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Positive Excess of Slow Mesotrons at an Altitude of 3.5 km

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Cloud-chamber tracks of mesotrons having momenta between 1.25×10^8 ev/c and 2.5×10^8 ev/c were photographed at an altitude of 3.5 km. Mesotrons in this momentum range were selected by a specially designed anticoincidence circuit. The tracks were curved by a magnetic field of 1670 gausses. A 1.25-cm lead plate above the chamber and two 1-cm lead plates within the chamber enabled one to distinguish electrons from mesotrons by multiplication phenomena. Mesotrons of these momenta easily penetrate several centimeters of lead, while protons of equal momenta have a range in lead of less than 0.2 mm. Thus, confusion of protons with mesotrons was very unlikely. Examination of 320 mesotron tracks which traversed both lead plates in the chamber and had momenta in the selected range showed that $47._2$ percent of the mesotrons carried positive charges while the remaining $52._8$ percent were negative. Hence, within the ±5.6 percent precision of this experiment, positive and negative mesotrons having energies between 0.6×10^8 ev and 1.7×10^8 ev occur in equal numbers at an elevation of 3.5 km.

I. INTRODUCTION

Several investigators,[1] who have used a cloud chamber in a magnetic field to study the charge carried by cosmic-ray mesotrons, have reported that there is an excess of those bearing a positive charge. The best measurements seem to indicate that, of the mesotrons at sea level having energies $E>5\times10^8$ ev, the ratio of the number of positive to that of negative mesotrons is about 1.2, or the positive excess is about 20 percent. Recently Bernardini[2] and his collaborators confirmed a positive excess of about 20 percent by deflecting the mesotrons in magnetized iron. In this system only mesotrons capable of traversing at least 40 cm of iron were registered; therefore, this measurement of the positive excess likewise pertained to mesotrons of energy $E>5\times10^8$ ev.

According to Carlson and Schein[3] the observed 20 percent positive-mesotron excess may be explained by supposing that the primary cosmic radiation consists of protons which interact with nucleons of air nuclei close to the top of the atmosphere. In their explanation each collision with a nucleon on the average produces several mesotrons and, in order that the positive charge of the primary proton be conserved, more positive than negative mesotrons are produced. In such an act the proton loses an appreciable amount of its kinetic energy and is finally changed into a neutron. If an average of 11 mesotrons is created in these events, and if all of them are of sufficiently high energy to reach sea level before decaying, the ratio of the number of positive to the number of negative mesotrons would be 6:5, or the positive excess would be 20 percent.

The assumptions of Carlson and Schein regarding the production of mesotrons in multiple processes to account for the 20 percent positive mesotron excess are based on the work of Schein, Jesse, and Wollan.[4] These investigators used a coincidence system, which included from 4 to 18 cm of lead, to measure the intensity of mesotrons as a function of altitude up to about 2-cm Hg. Their intensity-*vs.*-pressure curve showed no maximum up to the highest altitudes attained. This result, in conjunction with the fact that mesotrons themselves cannot be the primary radiation, since they decay spontaneously with a mean life of $\sim2\times10^{-6}$ second, led to the conclusion that most of the mesotrons observed in this experiment are produced close to the top of the atmosphere. Schein, Jesse, and Wollan also concluded from the results of their experiment that it is highly unlikely that the primary radiation consists of electrons. They decided that the primary radiation is probably composed of protons.

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[1] P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937); L. LePrince-Ringuet and J. Crussard, J. de phys. et rad. **8**, 207 (1937); H. Jones, Rev. Mod. Phys. **11**, 235 (1939); D. J. Hughes, Phys. Rev. **57**, 592 (1940).

[2] Bernardini, Conversi, Pancini, Scrocco, and Wick, Phys. Rev. **68**, 109 (1945).

[3] J. F. Carlson and M. Schein, Phys. Rev. **59**, 840 (1941).

[4] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 615 (1941).

Johnson[5] also concluded that part of the primary radiation consists of protons. In attempting to explain the east-west asymmetry of the hard component, observed near the equator at sea level, he attributed the origin of the hard component to these primary protons and showed that the deflection of the incoming protons in the earth's magnetic field could account for the observed asymmetry.

The assumption that mesotrons are produced in multiple is supported by the experiments of Schein, Iona, and Tabin.[6] At altitudes corresponding to 3-cm Hg they have found several penetrating particles ejected from paraffin, and they thought that these were probably mesotrons produced in a multiple act.

Heitler and Walsh[7] have used different assumptions to describe the elementary process of mesotron production. However, the positive excess predicted by their theory is smaller than that observed by a factor of from 3 to 5.

A detailed theory of collisions between protons and air nuclei to account for the observed positive mesotron excess is yet to be developed. Nevertheless, the existence at sea level of a positive excess among mesotrons having energies $E > 5\times 10^8$ ev is qualitatively consistent with the hypothesis that such mesotrons are produced multiply close to the top of the atmosphere by the interaction of primary protons with air nuclei and that the excess conserves the positive charge of the protons.

There are, however, lower energy mesotrons, existing at higher elevations, which are apparently not formed by the mechanism described above. Several investigations have confirmed the fact that, as the altitude of observation increases, the relative number of mesotrons of energies $E < 5\times 10^8$ ev is rapidly augmented. The best sea-level measurement of the mesotron differential energy spectrum is probably the one reported recently by Wilson.[8] Using a cloud chamber in a magnetic field, he found a definite maximum at an energy $E \sim 6.1\times 10^8$ ev. The approximate shape of the mesotron differential energy spectrum has been determined at an elevation of 3.24 km by Rossi, Greisen, Stearns, Froman, and Koontz,[9] at 4.35 km by Hall,[10] and at 6.7 km by Schein, Wollan, and Groetzinger.[11] These investigations were made with counter configurations which included various thicknesses of absorbers between the counters. Hall, at Mt. Evans (4.35 km), found that his spectrum showed a maximum for mesotrons of energy $E \sim 10^8$ ev. He used this spectrum to compute the mesotron energy spectrum at 3.24 km, the altitude of Echo Lake, and found good agreement with the measurements made there by Rossi, Greisen, Stearns, Froman, and Koontz. Schein, Wollan, and Groetzinger found that, at an altitude of 6.7 km, about 33 percent of the total mesotron intensity was comprised of mesotrons having energies $E < 5.2\times 10^8$ ev. Bhabha, Aiya, Hoteko, and Saxena[12] used counter telescopes to measure mesotron intensity-*vs.*-altitude curves at 3.3° N mag. lat. under 5.5, 20, and 30 cm of lead. They too have found a large increase of low energy mesotrons with increasing altitude.

A comparison of these spectra shows that the maximum of the mesotron differential energy spectrum becomes considerably more prominent

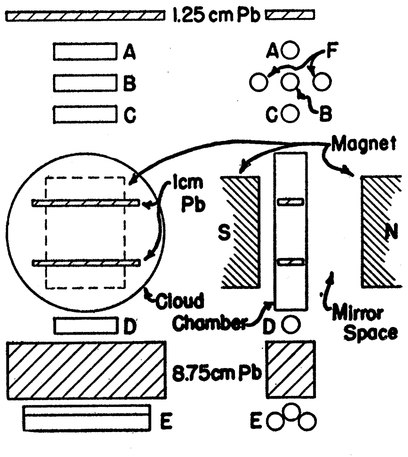

FIG. 1. Arrangement of apparatus. A mirror, set vertically in the mirror space at 45° with the magnetic-field direction, permitted a camera to take pictures in a plane perpendicular to the magnetic field. Counters *ABCD* were connected in coincidence, while *EF* were in anticoincidence.

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

[6] M. Schein, M. Iona, Jr., and J. Tabin, Phys. Rev. **64**, 253 (1943).

[7] W. Heitler and P. Walsh, Rev. Mod. Phys. **17**, 252 (1945).

[8] J. G. Wilson, Nature **158**, 414 (1946).

[9] B. Rossi, K. Greisen, J. C. Stearns, D. K. Froman, and P. G. Koontz, Phys. Rev. **61**, 678 (1942).

[10] D. B. Hall, Phys. Rev. **66**, 321 (1944).

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

[12] H. J. Bhabha, S. V. C. Aiya, H. E. Hoteko, and R. C. Saxena, Phys. Rev. **68**, 147 (1945).

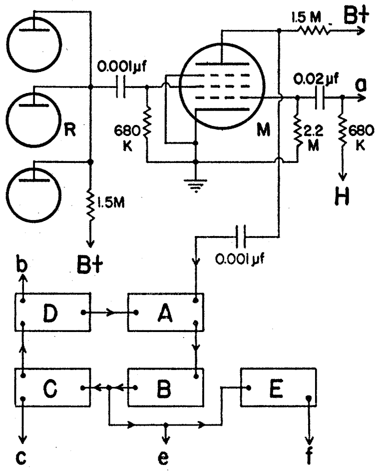

FIG. 2. Block diagram of timing circuits. Coincidence tubes *R* furnish positive pulse to screen of pentode mixer *M* when coincidence occurs. This makes *M* conduct unless anticounters at *a* simultaneously supply a strong bias to the control grid. Differentiation at plate of *M* supplies triggering pulse to trigger circuit *A* (detail in Fig. 3a). *B*, *C*, *D*, and *E* are unbalanced multi-vibrators (detail in Fig. 3b) and serve to delay the original pulse. *A* feeds pulse to *B*; *B*, after delay, feeds pulse to *C*; etc. Pulse *e* expands chamber, *f* flashes lamps, *c* compresses chamber and rewinds camera, and pulse from *D* to *A* retriggers *A* to original condition for next cycle of operation. *b* supplies a sustained boosted clearing-field voltage. $B+$ is 225 v and *H* is the high voltage for the anticounters. Tubes *R* and *M* were of type 9001.

and shifts toward lower energies as the altitude increases. This increase cannot easily be explained by the mechanism which Carlson and Schein proposed in accounting for the positive excess observed at sea level in mesotrons of energies $E>5\times10^8$ ev. It is, therefore, probable that at least some of these mesotrons are produced by another mechanism. Several different experiments have already indicated the production of mesotrons with energies $\sim10^8$ ev by *non-ionizing* radiation.[13] Such mesotrons would not be expected to show an excess of either charge. Hence, it is pertinent to ask whether the low energy mesotrons, which are increasingly prevalent as the altitude is increased, show a positive excess.

The present investigation is confined to mesotrons of energies $0.6\times10^8 \text{ ev}<E<1.7\times10^8$ ev at an altitude of 3.5 km and attempts to determine the relative numbers of positive and negative mesotrons.

II. APPARATUS

The apparatus consisted of a counter-controlled cloud chamber of the rubber diaphragm type mounted vertically against the south pole face of a permanent magnet (see Fig. 1). The cloud chamber was 10 inches in diameter and 2 inches deep. The chamber was filled in its compressed condition with commercial argon to a pressure of 20- to 24-cm Hg more than that of the atmosphere.

The magnet was made of Alnico V and weighed 1000 lb. It was designed as a horseshoe to provide an air gap 7 inches long, wherein the field strength would be fairly uniform over an area 7 inches high and 5 inches wide. The field was carefully mapped along the central plane of the photographable region of the chamber. It was found that the field strength was 1670 gausses at the center of the $5''\times7''$ area and was down about 10 percent at the edges. Since the heat treatment process in the manufacture of Alnico V makes it impossible to cast magnets of this size in one piece, this magnet was designed to be assembled as a horseshoe out of 11 castings of Alnico V, two soft steel corner blocks, and two soft-steel pole faces. These pieces were held together by threaded bronze tie-rods and by a rigid casing made of $\frac{1}{2}$-inch aluminum plates.

The chamber, when mounted in the air gap, occupied approximately $3\frac{1}{2}$ inches of the gap length. A plane mirror aluminized on the front surface was mounted in the remaining $3\frac{1}{2}$ inches of the air gap at 45° with the magnetic axis. By this arrangement a camera aimed into the mirror could take pictures through the front wall of the chamber. The photographable volume within the chamber was 4 inches wide, one inch deep, and 10 inches high. The pictures were taken by a specially designed, automatic camera, which was provided with a coated Kodak Ektar f: 2 lens and which used 35-mm Super-XX perforated movie film. The illumination was furnished by two FT-26 General Electric Flash tubes, each operating from 45 microfarads charged up to 1400 volts. It was found in practice that, with the illumination provided, a lens speed of f: 3 was sufficient and, of course, the focus was then less critical. The magnet, the chamber, the camera, and the counter telescope were all enclosed in a light-tight box so that the camera could be operated without using a shutter.

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[13] See summary in M. Schein and D. Montgomery, *Problems in Cosmic Ray Physics* (Princeton University Press, Princeton. 1946), Chapter VIII.

As may be seen from Fig. 1, the chamber expansions were controlled by a fourfold coincidence telescope composed of 4 GM counters (*ABCD*) one inch in diameter and 4 inches long. These counters were filled with argon and alcohol. A particle which discharged these 4 counters had traversed the chamber and, if it was unable to emerge from the 8.75-cm lead filter below the fourth counter, it was within the energy range selected for the experiment and its track was photographed. However, if it also discharged the anticounters (*E*) below the lead, its energy was too great and the chamber did not expand. The counters (*F*) also were connected as anticounters; their function was to protect the coincidence set (*ABCD*) from the effects of showers.

A block diagram of the timing circuits is shown in Fig. 2. The detail of the trigger circuit *A* is shown in Fig. 3a. The delay- or interval-timing circuits *B*, *C*, *D*, and *E* were all unbalanced multi-vibrators or "flip-flop" circuits. The detail of these circuits is shown in Fig. 3b, except for the particular values of the components *R* and *C* which determine the duration of the delay or of the interval and are optional within wide limits. Circuits of the types shown in Fig. 3 can easily be made sensitive to negative pulses only,[14] and this feature makes it possible to connect several such circuits in series about a closed ring, as is illustrated in the block diagram by the connections between blocks *A*, *B*, *C*, and *D*. When the counter telescope registered the occurrence of a suitable event, a positive pulse from the coincidence tubes, *R*, applied screen voltage to the pentode mixer, *M*, (Fig. 2). Normally, the bias on the control grid of this tube was zero, so that the sudden application of screen voltage resulted in a sudden rise in plate current; i.e., a negative pulse could be obtained from the plate of this tube. However, if the event registered by the coincidence set also discharged an anticounter, a negative pulse from this counter was applied to the control grid of the pentode mixer, so that no rise in the plate current of this tube could occur.

The negative pulses appearing on the plate of the mixer tube, *M*, were applied to the trigger circuit and caused it to trigger to the other stable condition. As long as this circuit remained so triggered it acted as a barrier to pulses from succeeding cosmic-ray events, which might interfere with the cycle of operation of the cloud chamber if the chamber were not yet ready for the next expansion. At the close of the cycle of operation, the trigger circuit was triggered back to its normal condition by a negative pulse from the circuit represented by block *D*.

Block *A* was so connected that a negative pulse from the plate of the mixer tube was passed immediately to block *B*. Block *B*, which was an unbalanced multi-vibrator, produced a single square wave of a duration adjustable from 0.001 to 0.1 second. The falling side of this wave was differentiated to obtain a sharp negative pulse for triggering blocks *C* and *E*, both of which were unbalanced multi-vibrators; this pulse also caused

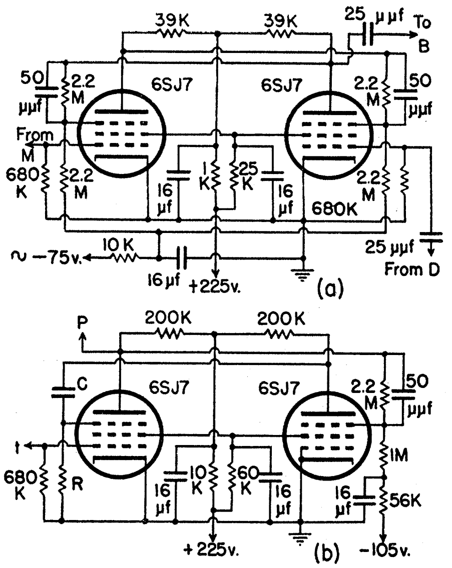

FIG. 3. Detail of blocks in Fig. 2. (a) shows trigger circuit (block *A*). Circuit is very sensitive to negative pulses on control grids and relatively insensitive to all other pulsings. Left tube is normally "on" and negative pulse from *M* is passed directly to block *B* by 25 $\mu\mu$f from right plate. At end of cycle, pulse from block *D* onto right control grid triggers circuit back to original condition. (b) shows unbalanced multi-vibrator circuits (blocks *B*, *C*, *D*, and *E*) which, upon being triggered, produce single, very square waves whose durations are determined by particular values of *R* and *C*. Left tube is normally "on" and negative triggering pulse is introduced at *t*; circuit is relatively insensitive to all other pulsings. The successive triggering pulse and pulses *c*, *e*, and *f* were obtained by differentiating the single square waves as they appeared at *P*; this produced sharp, delayed, negative pulses as the circuits returned to normal. Sustained positive voltage *b* was obtained from *P* directly. Where desirable, as on thyratron grids, the negative pulse was changed in sign by a stage of amplification.

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[14] H. J. Reich, *Theory and Application of Electron Tubes* (McGraw-Hill Book Company, Inc., New York, 1939).

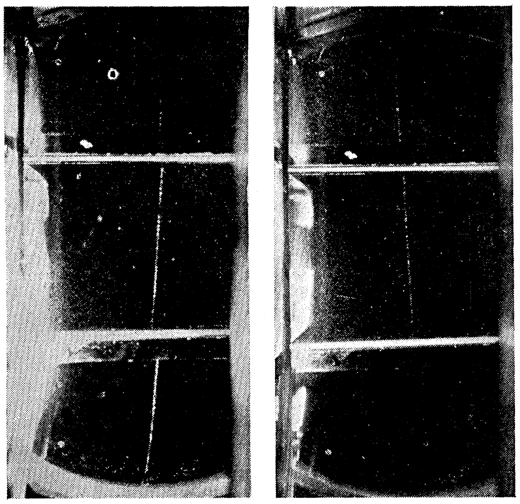

FIG. 4. Typical pictures. Each of these tracks is visible in all three sections of the chamber, and there is no evidence of cascade multiplication in the lead plates. The track in the right-hand picture has a radius of curvature of ~200 cm and was made by a negative mesotron. The other track has a radius of curvature of ~175 cm and was made by a positive mesotron.

the cloud chamber to expand. The single square wave produced by block E also had a duration adjustable from 0.001 to 0.1 second, and a sharp pulse obtained by differentiation as this circuit returned to its normal condition was used to flash the FT-26 lamps. The duration of the square wave from block C was about 3.5 seconds, and a sharp pulse produced at the close of this interval triggered the unbalanced multi-vibrator represented by block D; this pulse was also used to close the valves, so that compressed air introduced behind the rubber diaphragm could again compress the chamber. This same pulse started the motor for turning up the film in the camera. The circuit in block D remained in its triggered condition for about 30 seconds, and throughout this interval 180 volts was applied to the chamber as a field for clearing old ions from the interior. As was mentioned before, a sharp negative pulse obtained at the close of this interval returned the trigger circuit (block A) to its normal condition, and the entire apparatus was then ready to make the next picture.

The apparatus was installed at Climax, Colorado, in a small portable house,[15] whose roof was made of $\frac{1}{4}$-inch plywood. It was found necessary to control the temperature inside of the house to within 1°F to insure reliable operation of the chamber.

III. DISCUSSION OF THE ACCEPTABLE TRACKS

Two 1-cm lead plates were mounted 8.5 cm apart within the chamber, and a 1.25-cm lead plate was placed above the counter telescope ($ABCD$), (see Fig. 1). Any mesotron capable of causing a coincidence in the fourfold coincidence set must have had sufficient energy to traverse at least 3.25 cm of lead, since the fourth counter of the set was just below the cloud chamber. If, however, the mesotron had sufficient energy to traverse not only the 3.25 cm of lead but also the 8.75 cm of lead below the chamber, it also discharged one of the anticounters (E). Thus, in order to initiate automatic operation of the cloud chamber, a mesotron had to be able to pass through 3.25 cm of lead but be unable to pass through 12 cm of lead. From the curves given by Rossi and Greisen[16] it can be seen that such mesotrons must be in the momentum range 1.25×10^8 ev/c$<p<2.5\times10^8$ ev/c; this corresponds to a range in kinetic energy of 0.6×10^8 ev $<E<1.7\times10^8$ ev.[17]

The radius of curvature ρ of the path of a charged particle which travels with momentum p in a plane normal to a magnetic field of strength H is given by the relation,

$$p=300H\rho.$$

From this equation it is seen that an electron and a mesotron having equal momenta cannot be distinguished by the curvatures of their tracks. Furthermore, as long as the lower limit of the momentum range is well above 10^8 ev/c, the ionization produced by the passage of electrons and mesotrons through a gas is nearly the same, so that their tracks will be equally heavy and will not serve to distinguish the two kinds of particles. It was necessary, therefore, to employ the three lead plates in the upper part of the telescope in order to enable one to distinguish events involving

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[15] This house was constructed by Lewis and used in his experiments at Echo Lake: L. G. Lewis, Phys. Rev. **67**, 228 (1945).

[16] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

[17] For converting momenta to energies the mesotron mass was taken as 10^8 ev/c^2 or 200-electron masses. This is in close agreement with Fretter's recent measurement of mesotron mass ~202-electron masses: W. B. Fretter, Phys. Rev. **70**, 625 (1946).

electrons from those involving mesotrons, since, in general, electrons produce cascade showers in traversing lead, and hence should show many tracks, while mesotrons do not.

There is a small probability, however, that some incident electrons with energies of approximately 10^8 ev traversed the first lead plate (2.5-radiation lengths of matter) without multiplication.[18] For these electrons there is again a small probability that some of them traversed the second lead plate (2-radiation lengths) without multiplication. But the probability that an incident electron with energy $\sim 10^8$ ev traversed both of the first two plates without having initiated a shower is proportional to the product of two small probabilities. Furthermore, for the electrons which emerged from both the first and second lead plates without having multiplied, there is yet a small probability that some of them passed through the third lead plate without producing a shower. But the total probability that such an electron traversed all three lead plates (6.5-radiation lengths) without multiplication in any one of them is proportional to the product of three small probabilities. The likelihood that many such electrons will be mistaken for mesotrons is, therefore, negligibly small.

Electrons incident with considerably greater energies (up to 10^{10} ev at which energy they begin to affect the anticounters (E)) than that considered above would have produced showers of a large number of particles in traversing 2.5-radiation lengths and also 4.5-radiation lengths of matter. Hence, they should be definitely identifiable at any stage of their traversal of the telescope.

It is also well to note that the three lead plates make it practically impossible to confuse protons with mesotrons in the photographable region. This is true since those protons which would travel along an arc of measurable curvature, say 300-cm radius, have a range in lead of less than 0.2 mm.

Before the results are discussed it should be mentioned that a calculation was made to ascertain whether the scattering in the gas of the chamber might introduce apparent radii of curvature of such magnitude as to confuse the results. In order to make the hypothetical case severe, the calculation was carried out for a mesotron of momentum $p=4.8\times10^7$ ev/c, which is considerably below the range of momenta considered in the experiment. This mesotron would travel along an arc having a radius of 100 cm. The probable "scattering radius" for such a mesotron was calculated according to the recent formula given by Bethe[19] and is 950 cm. This is entirely negligible within the precision of this experiment, particularly since this research concerns only the determination of the kind of charge carried by the mesotron. Typical pictures are shown in Fig. 4.

IV. RESULTS

The curvature of a track was measured by projecting the image of the 35-mm negative onto a table top and then using a micrometer stage to determine sagitta measurements. There were 320 tracks which were visible in all three sections of the chamber. Of these 169 showed curvatures corresponding to negatively-charged particles. The remaining 151 tracks showed the opposite curvature and, consequently, had been made by positively-charged particles. It would thus appear that 52.8 percent of the mesotrons in the energy range 0.6×10^8 ev $<E<1.7\times10^8$ ev are negatively charged, while the other 47.2 percent of these mesotrons were positively charged. The statistical error for 320 observations is ±5.6 percent, so it would seem that the numbers of positive and negative slow mesotrons are equal within the precision of this experiment. At any rate, it is apparent that at an altitude of 3.5 km a positive mesotron excess as large as 20 percent does not exist for mesotrons of this energy range.

At present there are two possible explanations for the lack of a 20 percent positive excess among the slow mesotrons occurring abundantly at high elevations. These mesotrons may be produced in the atmosphere by a neutral radiation, which

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[18] On the average, the energy E of an electron after traversing a layer of matter of thickness t, measured in radiation lengths, is given with good approximation by

$$E=E_0e^{-t},$$

where E_0 is the energy with which the electron entered the layer. For lead the radiation length is about 0.5 cm. Thus, on the average, after having traversed the first lead plate in this experiment, an electron would have radiated, very approximately, all but 8 percent of its incident energy. This radiated energy, of course, should have initiated a shower provided E_0 is greater than the critical energy in lead, which is 7×10^6 ev.

[19] H. A. Bethe, Phys. Rev. **70**, 821 (1946).

might be either neutrons or γ-rays, in which case no positive mesotron excess would be expected. Or it may be that they are produced with very high multiplicity at the top of the atmosphere by a mechanism similar to that described by Heitler and Walsh.[7] According to their theoretical calculations, the excess should be 3 to 5 times smaller than that observed at higher energies. However, it is difficult to understand why this small excess is limited only to the lowest energies in the mesotron spectrum and does not extend to energies above 5×10^8 ev, where the observed excess is as high as 20 percent.

Bernardini and his collaborators,[2] using their magnetized iron at 3.3 km, have tried to investigate the positive-mesotron excess as a function of mesotron energy. They have concluded that their arrangement is not particularly suited to this use, but that, if the 20 percent excess persists down into the low energy regions, they should have obtained a larger effect at their lowest energies ($\sim5\times10^8$ ev) than they actually found.

ACKNOWLEDGMENTS

The author desires to express his deep appreciation to Prof. Marcel Schein, who suggested the problem and whose interest, encouragement, and advice were an indispensable factor in the successful execution of the experiment. The continuing support of Dr. Walter Orr Roberts and Dr. John W. Evans, both of the Harvard College Observatory at Climax, which was always available to the expedition, is gratefully acknowledged. The hospitality of Supt. C. J. Abrams of the Climax Molybdenum Company, who placed many facilities of his company at the disposal of the expedition, is deeply appreciated. Thanks are also due Mr. Ivar Kalberg for the machining of the metal parts of the cloud chamber and camera and for the assembly of the magnet.

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The Production of a Positron-Electron Pair in the Electrostatic Field of an Electron

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The production of positron-electron pairs in the electrostatic field of an electron is considered. In spite of the light mass of the recoil electron and the exchange effect between the two electrons, the process is quite similar to ordinary pair production. For the limiting case of high energy γ-rays, the ratio of triplet production to pair production should vary as $1/Z$. For $h\nu/mc^2<30$, pair production will have a relatively greater cross section for all values of Z, the nuclear charge.

It is found that in general (except near the γ-ray energy threshold of $4mc^2$) the positron and one electron will have relatively high energy compared to the second electron.

1. INTRODUCTION

THE production of "triplets," that is, pair creation in the vicinity of an electron, has been reported by Kruger.[1] This process is essentially equivalent to ordinary pair production, but differs from the latter in two details. First, an appreciable amount of the energy of the incident γ-ray can be carried away by the initial electron (as a matter of-fact, the energy threshold occurs at γ-ray energies of $4mc^2$ instead of at $2mc^2$ as for ordinary pair creation). Second, the process is complicated by the equivalence of the two electrons involved, which permits their roles to be interchanged.

2. THE CROSS SECTION FOR TRIPLET PRODUCTION

The differential cross section for a process initiated by γ-rays, and in which two particles

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[1] Private communication to Professor Jauch. See also J. A. Phillips and P. G. Kruger, Phys. Rev. **72**, 164 (1947).

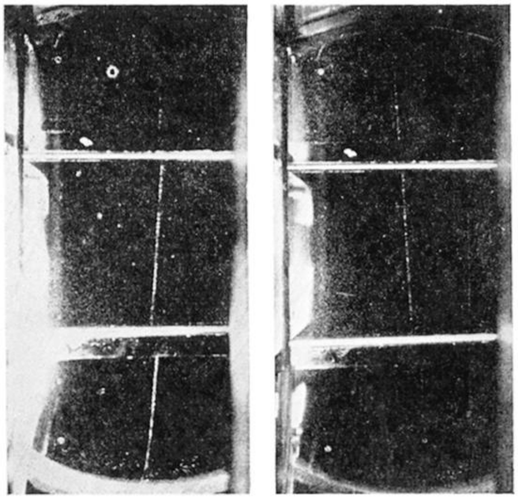

FIG. 4. Typical pictures. Each of these tracks is visible in all three sections of the chamber, and there is no evidence of cascade multiplication in the lead plates. The track in the right-hand picture has a radius of curvature of ~200 cm and was made by a negative mesotron. The other track has a radius of curvature of ~175 cm and was made by a positive mesotron.