantities at high altitudes where the creation process becomes important. The photons as a source of mesotron creation has been suggested by several investigators.[22] A test of this hypothesis can to some extent be made by calculating the ratio of the created mesotrons to the number of incident photons under the assumption that the photon spectrum does not change appreciably in the range of altitudes between 7 km and 18 km. This ratio N_y/N_s at various altitudes is plotted in Fig. 9. N_y gives our values of the number of mesotrons produced in the lead block (Fig. 1) and N_s represents the intensity of the soft component as obtained by Regener and Ehmert.[19] Although, as is to be expected, the errors are large, the results are suggestive of a constant value for the ratio of created mesotrons to the number of incident photons. This lends support to the hypothesis that photons are responsible for the excess mesotrons which we observe in our lower counter set. On the basis of this result we calculate a cross section σ_{ph} for the creation process by photons[4] and obtain a value $\sigma_{ph}=0.7\times 10^{-27}$ cm² per nuclear particle in lead.

The question arises whether the great number of mesotrons observed in the stratosphere and represented by curve B (Fig. 5) can be explained as a result of a similar creation process by photons in air. The observed value of the mesotron intensity (Fig. 5) at an altitude of 21.3 km (3.6 cm Hg) indicates that in an air layer corresponding to $\frac{1}{2}$ meter water equivalent 8 times as many mesotrons have to be produced as are present at sea level. Hence either the cross section for mesotron production by photons at the top of the atmosphere must be considerably greater than the value $\sigma_{ph}=10^{-27}$ cm² estimated by Nordheim and Hebb,[21] from the mesotron intensity at sea level or part of the mesotrons must be produced by some other primary radiation,[23] probably by protons.[24] Both possibilities have been discussed by Nordheim,[25] who showed that in both cases a serious difficulty for the theory arises if one considers the great penetration and hardening of the mesotrons observed at great depths.[10] From this fact it follows that the nuclear cross section for the absorption of mesotrons must be considerably smaller (by a factor of about 100) than the cross section for the creation of a mesotron by a photon or proton. This conclusion follows rather directly from the presence of the great number of mesotrons in the atmosphere (large creation cross section) in contrast to the great penetrating power of the mesotrons in great depths (small

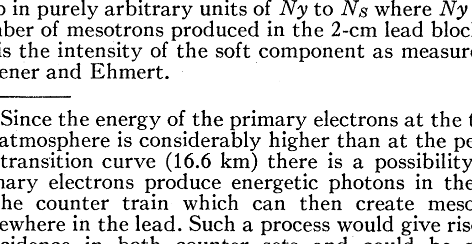

Fig. 9. The plot shows the approximate constancy of the ratio in purely arbitrary units of Ny to N_S where Ny is the number of mesotrons produced in the 2-cm lead block and N_S is the intensity of the soft component as measured by Regener and Ehmert.

[21] L. W. Nordheim and M. H. Hebb, Phys. Rev. **56**, 494 (1939).

[22] H. T. Bhabha, Proc. Roy. Soc. **A164**, 257 (1938); W. Heitler, Proc. Roy. Soc. **A166**, 529 (1938); M. Kobayasi and T. Okayama, Proc. Phys. Math. Soc. Japan **21**, 1 (1939).

[23] Since the energy of the primary electrons at the top of the atmosphere is considerably higher than at the peak of the transition curve (16.6 km) there is a possibility that primary electrons produce energetic photons in the lead of the counter train which can then create mesotrons somewhere in the lead. Such a process would give rise to a coincidence in both counter sets and could be partly responsible for the great number of mesotron counts measured in the upper counter set at an altitude corresponding to 3.6 cm Hg.

[24] T. H. Johnson, Rev. Mod. Phys. **11**, 208 (1939).

[25] L. W. Nordheim, Phys. Rev. **56**, 502 (1939).

absorption cross section). In this respect mesotrons seem to behave quite differently from high energy electrons where the cross section for pair creation by photons is of the same order of magnitude as that of the production of a photon by an electron.

Recalling the evidence brought forward by Bowen, Millikan and Neher[26] that the number of primary cosmic-ray particles is about 10 percent of the number of ionizing particles at the peak of the altitude ionization curve, it will be seen from Fig. 8 that the number of mesotrons at the maximum is likewise greater than the number of primary particles. This means, of course, that on the average there corresponds to each primary ray approximately one produced mesotron.

The Energy of the Mesotrons

In Fig. 6 where the log of the mesotron intensity is plotted against the pressure we see that the absorption coefficient remains approximately constant over the range from 50 cm Hg to 8 cm Hg. From this we can conclude that the average energy of the mesotrons in this altitude range remains approximately constant. In order that this can be the case the loss of mesotrons and the change of the energy spectrum by absorption must be nearly balanced by mesotrons which are added by creation.

Since at sea level the maximum of the energy spectrum[27] between 1 and 2×10^9 ev corresponds to an absorption coefficient of 0.7×10^{-3} g^{-1} cm^{-2}, the observed coefficient of 1.2×10^{-3} g^{-1} cm^{-2} above 5 km indicates that the energy maximum should occur at a value not greater than 10^9 ev.[28] Many of the produced mesotrons in the stratosphere must be of an energy considerably lower than 10^9 ev in order to maintain an approximately constant value of the mean energy of the mesotrons.

The energy of the primary cosmic-ray particles entering the earth's atmosphere as determined by Bowen, Millikan and Neher[17] has its maximum at about 6×10^9 ev. Taking into account that for primary electrons a considerable reduction of their energy takes place by cascade processes in the atmosphere,[29] one finds that the mean energy of the photons at the peak of the transition curve for the soft component (8 cm Hg) should be about 10^9 ev, which is of the same order of magnitude as the mean energy of the mesotrons estimated from the absorption curve of Fig. 6.

The result that at least the great majority of the mesotrons in the stratosphere must have energies around 10^9 ev is a direct proof of their secondary origin. This follows from the fact that no singly charged particles with energies smaller than about 3×10^9 ev can penetrate through the barrier of the earth's magnetic field at a geomagnetic latitude of 52.5°N.[30]

The writers wish to express to Professor A. H. Compton at whose suggestion this whole series of experiments was initiated, their appreciation of his continued interest.

[26] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **53**, 217 (1938).

[27] H. Jones, Rev. Mod. Phys. **11**, 235 (1939).

[28] This conclusion is supported by measurements recently made by M. Schein, E. O. Wollan and G. Groetzinger, who found by absorption measurements in lead that at 8.5 km altitude about 30 percent of the mesotrons have their energies between 2×10^8 and 5×10^8 ev.

[29] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **50**, 493 (1937); R. Serber, Phys. Rev. **54**, 311 (1938).

[30] G. Lemaître and M. S. Vallarta, Phys. Rev. **50**, 493 (1936).

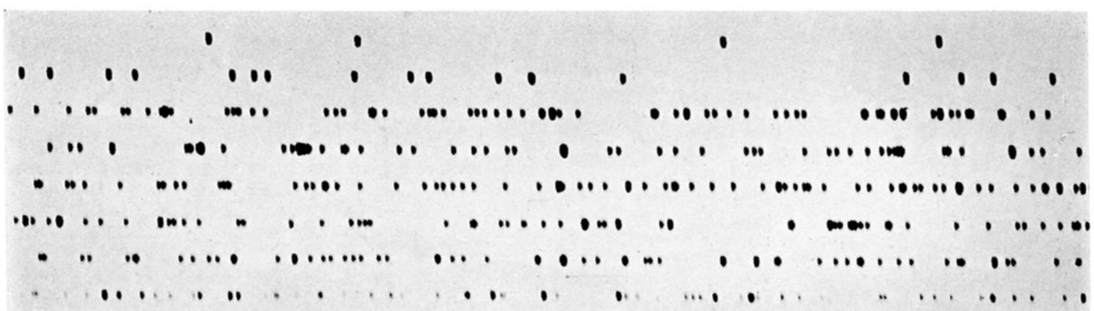

FIG. 3. A reproduction of part of the film showing a portion of each hour's record for threefold coincidence counts.