kind cooperation of the U. S. Army air-corps. Here again the consistency of the points attests the dependability of the curve.

The conclusions to be drawn from these two curves may be stated as follows:

1. *Within the uncertainty of the measurements* here estimated at five percent there is at 26,000 feet no difference between the cosmic-ray intensities in Peru and in the Philippines. The sea-level difference of four percent may continue up to the highest altitudes here reached, but the precision of the measurements is insufficient to determine whether it does or not. The difference cannot, however, be appreciably more than that.

2. In the equatorial belt on both sides of the world the cosmic-ray ionization rises essentially exponentially from sea level to an altitude of 29,000 feet with an apparent absorption coefficient of 0.5 per meter of water fitting well the upper part of the depth-ionization curve. In the temperate latitudes the coefficient that must be used to fit the observed curves equally well is only a little larger, namely, 0.55 per meter of water. This difference is sufficient, however, to make the ionization in the equatorial belt at 29,000 feet (about 50 ions cc/sec. in air at 1 atmos.) about 50 percent of its value at the same altitude in the temperate latitude 52, in which the Fordney-Settle flight was made. These results destroy the validity of the chief argument that has been advanced thus far for the great preponderance of the particle component over the photonic component of the cosmic rays which come into the earth's atmosphere in the equatorial belt.

We wish to express our appreciation to the Carnegie Corporation of New York and the Carnegie Institution of Washington as well as to the above-mentioned air services through whose aid the foregoing results have been made possible.

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The Heavy Particle Component of the Cosmic Radiation

R. B. BRODE, H. G. MACPHERSON AND M. A. STARR, *Department of Physics, University of California, Berkeley, California*

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A large Wilson cloud chamber was used to study the heavy particles in the cosmic radiation. The chamber had a volume of 7 liters and an illuminated section 5 cm deep by 30 cm in diameter, so that there was no danger of confusing alpha-particle tracks with heavy cosmic rays. Heavy tracks made in the 1.5 seconds preceding the expansion were recorded. In 8500 pictures, about 80 heavy tracks were observed. Of these, 21 were made by particles of about the ionization of slow protons. Their paths could be seen in the illumination for distances equivalent to path lengths of from 13 to 45 cm in air. 45 less dense old tracks were observed that had an ionization noticeably greater than an electron track. Of the tracks that appeared to have tripped the counters causing the expansion, 14 were considerably heavier than electron tracks. Three disintegrations with heavy tracks apparently arising from the wall of the chamber were observed. Most of the other old heavy tracks were also probably of secondary origin. It is estimated that about one percent of the sea-level cosmic ionization is due directly to heavy particles.

INTRODUCTION

THE analysis of the variation of the cosmic-ray intensity with altitude led Compton and Bethe[1] to propose that the primary cosmic radiation consisted in part of very high energy protons and alpha-particles. However, the Wilson cloud chamber photographs of the cosmic radiation did not seem to give much support to their hypothesis. Blackett[2] showed that the frequency of appearance and the magnitude and range of most of the heavy particles observed in cloud chamber photographs could be accounted for as contamination alpha-particles emitted from the walls of the chamber. Blackett and Occhialini,[3] reported two heavy tracks which were probably due to protons. In a large chamber located on

[1] A. H. Compton and H. A. Bethe, Nature **134**, 734 (1934).

[2] P. M. S. Blackett, Proc. Roy. Soc. **A146**, 281 (1934).

[3] P. M. S. Blackett and G. P. S. Occhialini, Proc. Roy. Soc. **A139**, 699 (1933).

the Jungfrau (3500 meters elevation) Herzog and Scherrer[4] observed one probable proton track in 165 pictures. Rieder and Hess[5] in 1200 pictures taken in a chamber at an elevation of 2300 meters found 3 tracks with a range of 5 cm which they concluded were not due to contaminating alpha-particles. Most of the proton tracks reported by Kunze[6] are undoubtedly positrons but a few of his tracks appear to be due to heavy particles. Anderson[7] has recently reported the results of his cloud chamber experiment on Pike's Peak (elevation 4300 meters) in which he observed a number of heavy particle tracks. The existence of heavy particles in the cosmic radiation at very great altitude has also been verified by the tracks left in photographic emulsion.[8,9]

Montgomery, Ramsey and Swann[10] attempted to identify heavy particles as a component of the cosmic radiation at sea level by measurements with an ionization chamber combined with a coincidence counter. From their measurements they concluded that if heavy particles existed at sea level they were present in negligible numbers. Clay,[11] however, concluded that heavy particles were occasionally present in an ionization chamber as the result of some disintegration phenomena occurring in the walls of the chamber.

In a chamber where the illuminated region is only 1 or 2 cm broad it is not possible to distinguish an alpha-particle track that passes perpendicularly through the light beam from a cosmic heavy particle. However, if the depth of the chamber is considerably greater than the range of an alpha-particle it can easily be identified. In the chamber used in this experiment the depth corresponded to 20 cm range and it was possible to observe particles with ranges up to 60 cm in the chamber. All tracks shorter than 10 cm range were not counted as possible heavy cosmic particles.

[4] G. Herzog and P. Scherrer, J. de phys. et rad. (VII) **6**, 489 (1935).
[5] F. Rieder and V. F. Hess, Nature **134**, 772 (1934).
[6] P. Kunze, Zeits. f. Physik **83**, 1 (1933).
[7] C. A. Anderson and S. H. Neddermeyer, Phys. Rev. **49**, 415 (1936).
[8] T. R. Wilkins and H. St. Helens, Phys. Rev. **49**, 403 (1936).
[9] L. H. Rumbaugh and G. L. Locher, Phys. Rev. **49**, 889 (1936).
[10] C. G. Montgomery, D. D. Montgomery, W. E. Ramsey and W. F. G. Swann, Phys. Rev. **49**, 890 (1936).
[11] J. Clay, Physica **2**, 111 (1935).

Apparatus

The Wilson cloud chamber used in these experiments was not essentially different from the chamber designed by Blackett. The chamber was 30 cm in diameter and 10 cm deep. It had a front glass of half-inch "Tufflex" glass and in the back a wire gauze covered with black velvet. The piston was a thin aluminum sheet attached to a rubber ring at the edges. The face of the aluminum sheet was covered with a thin layer of paraffin to keep the gas of the chamber from contact with the aluminum. Compressed air pushed the piston up against stops whose position could be adjusted to vary the expansion ratio. With nitrogen in the chamber at two atmospheres pressure and a mixture of 3 parts ethyl alcohol and one of water, an expansion ratio of 1.125 gave good tracks. To keep a more uniform distribution of vapor in the chamber a small dish of the mixed liquids was placed above a lead shelf at the top of the chamber. The lead shelf was introduced to study the showers produced in the lead.

The chamber was tripped by a coincidence beween a Geiger-Müller counter above and one below the chamber. The thyratron that was tripped by the counter sent a current through the moving coil of a dynamic loudspeaker. This speaker coil pulled a small roller bearing trip from under a valve and released the air from the chamber. The breadth of the tracks of the cosmic rays indicated a delay of 0.015 second from the arrival of the cosmic ray to the full expansion. 0.035 second later the illumination began and continued for about 0.1 second. As a source of light eight 150-watt 110-volt type C Mazda lamps were used on 220 volts d.c. They were focused through the chamber by cylindrical lenses. To prevent the breaking of the lamps at the seal-in a choke was placed in the supply line to limit the current until the filaments became hot. The first set of lamps was destroyed by an accident but the present set show no signs of wear after over 6000 pictures.

A pair of Kodak Retina cameras with Schneider-Kreuznach f: 3.5 lenses were used to photograph the chamber. The cameras were set on opposite sides of the normal to the plane of the chamber at angles 15° to the normal. The photographs were taken on Eastman Super X film which was developed two minutes in Eastman D-8 developer. The lenses were tested[12] by photographing straight lines through the front glass of the chamber and were found to introduce fictitious curvatures of about 40 meters radius in lines 7 cm from the center. This distortion was negligible compared with a distortion of 10 meters radius of curvature introduced by turbulence in the chamber. The chamber turbulence was however sufficiently consistent so that tracks could be measured to a radius of curvature of 20 meters.

The operation of the chamber was entirely automatic. To eliminate the turbulence that followed an expansion, the chamber was allowed to stand from 40 sec. to 1 min. after an expansion. No slow or clearing expansions were required. The average time elapsed in waiting for a coincidence was two minutes. 75 percent of the pictures showed a cosmic-ray track that passed through the two counters. A clearing field of 45 volts was applied between the front and back of the chamber. This clearing field did not cause a measurable separation of the ions in the track of the cosmic ray that tripped the chamber. The tracks produced in the second before the expansion are still visible but because of their diffuseness they do not interfere with the study of the sharp tracks.

The apparatus was located on the top floor of a 3-story reinforced concrete building. Directly over the apparatus was only a thin sheet iron roof. Although the Lawrence cyclotron was located in a building 200 feet away, no correlation between its operation and the appearance of heavy particles in the chamber was observed.

Identification of Proton Tracks

Heavy particles are recognizable in a cloud chamber by the fact that at moderate and slow speeds they produce greater ionization than an electron. It is possible to estimate the relative ionizing power of a particle from the apparent breadth of its track if the length of time between the passage of the particle and the completion of the expansion is known.[2] The ionizing particle leaves ions in its path concentrated in a very narrow column. The ions will rapidly diffuse away from the center of this column, producing a broadening of the track. The diffusion of the tracks will be effectively stopped at the completion of the expansion when each ion becomes the nucleus of a relatively heavy water drop. Although the distribution of ions in any track will be of a Gaussian character, the photographic film will show a complete blackening in the case of a heavy track to a point where the density of water drops reaches a certain minimum critical value, and will show a rapidly fading shaded edge outside this region. The distance from the center at which the critical density of ions is reached will be a function of the total number of ions in the track. In measuring the width of a track it is convenient to measure to the point where the blackness shades off rapidly at about the critical density of droplets for blackening of the film.

The superficial density of ions at any distance x from the center of the column of ionization at a time τ after the passage of the ray is[2]

$$\rho(x) = [N_0'/(4\pi D\tau)^{\frac{1}{2}}]e^{-x^2/4D\tau}, \tag{1}$$

where D is the diffusion coefficient for the ions and N_0' is the total number of ions per cm path length after allowing for the effect of recombination. From this, the distance from the center of the track to the point where the superficial density of ions is ρ_1 is given by

$$x_1 = (4D\tau \ln [N_0'/\rho_1(4\pi D\tau)^{\frac{1}{2}}])^{\frac{1}{2}}. \tag{2}$$

The diameter or effective track width is twice this. The breadth of track for a particle of given ionizing power is then nearly proportional to the square root of the time between the passage of the particle and the formation of the droplets on the ions. In cases where the separation of the positive and negative ion columns can be measured this time can be calculated from the strength of the clearing field and the mobility of the ions. The width of the track is also a function of the ionizing power of the particle, varying as the square root of the logarithm of the number of ions formed per cm path. The value of ρ_1 will vary with the intensity of illumination and position of the track in the chamber. An average value can, however, be calculated by fitting the data for alpha-particles of known age to a curve of the type given by Eq. (2).

[12] P. M. S. Blackett and R. B. Brode, Proc. Roy. Soc. **A154**, 573 (1936).

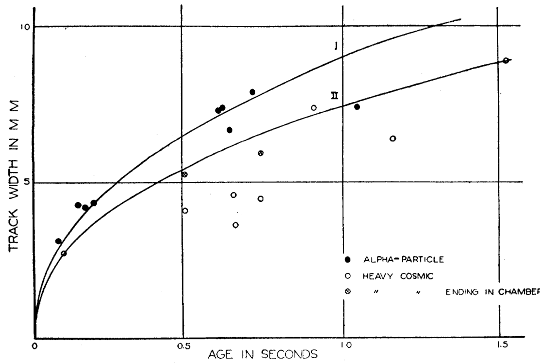


FIG. 1. Breadth of tracks as a function of age. Curve I is a theoretical curve fitted to the 4 cm range alpha-particle data by suitable choice of one constant. With the same constant, curve II is calculated for 2-million-volt protons.

In calculating the age of the tracks an average mobility for the positive and negative ions was used. The presence of alcohol vapor in the nitrogen gas of the chamber reduces the ion mobility considerably.[13] For 2.2 percent alcohol vapor a mobility constant k of 1 cm^2/volt sec. is obtained. The relation $k/D=$constant gives for the diffusion coefficient a value of 0.0207 cm^2 $sec.^{-1}$.

The value of N_0' used in Eq. (2) must be calculated taking into account the effect of recombination of the ions before the positive and negative columns are separated. This problem has been considered by Jaffé.[14]

The amount of recombination will depend on the initial density of the ions, the rate of diffusion, and the length of time that the positive and negative ion clouds are allowed to overlap each other as they are pulled apart by the clearing field. For alpha-particles of 4 cm range an average of about 8×10^4 ion pairs are formed per cm path at 1.8 atmospheres pressure. About 4.16×10^4 ions/cm path are calculated to be present after recombination has been taken into account. We have measured the widths of alpha-particle tracks and calculated their age by the separation of their positive and negative ion clouds in the clearing field. The alpha-particle data are represented by the black dots in Fig. 1. Curve I is calculated from Eq. (2), and is fitted to the data at one point by choosing a suitable value of ρ_1, the critical superficial density of water droplets to blacken the film. The value of ρ_1 used is 1250 ions/cm^2. Curve II is calculated for an agent producing 15 percent of the ionization of an alpha-particle. This is the average ionization density in the last 16 cm of a proton's range. The circles in Fig. 1 represent the data for long heavy tracks of cosmic origin for which the time of formation could be calculated from the separation in the clearing field. It is to be seen that curve II fits the maximum track widths observed quite well. The two circles with crosses in them represent tracks that ended in the gas of the chamber. Since any ionizing particle has its maximum density of ionization at its end, it seems probable from the observed widths that these at least are protons.

The ionization to be expected from a proton goes down as the energy of the particle increases, until at 5×10^8 volts a proton has about the same ionization as an electron.[15] Since a fast proton has a less dense ionization, the photographically

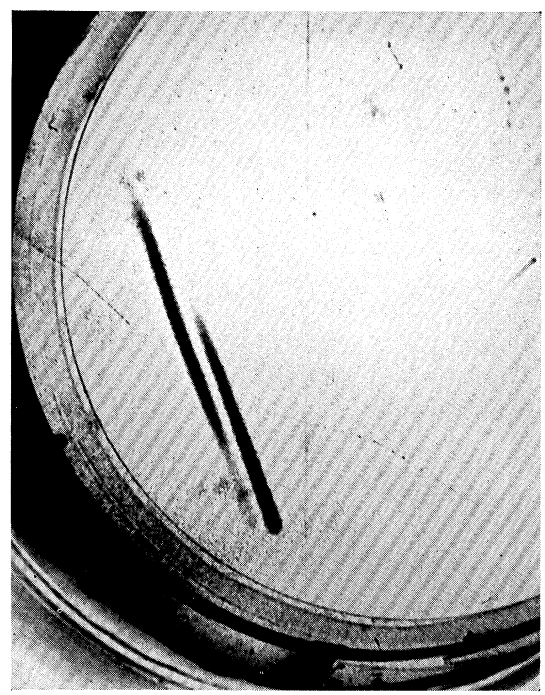


FIG. 2. Heavy cosmic-ray track with a length of 15 cm showing in the chamber at 1.8 atmospheres of nitrogen. The positive and negative ion columns have been pulled apart by the clearing field, enabling the age of the track to be determined. Stereoscopic measurements show that this track ended in the gas of the chamber. Its apparent width indicates that it is probably a proton. The fine vertical line in the center of the picture is a stretched wire used as a reference line for position measurements.

[13] L. B. Loeb, Int. Crit. Tables **6**, 110 (1929).
[14] G. Jaffé, Ann. d. Physik, **42**, 303 (1913).
[15] H. Bethe, *Handbuch der Physik*, vol. 24/1, 2nd ed., (1933), p. 522.

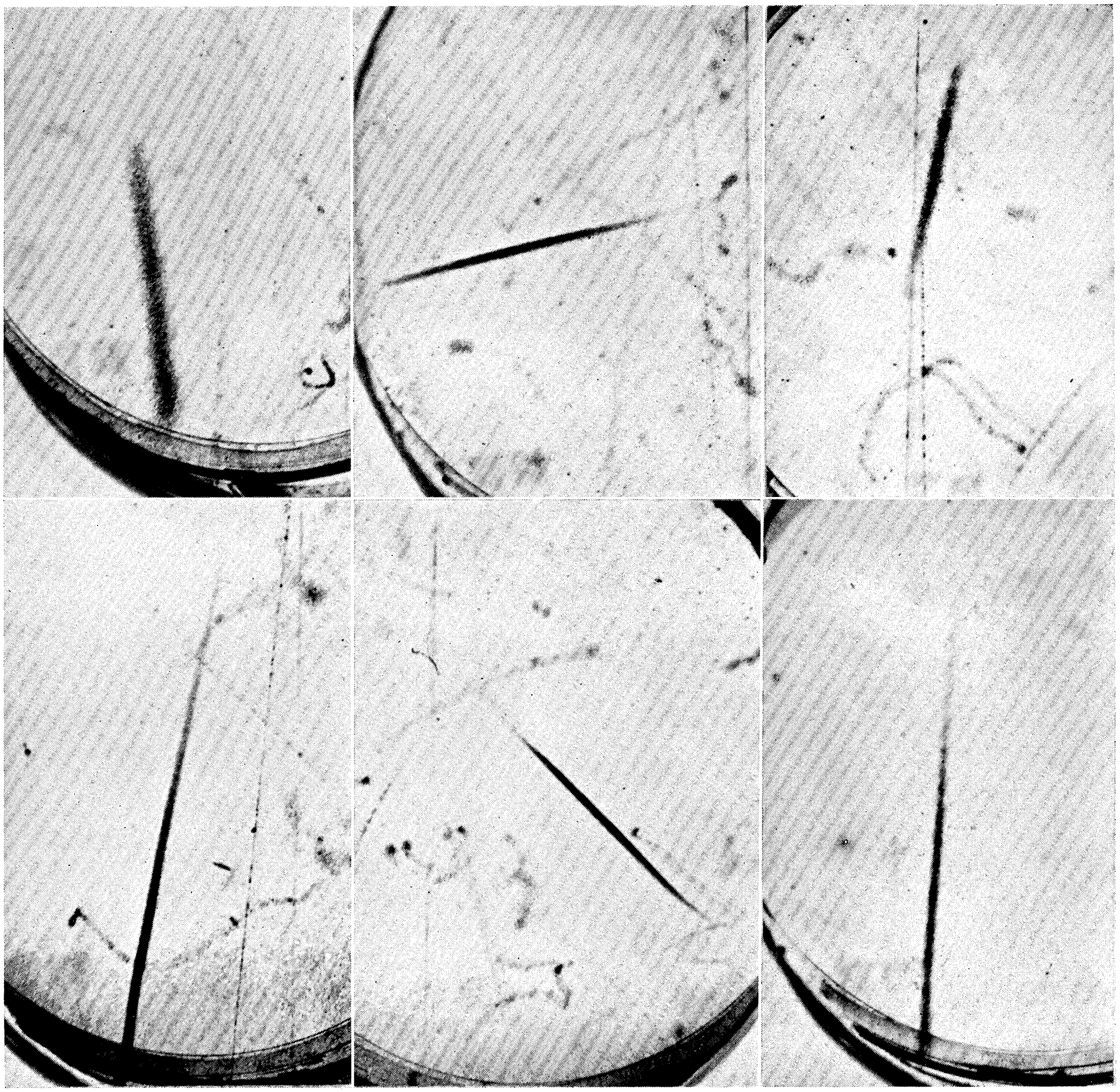


FIG. 3. Tracks of heavy particles producing intense ionization. The tracks in Figs. 3 and 4 are all due to particles that passed through the chamber a short time previous to the expansion.

observed track will be narrower than that calculated for a slow proton. This means that any tracks of width less than that calculated for slow protons are to be ascribed to higher speed particles. In fact the width of the tracks could be used to calculate the ionization per cm path for particles whose age is known from the clearing field separation and the approximate energy of the particles could then be obtained from ionization-energy relations. However, the error of an individual observation is so great as to make this method of obtaining energies very approximate. Such a calculation involves the assumption of the nature of the ionizing particle.

From the range-energy relations given by Bethe one can calculate the maximum ionization to be expected in the track of a proton that trips the Geiger counters and expands the chamber. The glass wall of the chamber, the glass wall of the Geiger counter tube and the side of the copper cylinder which forms its outside electrode have a combined absorbing power equivalent to that of 21 meters of air. Consequently, for a particle to penetrate to the

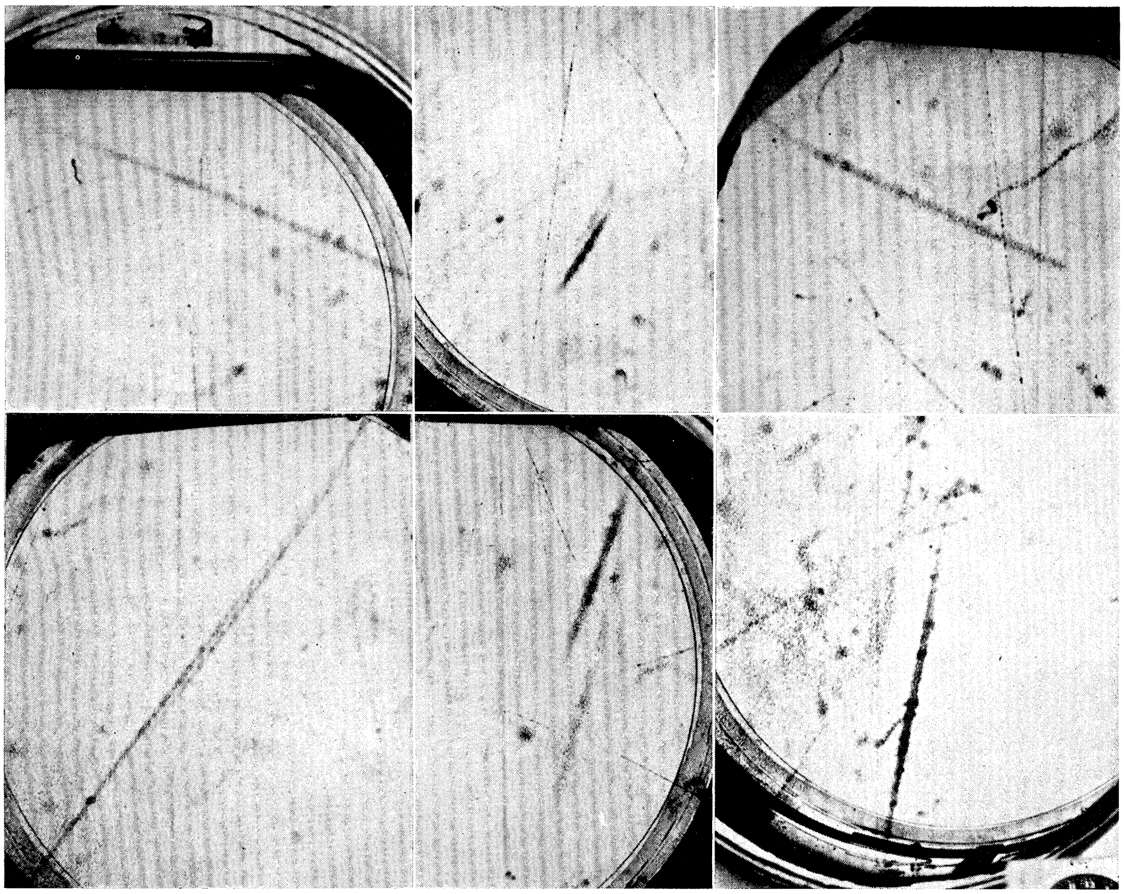


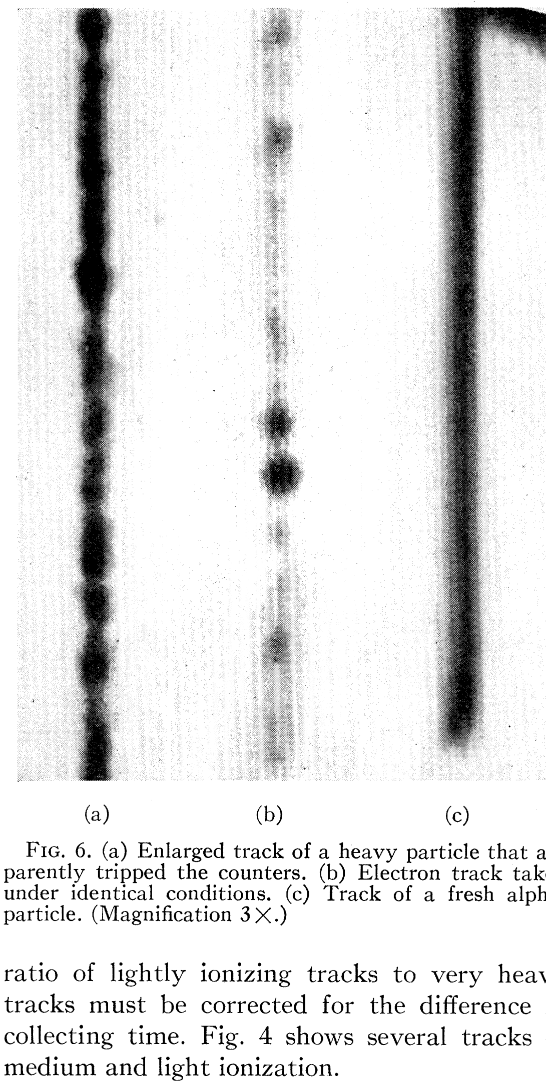
Fig. 4. Heavy cosmic-ray tracks of medium and light ionization. These tracks are presumably made by high speed protons or alpha-particles.

lower counter it must have a range of at least 21 meters of air while in the chamber. A proton of this range would have an energy of 5.6×10^7 volts, and an alpha-particle would have 2.6×10^8 volts. These are the minimum energies that a particle could have while in the chamber and still get into the bottom counters to cause the expansion. Corresponding to these minimum energies there is a maximum ionization to be expected for counter tripping tracks. From Bethe's tables a proton at 5.6×10^7 volts has an energy loss per cm path about 6 times that for a high speed electron, and an alpha-particle of 2.6×10^8 volts loses energy about 25 times as fast as an electron. If the same proportion of energy loss goes into ionization in the case of the electron, proton and alpha-particle, the maximum ionization to be expected from a counter tripping proton is only about 6 times the ionization of an electron while a counter tripping alpha-particle could have up to 25 times the ionization of an electron.

Summary of Results

In the 8500 photographs, a total of 80 tracks were observed that showed a markedly heavier ionization than an electron track. Of these 21 were estimated to have an ionization of more than 50 times that of an electron, appearing to be almost as dense as an alpha-particle or a proton track. They are clearly distinguished from alpha-tracks however by their lengths. The longest alpha-particle ranges are less than 9 cm, while the sections of the ranges of these very heavy tracks made visible in the illuminated portion of the chamber varied from 13 to 44 cm, with an average range of 25 cm visible. Only

FIG. 5. A heavy cosmic ray that apparently tripped the counters and caused the expansion. It is estimated to have between 5 and 20 times the ionization of a fast electron.



(a) (b) (c)

FIG. 6. (a) Enlarged track of a heavy particle that apparently tripped the counters. (b) Electron track taken under identical conditions. (c) Track of a fresh alpha-particle. (Magnification 3×.)

two of these tracks appear certainly to terminate in the gas of the chamber. One of these is shown in Fig. 2. In most of the tracks both ends fade out of the illuminated section or end at a wall of the chamber, indicating that only a portion of the total range was observed. The longest range observed, 44 cm, corresponds to an energy loss in the chamber of 5.8 million volts for a proton and of 25 million volts for an alpha-particle. Fig. 3 shows several of these heavy tracks at 0.31 scale.

24 old tracks occurred with a density of ionization estimated to be between 10 and 50 times the ionization in an electron track. Such tracks could be made only by very fast particles, whatever their nature. These tracks show no signs of terminating except at the walls of the chamber and without question are capable of passing entirely through the gas of the chamber. There were 21 old tracks of density of ionization of from 3 to 10 times the ionization of an electron. Tracks of this density older than 0.2 second cannot easily be distinguished from old electron tracks, while the heaviest tracks as old as 1.5 seconds can be seen readily. Consequently the ratio of lightly ionizing tracks to very heavy tracks must be corrected for the difference in collecting time. Fig. 4 shows several tracks of medium and light ionization.

In addition to these tracks that occurred in the chamber at any time during the 1.5 seconds preceding the expansion, there were 14 tracks of particles of higher ionizing power than an ordinary electron that appeared to have passed through both Geiger counters and caused the expansion of the chamber. Seven of these are estimated to have an ionization of from 5 to 20 times that of an electron. Such a track is shown in Fig. 5. Fig. 6 (a) shows an enlarged section of another track of this nature. The track (b) of Fig. 6 is an electron track enlarged to the same scale. It was taken in the same region of the chamber under identical conditions on the same day. A fresh alpha-track is shown in (c) for comparison. The other seven of the 14 heavy

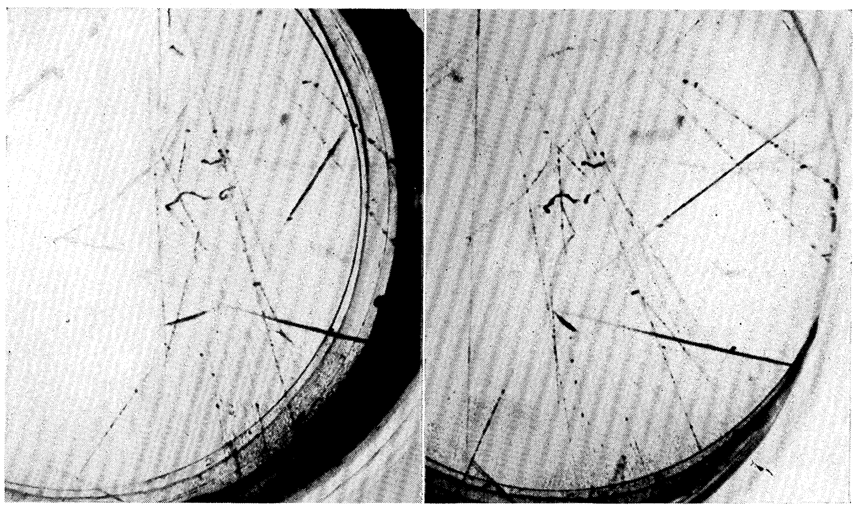


FIG. 7. Stereoscopic views of a disintegration in which three heavy particles are ejected from the front glass of the chamber.

counter tripping tracks are estimated to have had from 2 to 5 times the ionizing power of a fast electron.

Three pictures of disintegrations were obtained in which heavy particles were emitted. They apparently originated in the front glass of the chamber. One showed 3 heavy tracks, one two, and one had two heavy tracks and three electron tracks coming from a point. The disintegration with three heavy particles is shown in Fig. 7.

Conclusions

It can be seen from the calculation of Bethe that it is not easy to distinguish by ionization alone between a proton and an electron of energies over 5×10^8 electron volts. Probably all of the 80 heavy tracks observed are due to protons of energies less than 3×10^8 electron volts. To penetrate the earth's atmosphere a primary cosmic proton would require an energy of over 4×10^9 electron volts. Unless the cloud chamber happened to be just at the end of the range of a primary cosmic-ray proton it would probably not be distinguished from an electron by its ionization. The 44 particles observed with the heaviest ionization are very likely secondary particles resulting from a disintegration similar to the 3 disintegrations observed. The random distribution in direction is also consistent with the probable secondary origin of these particles. Their energies are insufficient to permit the particle to penetrate the glass walls of the chamber. There seemed to be no evidence of any association of the heavy particles with showers or other cosmic-ray tracks. Two of the disintegrations seem to be associated with a shower and the third disintegration is too old to identify electron tracks.

The chamber was sensitive to heavy tracks for over 1.5 seconds and had a volume of over 7 liters. The amount of cosmic ionization in this volume due to the heavy particles in the 10,500 seconds included in the photographed observations is roughly estimated as about one percent of the total ionization. This contribution to the ionization although small is not to be considered as negligible. The heavy particles whose tracks are only slightly denser than an electron track might be either primary or secondary particles. It is not possible to conclude from these tracks that the primary cosmic radiation contains high speed protons as one of its components. It is now, however, not possible to say that the failure to observe heavy particles in the cosmic radiation in a cloud chamber is evidence against the existence of primary protons.

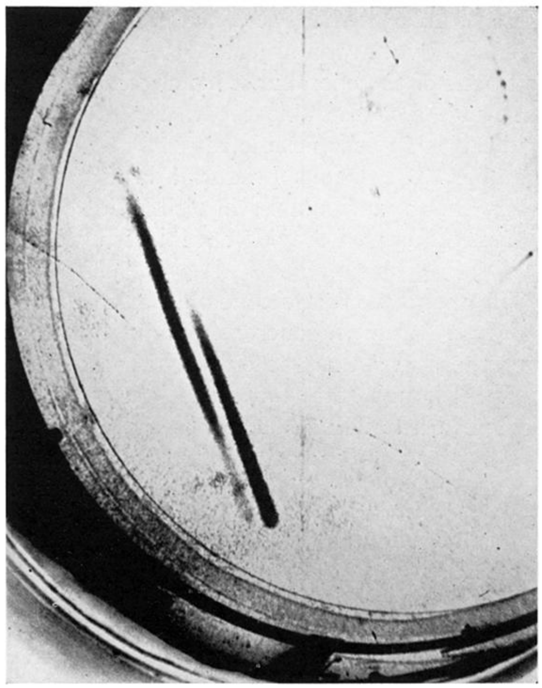


FIG. 2. Heavy cosmic-ray track with a length of 15 cm showing in the chamber at 1.8 atmospheres of nitrogen. The positive and negative ion columns have been pulled apart by the clearing field, enabling the age of the track to be determined. Stereoscopic measurements show that this track ended in the gas of the chamber. Its apparent width indicates that it is probably a proton. The fine vertical line in the center of the picture is a stretched wire used as a reference line for position measurements.

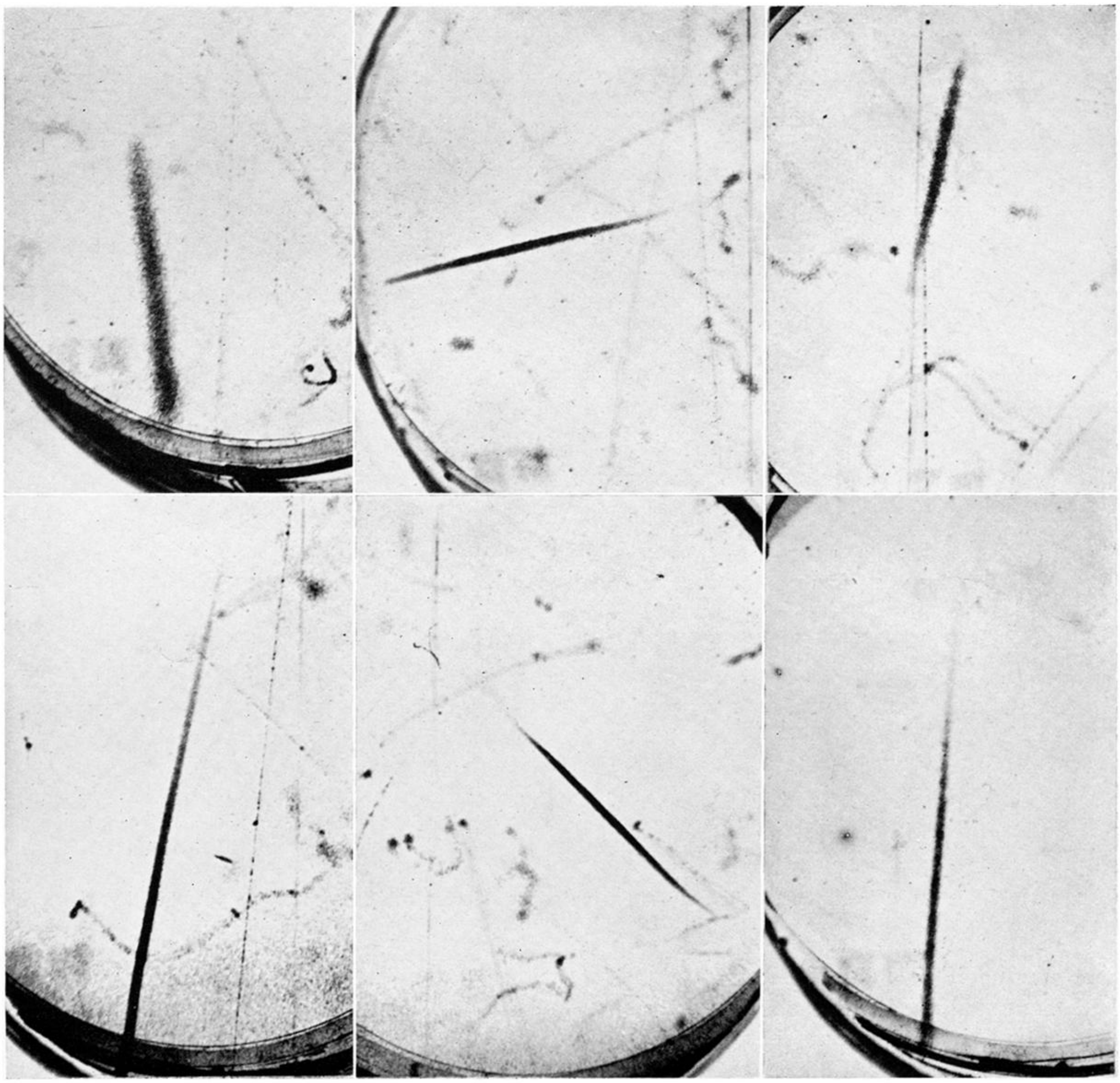


FIG. 3. Tracks of heavy particles producing intense ionization. The tracks in Figs. 3 and 4 are all due to particles that passed through the chamber a short time previous to the expansion.

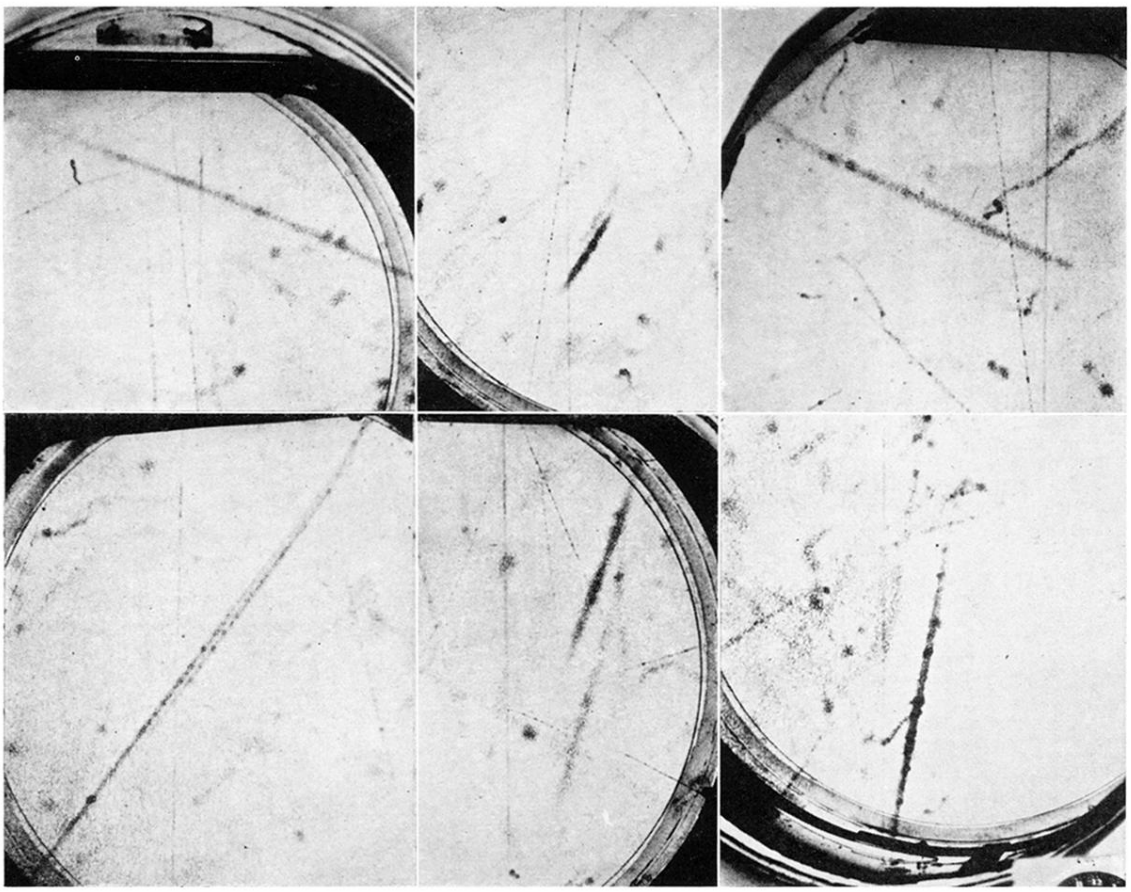


FIG. 4. Heavy cosmic-ray tracks of medium and light ionization. These tracks are presumably made by high speed protons or alpha-particles.

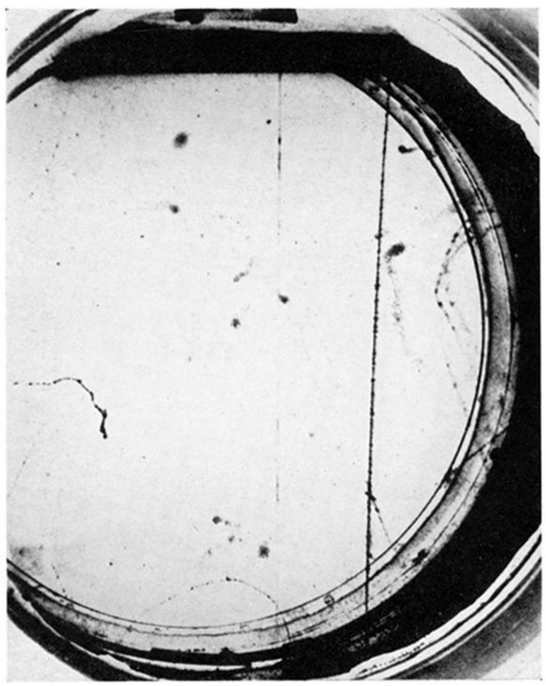
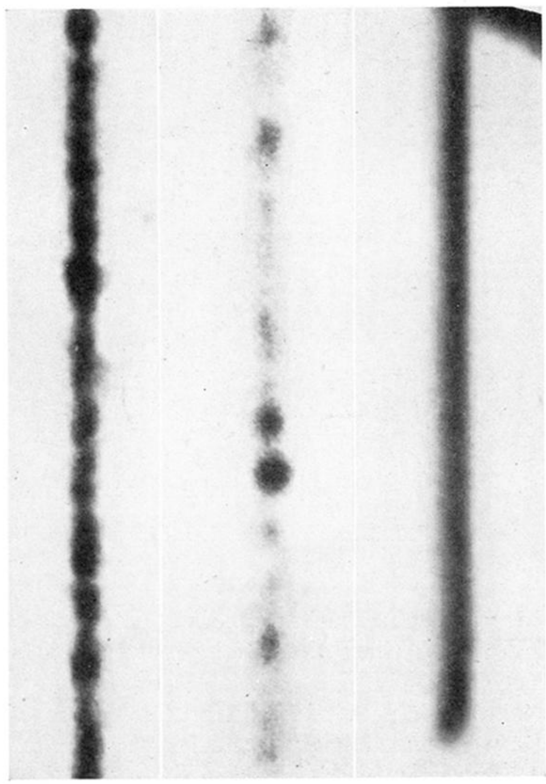


FIG. 5. A heavy cosmic ray that apparently tripped the counters and caused the expansion. It is estimated to have between 5 and 20 times the ionization of a fast electron.



(a) (b) (c)

FIG. 6. (a) Enlarged track of a heavy particle that apparently tripped the counters. (b) Electron track taken under identical conditions. (c) Track of a fresh alpha-particle. (Magnification 3×.)

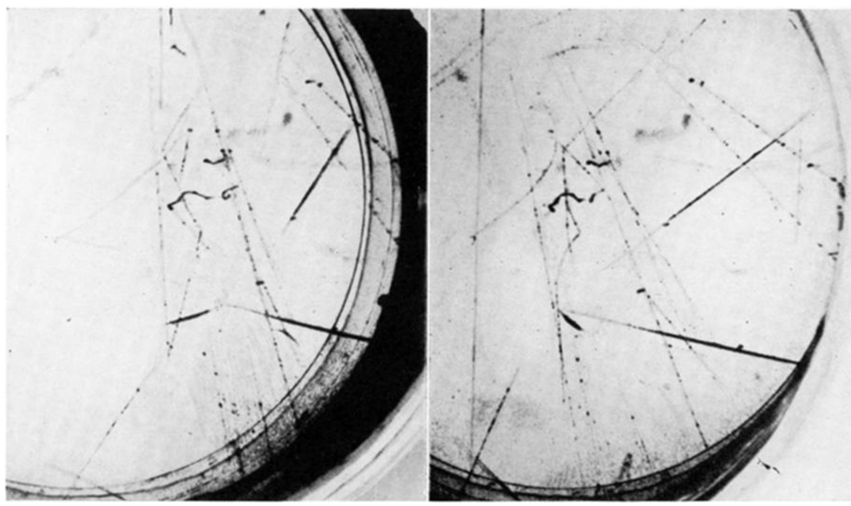


FIG. 7. Stereoscopic views of a disintegration in which three heavy particles are ejected from the front glass of the chamber.