The Heavy Component of Primary Cosmic Rays*, **

PHYLLIS FREIER, E. J. LOFGREN,*** E. P. NEY, AND F. OPPENHEIMER
University of Minnesota, Minneapolis, Minnesota

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Further evidence is presented for the existence of heavy nuclei as components of the primary cosmic radiation. Preliminary results are given for the distribution in atomic numbers of these components. Lower limits of the energies of the particles on entrance into the atmosphere are calculated. These are, in general, above the cut-off imposed by the earth's magnetic field. The mean free path for nuclear collisions is of the order of 14 cm of photographic emulsion. This is longer than that expected from the geometrical cross section and may indicate velocity dependence of nuclear forces. An example of a track that stops in emulsion is shown. This particle gives further evidence for the nuclear character of the rays, because as it slows down it captures planetary electrons and decreases its rate of energy loss. An approximate value of the hydrogen-helium ratio of 4 is reported.

I. INTRODUCTION

IN a previous publication[1] evidence was presented for the existence of heavy nuclei as components of the primary cosmic rays. Further experiments with free balloons at 80,000 to 95,000 ft. have shown that this component consists of nuclei with atomic numbers ranging from that of helium to those of the region around molybdenum. Because these nuclei have average energies which increase regularly with their atomic number, they appear to have been accelerated as partially or completely stripped nuclei probably by the same mechanism as the more abundant proton component. Conclusions regarding the very heavy nuclei can best be drawn from the work with photographic emulsions, while the cloud chamber is more suitable for study of the lighter component.

II. OBSERVATION IN PHOTOGRAPHIC EMULSIONS

In four high altitude flights at 55° geomagnetic latitude (Camp Ripley, Minnesota) a total of approximately 300 penetrating particles heavier than α-particles have been observed in photographic plates. Previously[1] estimates of atomic numbers were made on the basis of the volume of developed silver in the solid core of the tracks. However, a much better estimate can be made by counting the number of δ-rays (knock-on electrons) of greater than a given energy which the particle produces at a known speed. This number can be compared with the corresponding number for α-particles produced in the Berkeley cyclotron.[2] To make accurate estimates of the atomic number in this manner, it is necessary that the particles stop in the stack of photographic plates or at least be near the end of their range in order that β, the ratio of the velocity of the particle to the velocity of light, may be determined.

Another method for estimating Z is possible for the particles which actually stop in an emulsion. Two of these have been observed. At the end of the range, the solid silver filament reaches a maximum diameter, then becomes thinner as the particle slows down to the speed of its several electron shells. That is, as the particle slows down, it captures electrons and thus neutralizes some of its nuclear charge. This "thin down length" should be a function of Z, since the thinning starts when the K electrons are caught and the K electron velocities are proportional to Z.

Figure 1 shows an example of the effect for the particle whose atomic number is estimated

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** The photographic emulsion experiments and techniques described in this paper were developed jointly with H. Bradt and B. Peters of the University of Rochester. The data presented in this paper and in the accompanying one of Bradt and Peters is an extension of the earlier data on heavy particles that we published with them. We wish to convey our gratitude for discussions with them.

*** Now at Radiation Laboratory, University of California.

[1] Freier, Lofgren, Ney, Oppenheimer, Bradt, and Peters, Phys. Rev. 74, 213 (1948).

[2] Plates exposed to 380-Mev α-particles were supplied by Eugene Gardner.

by δ-ray counts to be 15. The thinning down takes place in a path length of 140 microns. The importance of this effect is that it gives further evidence that the heavy component of the cosmic radiation really consists of atomic nuclei. The effect is not observed for fission tracks because their ranges are only 10 to 20 microns.

An approximate calculation of Z from the "thin down length" can be made by using the Bohr model of the atom and assuming that capture of electrons takes place when the speed of the nucleus is that of electrons in the various atomic shells. The mass of the heavy nucleus is assumed to be $2Z$ times the proton mass. The heavy nucleus then has an energy of $0.05Z^3$ Mev when it picks up its first electron. If one assumes that at all lower energies the energy $E=0.05Zz^2$ Mev, where z is the effective charge at the energy E and Z is the nuclear charge, one can obtain the "thin down length" as a function of Z by numerical integration of Eq. (1).

$$L=\int_0^Z (dx)/(dz)dz=\int_0^Z (dE/dz)/(dE/dx)dz, \quad (1)$$

dE/dz is obtained from the assumed relationship between energy and charge; dE/dx for a particle of effective charge, z, is equal to z^2 times dE/dx for a proton of the same velocity. dE/dx for protons was obtained by differentiating the experimental range-energy curves for protons in Ilford emulsions.[3] Figure 2 shows the variation of the calculated "thin down length" with Z. Z for the particle of Fig. 1 is 17 by this method, in good agreement with 15 obtained from δ-ray counts.

III. RESULTS OF δ-RAY COUNTING IN EMULSIONS

Eight heavy particles satisfied the condition for estimating Z by δ-ray counts. Two particles actually stopped in emulsion, but one of them penetrated some of the cloud-chamber lead and its range in the photographic plates is very short. The others stopped in the glass between emulsions, and ionized heavily near the end of their range. To justify the δ-ray method, δ-rays were counted in several emulsions along two tracks.

[3] Lattes, Fowler, and Cuer, Proc. Phys. Soc. 59, 884 (1947).

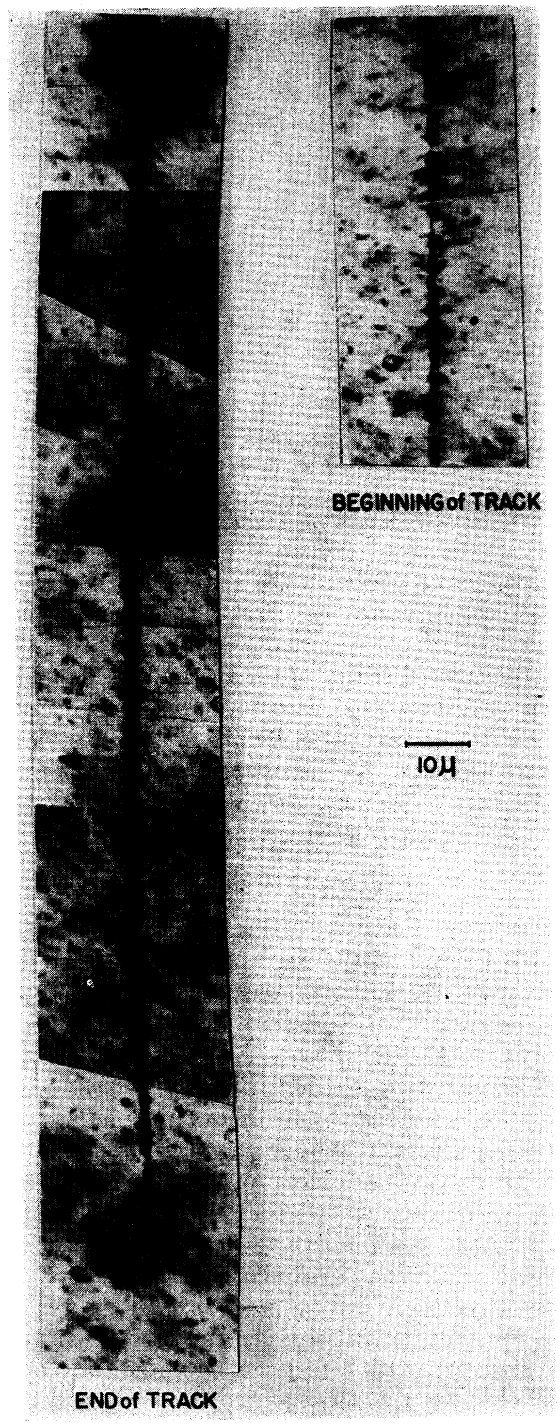

FIG. 1. Photomicrograph of track with $Z=15$ (estimated from δ-rays) stopping in emulsion. The insert shows the track when it enters the stack of photographic plates with $\beta\cong 0.7$. The thin down shown at the left occurs after the particle has penetrated 9.6 g/cm² of glass and emulsion.

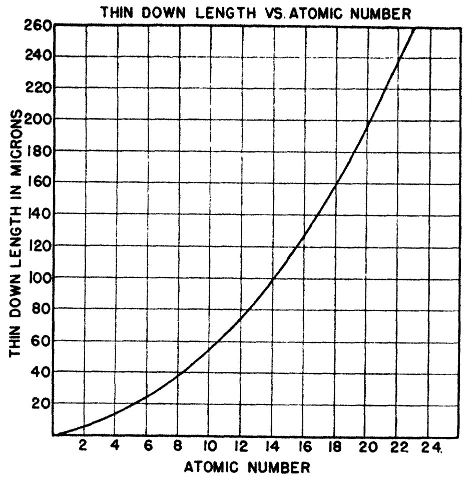

FIG. 2. Graph of the theoretical relation between "thin down length" and atomic number.

This allows a check on the assumption that the δ-ray count varies as Z^2/v^2. All δ-rays which have ranges great enough to bring them 1.5 microns on either side of the track were counted. This corresponds to δ-rays with energies in excess of about 10 kev. The results of this test are shown in Table I. The method was as follows: The δ-ray count on the α-particle gives the proportionality constant K, in the equation,

$$N=(Z^2)/(\beta^2)K, \tag{2}$$

where N is the number of δ-rays per 100 microns, and Z for the α-particles is 2. The measured K for the α-particle must, however, be increased in the ratio of 8.2/7.5, because at a β of 0.35 one would expect a deviation from the $1/v^2$ law, as can be seen from Fig. 3. This curve, which will be explained in detail later, shows the number of δ-rays of greater than a given energy divided by the corresponding number for $v=c$. Reference to the 10-kev curve shows that if the δ-rays went as $1/v^2$ the ordinate at $\beta=0.35$ should be 8.2 instead of 7.5 (i.e., it should be $1/(0.35)^2=8.2$). The corrected K will be used throughout. With this constant determined, one can then get Z for a heavy particle when β can be obtained. This requires that the residual range be known. In order to determine Z and β from the residual range and the δ-ray count, one first guesses a value of β and determines Z from Eq. (2). This value of Z and the residual range allow calculation of the quantity $Z^2R/\mu c^2$. (R is the residual range and μ is the rest mass appropriate for the Z.) For most of the particles considered μc^2 is 2 (0.93) Z Bev. By using range energy curves one can determine $P/\mu c$ and β and compare this with the β originally chosen. By successive approximations both Z and β can then be determined. The curves used for this transformation were obtained from a publication by Rossi[4] with the ordinate modified to read $Z^2R/\mu c^2$ and the values corrected to apply to charged particles in glass. The curves are reproduced in Fig. 4. In order to check the Z^2/v^2 law, Z and β were determined for the particle in the first emulsion in which it was seen. For every other residual range β can be determined using the same Z, and the product, $N\beta^2$, examined for constancy. Columns A and B are the results obtained by different observers. The δ-ray counts of both observers gave $Z=13$ for H_{29} and $Z=15$ for H_4. It should be borne in mind in examining Table I that the Z estimate depends on $(N\beta^2)^{\frac{1}{2}}$.

The results of the Z estimation for the eight chosen particles are shown in Table II. The track for which the highest Z was estimated is shown in Fig. 5. The heavy particles described were obtained in two flights, one of which remained aloft for about 30 hours. The altitude was unknown after the first six hours, but the incidence of heavy particles was less than that predicted from the other flight of known altitude and duration. For this reason we believe the balloon went to lower altitudes as the flight progressed. This means that for this flight one cannot calculate energy of entrance into the, atmosphere because the residual atmosphere was unknown for most of the flight. Because of the reason stated and the fact that other equipment was around, one can only compute a lower limit on the energy of entrance into the atmosphere. The minimum energy of entrance into the atmosphere was calculated for both flights by using the residual atmosphere at maximum altitude for the direction in which the particle entered the stack.

In many cases where the particles do not stop, it is possible from δ-ray counting to obtain limits on the atomic number (Table III). The upper limit is obtained by assuming that the

[4] B. Rossi, Rev. Mod. Phys. 20, 537 (1948).

particle is at minimum ionization when it enters the stack, the lower limit by assuming that the observed range is the actual range. By applying this procedure to twenty-eight tracks, a preliminary Z spectrum was obtained. The spectrum is shown in Fig. 6. Particles with Z's of 10–15 may have been discriminated against by our visual method of choosing heavy tracks for study.

IV. OBSERVATION IN VARIOUS EMULSIONS

The results reported for the photographic technique were all obtained with Ilford C-2 nuclear research emulsions. Preliminary experiments have been done with Eastman NTB and some special diluted (low silver content) Ilford plates furnished by Eugene Gardner. The core of the tracks in the NTB plates was not as pronounced as in the Ilford C-2 plates, but the δ-rays appeared to be better in NTB's. The diluted Ilford plates showed δ-rays, and the density of ionization in the core was less. It seems feasible with highly diluted plates to obtain atomic numbers by grain counting. Experiments are now in progress with diluted Eastman plates furnished through the courtesy of Dr. Julian Webb.

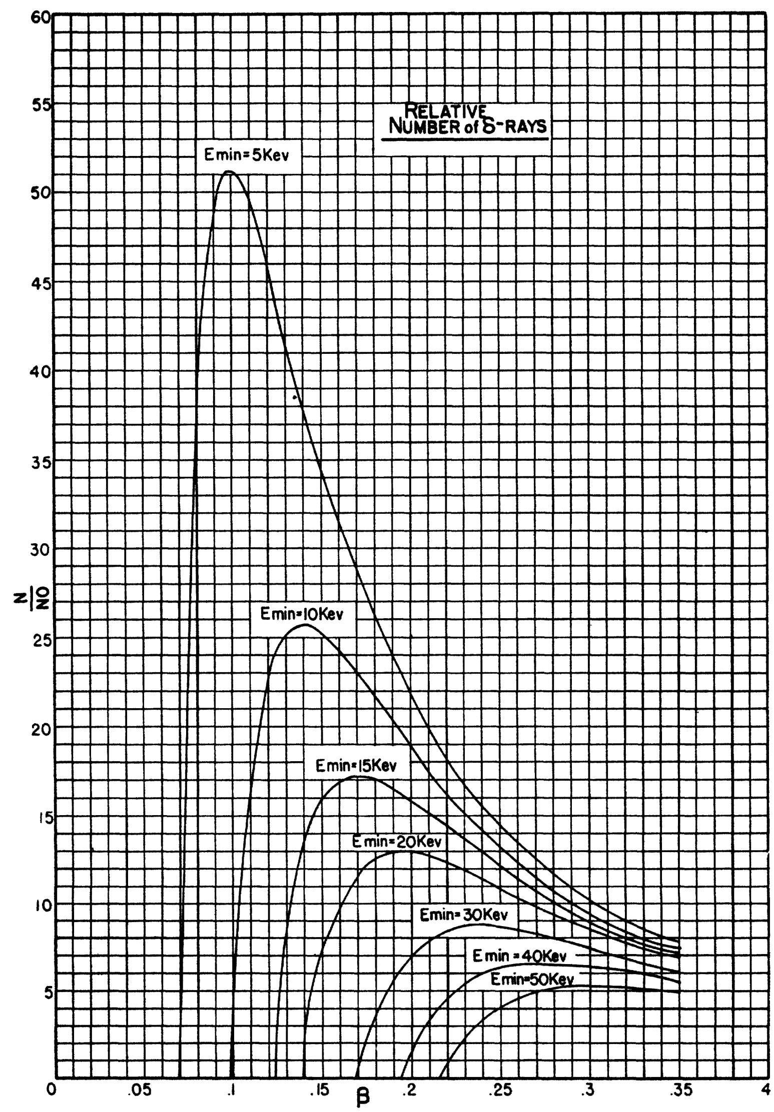

FIG. 3. Graph of the number of knock-on electrons of energy greater than E_{min} relative to the corresponding number when $v=c$ as a function of β.

TABLE I.

Track	Residual range g/cm²	β^2	β	A *$N\beta^2$	B *$N\beta^2$
α-particle	5.2	0.12	0.35	0.14	0.17
H.4 $Z=15$	9.6	0.47	0.69	8.7	9.1
	9.4	0.46	0.68	8.8	9.0
	4.85	0.35	0.59	7.9	8.2
	4.6	0.34	0.58	8.0	8.2
H.29 $Z=13$	9.4	0.43	0.66	5.6	6.4
	7.8	0.41	0.64	5.8	7.0
	7.0	0.38	0.62	5.7	7.9
	6.0	0.35	0.59	5.4	6.8
	4.3	0.31	0.56	5.6	6.0
	2.6	0.25	0.50	5.9	8.5
	1.0	0.17	0.41	6.4	8.0

* The value of N here for the α-particle has been corrected for the $1/v^2$ law deviation.

TABLE II. Results of the Z estimate for the eight chosen particles.

Track	Estimated Z	Energy on entering stack of plates	β on entering plates	Minimum energy on entering atmosphere	Minimum β on entering atmosphere	Angle with vert.	*Energy to penetrate earth's field
H.1	41	54 Bev	0.8	110 Bev	0.9	30°	45 Bev
H.4A	15	12	0.7	22	0.8	45°	17
H.29	13	8.5	0.7	16	0.8	35°	15
H.16	19	15	0.7	33	0.85	48°	22
H.12	12	4.5	0.55	13	0.8	41°	12.5
H.19	22	13.5	0.6	56	0.9	68°	25
H.22	10	4.5	0.6	9	0.75	10°	12
H.5A	20	9	0.6	41	0.9	64°	24

* The energy was calculated for a Stoermer variable of 0.2. According to G. Lemaitre and M. S. Vallarta, Phys. Rev. **43**, 89 (1933), Fig. 1, p. 92, particles would be able to come in from the whole sky at 55° latitude for this value of the Stoermer variable.

V. FLUX OF HEAVY PRIMARIES

It is possible to estimate the primary flux of particles of $Z>10$ from the angular distribution at a given altitude. The fact that the distribution is not isotropic at 15-g/cm² residual atmosphere is a consequence of the high rate of energy loss of these particles. Those that come in at large angles cannot penetrate the residual atmosphere. The flight from which the data were obtained reached a maximum altitude of 94,000 feet (15 g/cm²). The angular distribution is shown in Fig. 7. Forty particles make up the distribution. If one assumes that the probability of detection is unity and that all particles from

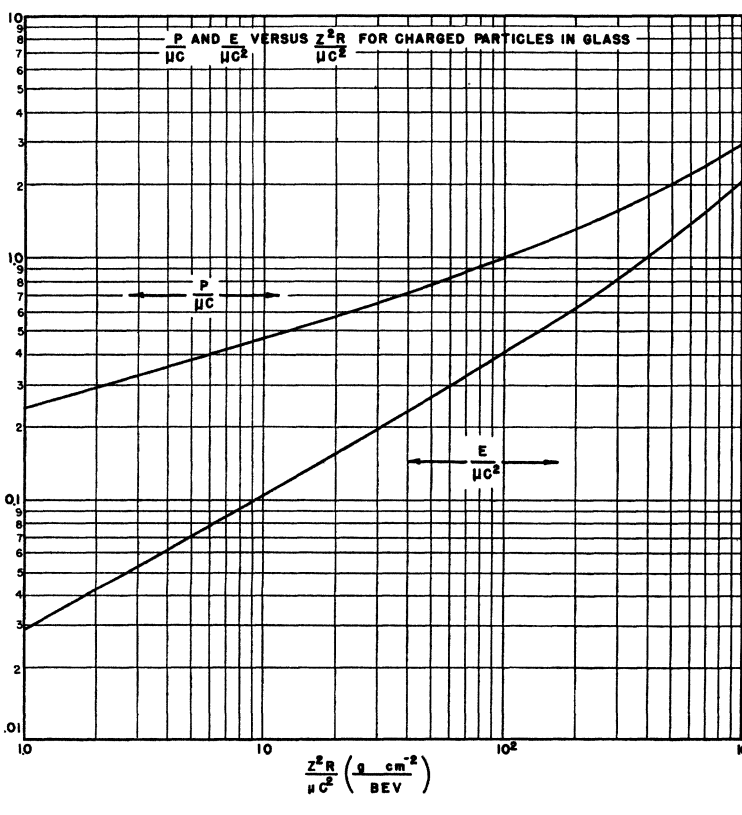

FIG. 4. Graph of $[\beta(1-\beta^2)^{-\frac{1}{2}}]$ and $[(1-\beta^2)^{-\frac{1}{2}}-1]$ as a function of $Z^2R/\mu c^2$ for charged particles in glass.

angles near the vertical penetrate the residual atmosphere, the flux of heavy primaries would be 3.2×10^{-4} particles/cm^2 sec. steradian, using the data from 0–20°. The foregoing estimate, however, is based on six particles observed in this interval. If one uses 0–30°, twelve particles are involved and the flux would be 1.9×10^{-4} particles/cm^2 sec. steradian. All particles with energies above the magnetic cut-off energy and Z less than about 25 will penetrate from the vertical. Because the mean free path for nuclear processes is so long (see Section VI) the correction for particles which stop in the 15 g/cm^2 by making stars is negligible. In Fig. 6 we have also plotted the relative numbers of hydrogen and helium nuclei with respect to the heavy nuclei. The hydrogen helium ratio was measured in the cloud chamber (see Section VIII). The hydrogen to total heavy particle ratio was obtained using 3.2×10^{-4}/cm^2 sec. steradian for the flux of heavy particles and comparing this with the figure of 12×10^{-2} particles/cm^2 sec. steradian for the total primary flux.[5]

VII. MEAN FREE PATH FOR NUCLEAR PROCESSES

Because one cannot observe what happens to particles while they are in the glass, it is difficult to use total path of glass and emulsion to estimate free paths. It is true that some particles disappear between emulsions without increasing their ionization while others become heavy before disappearing. It may well be that the first group disappears by making stars. Probably the best estimate of free path comes from comparing the total path observed in emulsion with the number of stars produced in the emulsion. Only one† heavy particle-produced star has been observed in 56 g/cm^2 of emulsion. This corresponds to a free path of 14 cm. If one assumes that the radius of a nucleus is $1.5\times10^{-13}A^{\frac{1}{3}}$ cm, that the average Z of the heavy particles is 20, and that the cross section for events is the geometric nuclear cross section, then the free path for star production should be 5 cm. The experimental result indicates a cross section which is smaller than the geometrical cross section. In measuring the mean free path, our observations are mostly on particles with high β's. This "transparency" of nuclei to high energy bombarding particles[6]

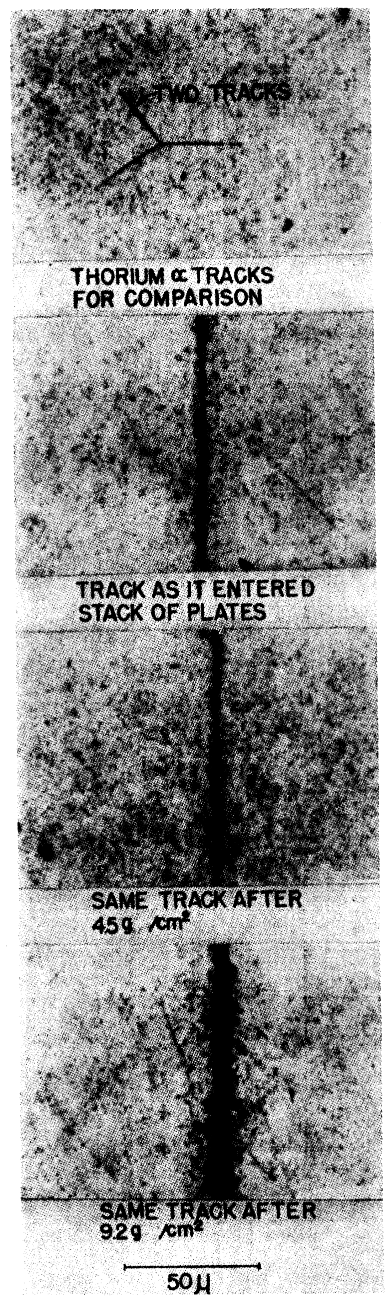

FIG. 5. Photomicrograph of sections of the heaviest track observed. The atomic number of this track was estimated to be 41 by δ-ray counting.

[5] J. A. Van Allen and H. E. Tatel, Phys. Rev. **73**, 245 (1948).

† *Note added in proof:* Three stars produced by particles with $z>10$ have been observed, yielding a mean-free path of 12 cm of emulsion.

[6] R. Serber, Phys. Rev. **72**, 1114 (1947).

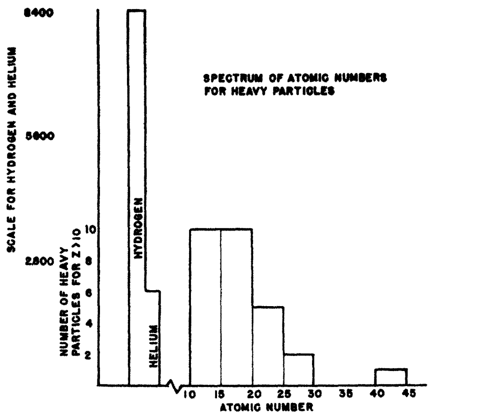

FIG. 6. Spectrum of atomic numbers. The scales for the ordinate read in relative numbers of atoms.

might well be more pronounced at the high β's encountered here than with the lower β's of cyclotron accelerated particles. Our result therefore suggests a velocity dependence of nuclear forces.

The single example of a heavy particle-induced star is shown in Fig. 8. The Z of the incoming particle is estimated to be from 8 to 14. One particle, not clearly evident in the picture, proceeds within 2° of the direction of the incident particle. It is probably a fast α-particle or proton. Of the remaining particles one is identified is an α-particle and the other three as particles with $Z \geqq 2$. A possible interpretation is that the star was produced when the heavy nucleus struck a proton in the emulsion.

TABLE III. Particles for which minimum and maximum Z are available.

Particle	Z minimum	Z maximum
H.21	14	19
H.3	15	21
H.7	19	27
H.34	18	26
H.20	10	16
H.30A	14	21
H.30	8	14
H.28A	12	18
H.16A	11	18
H.22A	12	19
H.7A	23	34
H.27A	15	22
H.13A	12	19
H.14A	25	33
H.19A	18	22
H.20A	10	15
H.24	14	19
H.27	18	25
H.28	16	23
H.35	10	16

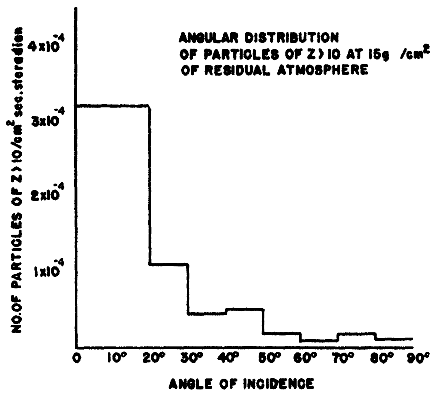

FIG. 7. Angular distribution at 94,000 feet. A total of forty particles was used for this distribution.

VII. CLOUD-CHAMBER OBSERVATIONS OF NUCLEI

The equipment developed for cloud-chamber experiments with free balloons has been described.[7] One cloud-chamber picture of a heavy penetrating particle has been published.[1] Several more examples have been obtained. Two of these are shown in Figs. 9 and 10. For the particle of Fig. 9, probable limits on the Z can be set from the δ-rays alone. The curves from which the conclusions are drawn are shown in Fig. 3. Figure 3 was calculated by the method outlined by Hazen.[8] It shows as a function of Z the number of δ-rays of energy greater than E min. at a given particle velocity divided by the number with energy greater than E min. when $v=c$. The number of δ-rays of energy greater than E min. at $v=c$ for a singly charged particle is called N_0. N_0 is 0.0056 per cm in nitrogen at 76 cm mercury pressure and 15°C for E min. $=20$ kev.[9] Our cloud chamber was filled with argon and a 30 percent–70 percent water alcohol mixture at 115 cm pressure and 20°C. N_0 for

TABLE IV. Estimates of the H/He ratio.

Date of flight	g/cm² residual atmosphere	Number of pictures considered	No. of penetrating singly charged particles	No. of particles identified as He	Total No. of particles	H/He ratios
July 23	14 g/cm²	44	14	3	17	4.7
July 16	25	30	5	2	7	2.5
Average						4

[7] E. J. Lofgren, E. P. Ney, and F. Oppenheimer, Rev. Sci. Inst. (in press).
[8] Wayne E. Hazen, Phys. Rev. 65, 70 (1944).
[9] G. Hornbeck and I. Howell, Proc. Am. Soc. 84, 33 (1941).

these conditions should be 0.010 per cm for E min. $=20$ kev. In Fig. 9, the particle has four δ-rays in 5 cm of path under the top lead plate. Three of these definitely originate in the gas and the fourth probably does also. The longest of these is about 2 cm long, which corresponds to an energy of 45 kev. This means that β for the particle must be greater than 0.2. See Fig. 3. The 4δ-rays are all longer than 0.5 cm, or 20 kev. From Fig. 3N/N_0 for 20 kev and $\beta=0.2$ is 13. N for a singly charged particle of $\beta=0.2$ would then be $13(0.01)=0.13$ δ-rays/cm. The observed number is $\frac{4}{5}$ δ-rays/cm, which is 6 times that of a singly charged particle. This means that $Z\geqq(6)^{\frac{1}{2}}$. $Z\geqq3$ is the lower limit. To get the upper limit, one assumes that the particle is at minimum ionization. It has $0.8/0.01=80$ times as many δ-rays as a singly charged particle at $v=c$, and hence $Z\leqq(80)^{\frac{1}{2}}$ or $Z\leqq9$. The δ-ray estimate then sets $3\leqq Z\leqq9$. The track passes in and out of the illuminated region and can only be seen passing through one $\frac{1}{4}$-inch lead plate

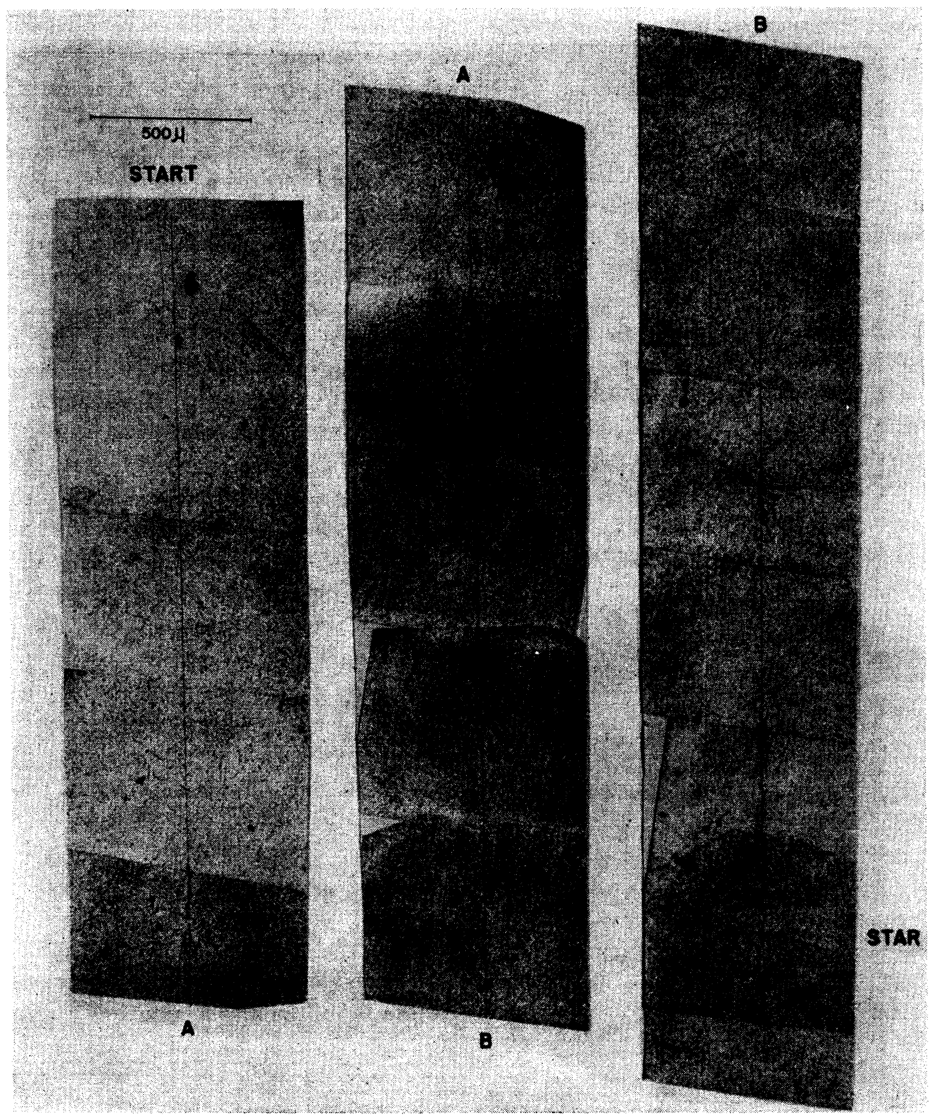

FIG. 8. Photomicrograph of heavy particle (Z estimated between 8 and 14) ending in the emulsion with a nuclear collision.

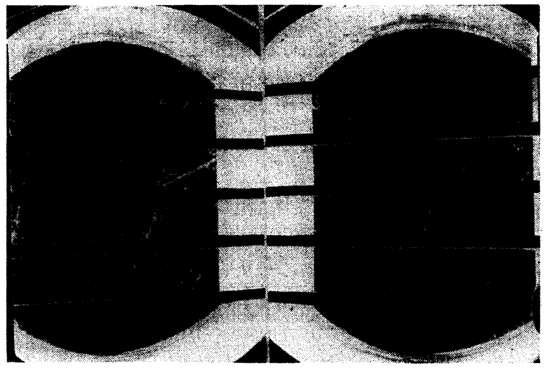

FIG. 9. A cloud-chamber stereophotograph of a heavy particle (upper right) penetrating a lead plate and ionizing heavily on both sides. The δ-rays in the section below the plate are quite evident. The particle passes in and out of the illuminated region.

For the track of Fig. 10, the particle passes through 30 g/cm^2 of lead. It comes into the illuminated region from the rear and passes out through the side plate. It has four δ-rays of greater than 20-kev energy in the region where δ-rays could be seen. This leads to an upper limit for Z of 6. Its ionization is estimated to be about $\frac{1}{10}$ that of a 10-Mev α-particle. If one assumes the value of $\frac{1}{10}$ the ionization of a 10-Mev α-particle, one gets a value of 60-Mev/(g/cm^2) for the rate of energy loss and an energy of 75×10^6 electron volts.[10] Such an α-particle would have a range of 1 g/cm^2, as opposed to the observed range of greater than 30 g/cm^2. From the above argument it seems likely that the atomic number is $3\leqq Z\leqq 6$.

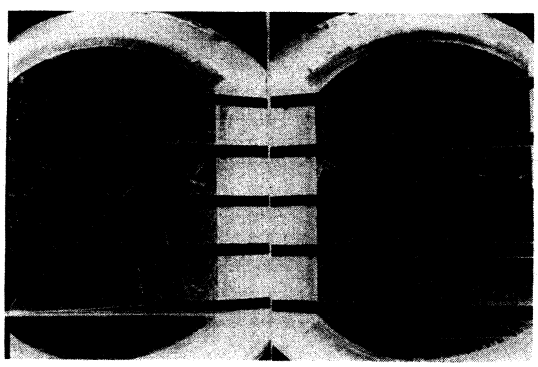

FIG. 10. A particle heavier than an α-particle comes in at the back of the chamber, penetrates three $\frac{1}{4}$-inch lead plates, and passes out through the left side plate.

[10] The rate at energy loss of a 10-Mev α-particle was obtained from Bethe's calculation reported by R. Serber—private communication. The other rates of energy loss and ranges were obtained from the collection by Aron, Hoffman, and Williams—private communication.

Figure 11 shows an interesting case of a heavy particle for which no estimate could be made because of the age of the track. The track has been pulled apart by the clearing field, and two columns of ionization may be seen in each section. The same picture shows a star in the lead plate with the production of two penetrating particles.

VIII. HYDROGEN-HELIUM RATIO

By examining a number of cloud-chamber pictures, an approximate value for the ratio of the number of protons to the number of α-particles was obtained. It is believed that the figures apply to primary cosmic rays. The cloud chamber used had five $\frac{1}{4}$-inch lead plates and, for studying the H–He ratio, photographs were chosen in which all sections of the cloud chamber were operating well. One flight had 44 such pictures at 95,000 feet (14 g/cm^2 of residual atmosphere), another had 30 pictures at 80,000 to 85,000 feet (25 g/cm^2 of residual atmosphere). The only particles considered were those which entered the chamber in such a way as to penetrate at least 3 lead plates and which scattered less than the limit imposed by turbulence (1 or 2°). This requirement and the high altitude discriminate against mesons. The tracks which satisfied these conditions were classified as to ionization and thereby placed in two groups, depending on whether their ionization was minimum for a singly charged particle or about four times this value. In only one case did the ionization change appreciably in penetrating $\frac{3}{4}$ inch of lead. Because of the manner in which the ionization changed with residual range, this particle was identified as a low energy proton. Table IV summarizes the results. The average value of the H/He ratio is 4. It should be pointed out that what was measured were the relative numbers of penetrating singly charged and multiply charged particles, and the presence of mesons could make the H/He ratio considerably different. It is interesting to note, however, that this value is consistent with astrophysical estimates. Using spectroscopic methods, Menzel and Goldberg[11] determined 4 as the value for the H/He ratio on the sun, and Aller and Menzel[12] find 10 as the ratio for planetary nebulae.

IX. CONCLUSIONS

When experiments are made at altitudes corresponding to 25 g/cm² of residual atmosphere or less, heavily ionizing particles appear, and these heavily ionizing particles show the properties of the nuclei of the elements.

Because of their energy and their angular distribution at the altitudes investigated, they appear to be present as a component of primary cosmic rays.

Examination of Table II leads to the conclusion that the kinetic energies of the heavy nuclei so far investigated range from 0.5 to 1.5 Bev per nucleon. Serber[13] has estimated that the primaries (assumed to be protons) have an average energy of about 7 Bev.

The hydrogen-helium ratio for these particles is not inconsistent with hydrogen-helium ratio for the sun or for planetary nebulae. The relative abundance of the heavy elements with respect to hydrogen and helium seems to be consistent with that assumed by astrophysicists.

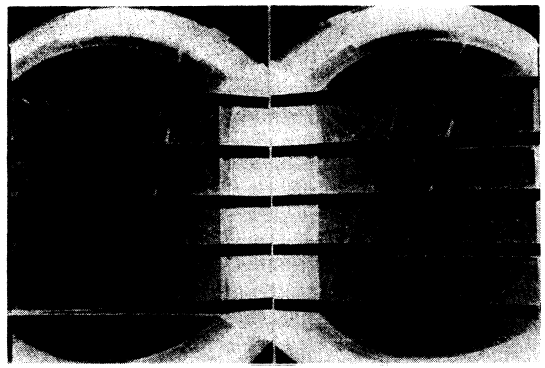

FIG. 11. A stereophotograph of a heavy particle that penetrated five ¼-inch lead plates. It traversed the cloud chamber early, and the two columns of ionization are pulled apart by the clearing field. It ionizes like a slow α-particle, but it has a range very much greater. Three other interesting events also occur. In the center of the top plate a star is formed by non-ionizing radiation. This star has one fragment which penetrates one-inch of lead and another which penetrates ¼ inch. In the left side of the upper lead plate, a shower of penetrating particles is initiated by an ionizing particle. Two of the particles in this shower can be seen penetrating three-quarters of an inch of lead without radiation or detectable scattering. There is also a rather large shower of fast particles originating at the right side of the second from the top lead plate.

X. ACKNOWLEDGMENTS

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[11] L. Goldberg and L. H. Aller, *Atoms, Stars, and Nebulae* (The Blakiston Company, Philadelphia, 1943).
[12] L. H. Aller and D. H. Menzel, Astrophys. J. **102**, 239 (1945).
[13] R. Serber, Phys. Rev. **54**, 317 (1938).

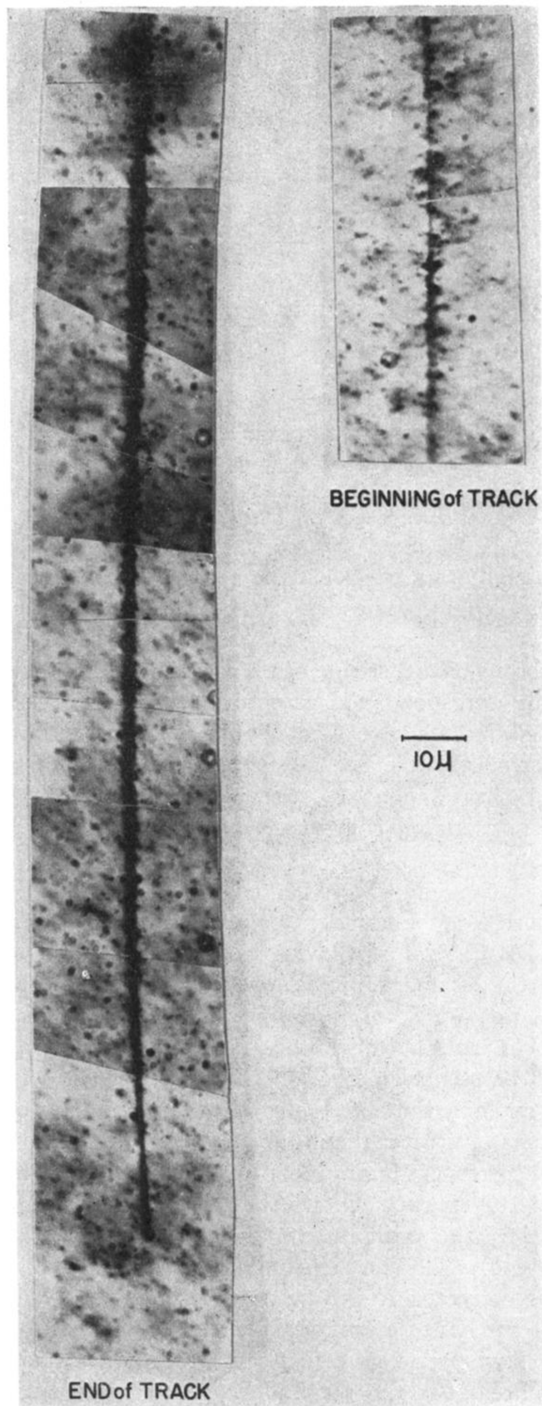

FIG. 1. Photomicrograph of track with $Z=15$ (estimated from δ-rays) stopping in emulsion. The insert shows the track when it enters the stack of photographic plates with $\beta \gtreqqless 0.7$. The thin down shown at the left occurs after the particle has penetrated 9.6 g/cm^2 of glass and emulsion.

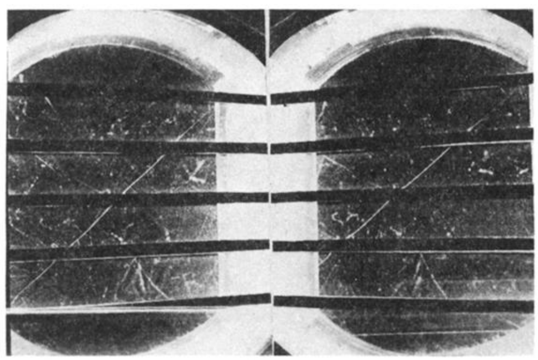

FIG. 10. A particle heavier than an α-particle comes in at the back of the chamber, penetrates three $\frac{1}{4}$-inch lead plates, and passes out through the left side plate.

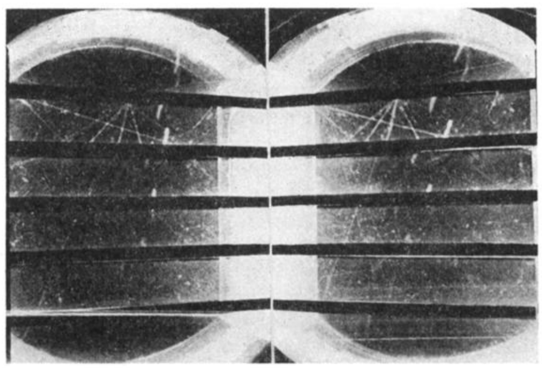

FIG. 11. A stereophotograph of a heavy particle that penetrated five $\frac{1}{4}$-inch lead plates. It traversed the cloud chamber early, and the two columns of ionization are pulled apart by the clearing field. It ionizes like a slow α-particle, but it has a range very much greater. Three other interesting events also occur. In the center of the top plate a star is formed by non-ionizing radiation. This star has one fragment which penetrates one-inch of lead and another which penetrates $\frac{1}{4}$ inch. In the left side of the upper lead plate, a shower of penetrating particles is initiated by an ionizing particle. Two of the particles in this shower can be seen penetrating three-quarters of an inch of lead without radiation or detectable scattering. There is also a rather large shower of fast particles originating at the right side of the second from the top lead plate.

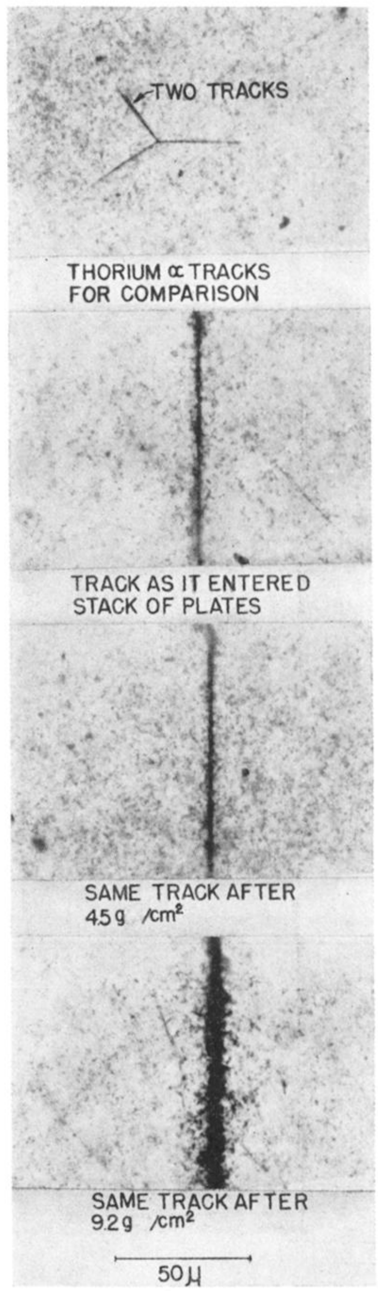

FIG. 5. Photomicrograph of sections of the heaviest track observed. The atomic number of this track was estimated to be 41 by δ-ray counting.

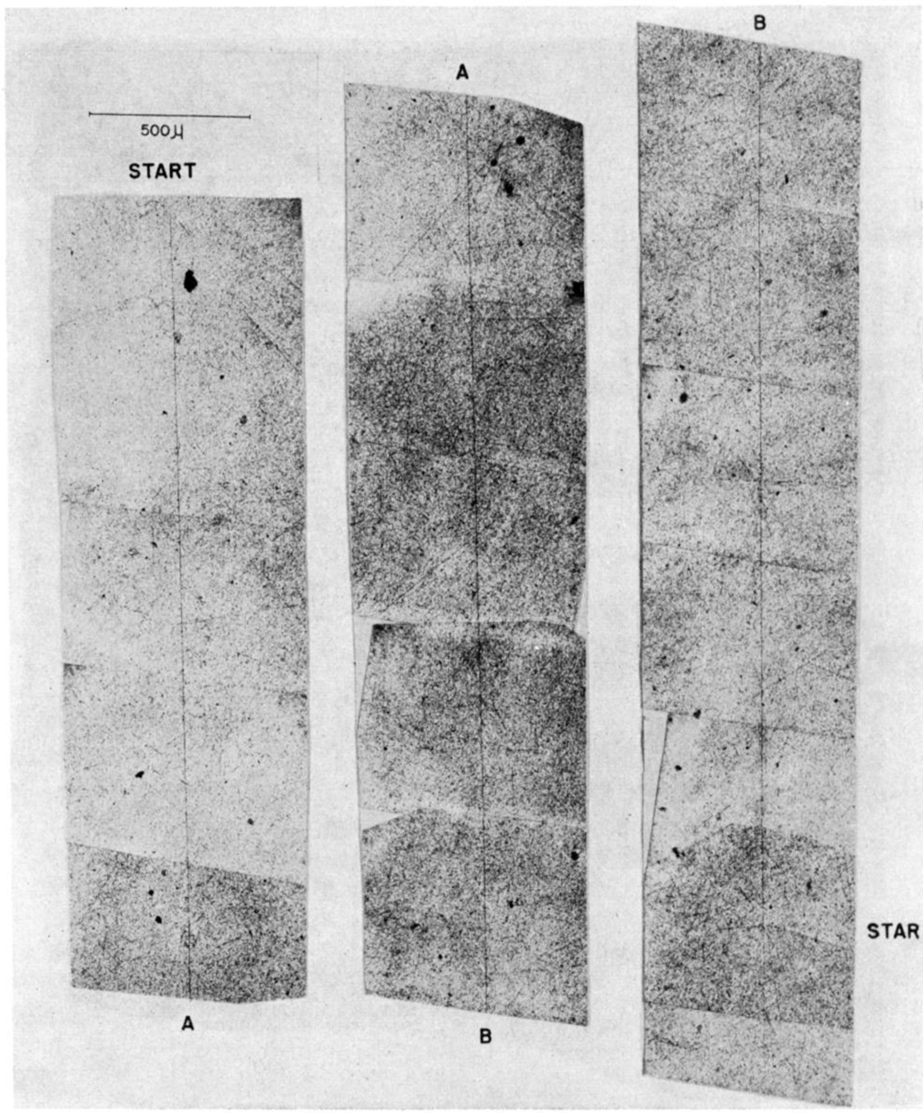

FIG. 8. Photomicrograph of heavy particle (Z estimated between 8 and 14) ending in the emulsion with a nuclear collision.

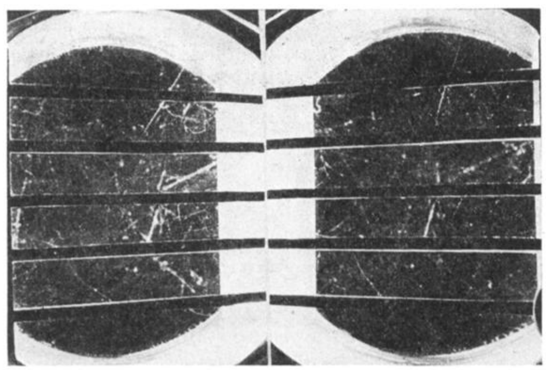

FIG. 9. A cloud-chamber stereophotograph of a heavy particle (upper right) penetrating a lead plate and ionizing heavily on both sides. The δ-rays in the section below the plate are quite evident. The particle passes in and out of the illuminated region.