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Observation of Cosmic-Rays with Nuclear Emulsions

By

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We have been observing cosmic-ray phenomena with nuclear emulsions NTB since last summer. A part of our results has been already published this winter (1). In this paper we shall report the results so far obtained. Our observation is mainly about cosmic-ray stars, but we also tried to examine the existence of the varitrons (2) by means of the grain counting of many single tracks.

1. Experimental procedure (3)

We obtained the nuclear emulsion plates Eastman Kodak NTB (50 microns in thickness) at the beginning of July 1949 and exposed them to cosmic-rays for 47 days (i. e., from July 29 to September 1) placing the surface of the emulsion vertically at the Meteorological Observatory on Mt. Norikura (2840 m a. s. l.). We developed them for twenty minutes with undiluted D–19 developer (20° C). In order to scan emulsions we used microscopes with the magnification of 450. For scanning, the plates were put on the stand reconstructed with the comparator for spectroscopy, and made to move with constant speed by a motor. The speed was comparatively slow with about 0.1 mm per second, and moreover, it can be stopped whenever in need. So we think there are few cases when we miss some of the events in the emulsion. Most of the stars were examined in detail with oil immersion lens ($\times 90 \sim 135$), and the grain counting was performed by magnifying them $1200 \sim 1500$ times.

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2. Cosmic-ray stars

(a) Distribution of the number of stars about the number of prongs.

We investigated the distribution of the number of stars about the number of prongs. In Table I we show the number of stars with more than three prongs observed in detail in two and a third sheets of emulsions and the frequency of stars per cc. of emulsion per day. Some photomicrographs of them are illustrated in Plates I (a), (b), (c) and (d).

TABLE I. Number of stars observed at 2840 m a. s. l.

Number of prongs	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Number of stars in 2.3 sheets of plates	43	25	16	12	3	1	2	1	1	0	0	1	1	106
Frequency of stars per cc. of emulsion per day	4.25	2.47	1.58	1.18	0.30	0.10	0.20	0.10	0.10	0	0	0.10	0.10	10.5

As it seemed that the considerable time had elapsed since the time of production until our plates were brought to the mountain, we took much care of the background in the emulsion, of which we shall describe in (c) of this paragraph. We have omitted such background in the first table.

(b) Variation of the number of stars with altitude.

The distribution of stars about the number of prongs has been so far reported by Wambacher (4), Bernardini et al. (5), Addario et al. (6), Salant et al. (7) and other authors at various altitudes. From their results it is learned that the distribution of stars about prong numbers at high altitudes investigated by baloon is different from that at the altitude of high mountains (about 3000 m a. s. l.). Namely, the number of stars with many prongs increases rapidly at high altitudes. The phenomena seem to be reasonable from the view that in high altitude there may exist many more nucleons with high energy, and heavy primary particles play an important role in the phenomena. In Fig. 1 is given the integral frequency curve of the stars about the number of prongs and our results are compared with those of previous investigators.

As the number of stars by the traces of radioactive substances contained in the emulsion is not negligible in the measurement at low altitudes, there seems to be not a few cases when the number of stars with less than five prongs becomes larger to a certain degree. At any rate, comparing our results with others the difference between the distribution at high mountains and that at high altitudes seems to be conclusive.

From the data of ours, of Bernardini et al. at Laboratorio Testa Grigia (3500 m a. s. l.), and of Bernardini et al. by baloon (29000 m a. s. l.), we could obtain the altitude variation of the frequency of stars as shown in Fig. 2.

As shown in the figure the three data concerning the total number of stars with more than three prongs at different altitudes are expressed by exponential law, $\exp(-x/L_a)$, where x is the atmospheric depth expressed in $g\,cm^{-2}$, and L_a the absorption depth in $g\,cm^{-2}$. The value of L_a was found to be $137\ g\,cm^{-2}$. Also, the data concerning the number of stars with more than six prongs lie on a straight line as shown in the figure. In this case the value of L_a was found to be $124\,g\,cm^{-2}$. The value $137\,g\,cm^{-2}$ is nearly equal to the hitherto known value $138\,g\,cm^{-2}$ (8), and

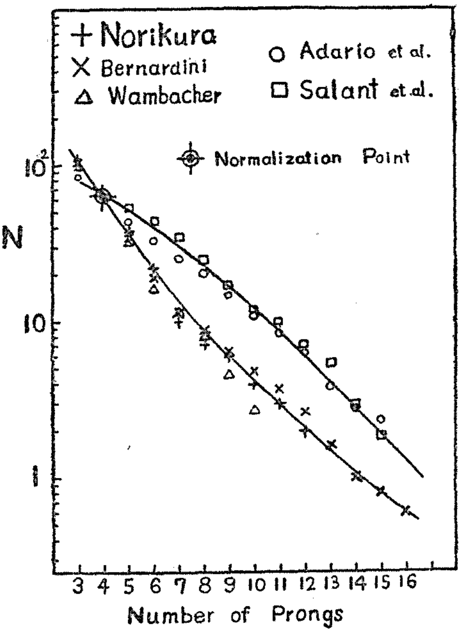

Fig. 1. Integral size frequency distribution of stars. (N in arbitrary unit.)

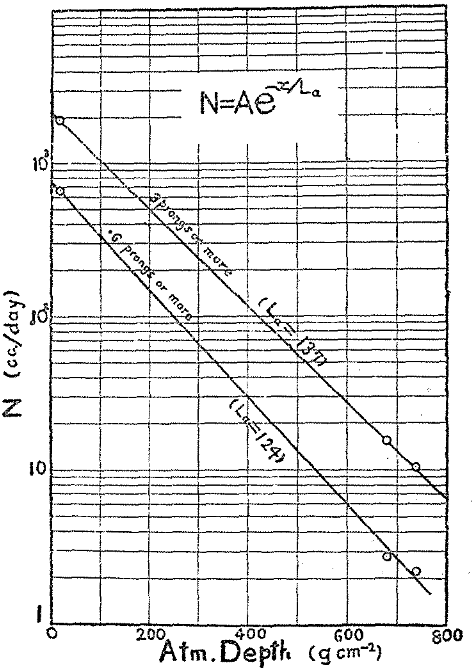

Fig. 2. Altitude variation of the frequency of stars.

that of L_a, 124 g cm^{-2}, is nearly of the same value for high energy events, i. e. 125 g cm^{-2}. Recently, Forster (9) has reported that the absorption depth for stars with prong number equal to or greater than two is 125 ± 8 g cm^{-2} which was obtained from his experiments at 11000 m, 4160 m a. s. l. and sea level respectively, but in his results the frequency of stars is much larger than that hitherto reported, which makes us feel strange.

(c) The background in the emulsion.

If we want to know exactly the effect of the cosmic-rays on Mt. Norikura, we must have a precise knowledge about the background produced after the emulsion was prepared. The background is originated from radioactive substances contained as contaminations in the emulsions and cosmic-rays which entered into the emulsions before they were brought to the mountain.

For this purpose, it will be desirable to compare them with two kinds of control plates in the same batch of our emulsions: one of which is developed at the time when our plates are brought to the mountain, and the other after they are carried back from there.

Since, however, it was not realized unfortunately, we compared them with a plate which was in the same packing in which the plates exposed on Mt. Norikura were contained, and had been kept in the laboratory. It was developed 100 days after the plates used on Mt. Norikura were developed (on 21 Dec.). A quarter of this plate was scanned, and the number of stars found in this area is shown in Table II.

TABLE II. Number of stars in the control plate (¼ of a plate).

Number of prongs	2	3	4	5	6
Number of stars	5	15	20	23	2

As it was impossible to correct our observation with the results, we adopted a means to eliminate all the stars which are distinguishable as due to radioactive substances judging from their prong lengths. Because all the stars found in the plate which was kept in the laboratory are distinguished to be of radioactive origin, we neglected the effect of cosmic-rays before the plate was brought to the mountain.

The radioactive substances expected to be in the emulsion are mainly those of Uranium-Radium series and Thorium series. In the emulsion which passed more than a month or so, the majority of stars due to radioactive elements will be five pronged RdTh stars, and four pronged Ra stars, while the six pronged Th stars, and other three or two pronged stars will be of negligible quantity.

In the actual plates, however, we found many three or two pronged stars, and the ranges of their prongs agree with those of alpha-rays due to natural radioactive elements. As to such three or two pronged stars, we excluded them on the ground discussed in the Appendix.

All the stars were sketched with a camera lucida, and were examined about the range of every prong. As the stars in question had short prongs of 20~40 microns, their ranges were estimated exactly.

In this case there are some dangers to eliminate cosmic-ray stars with similar aspects to those of radioactive origin, but its proportion will be small.

In Table III, the number of stars is shown which we eliminated in the statistics of Table I from above considerations. The total of these stars is some 10 stars/cc./day. This number agrees with the result obtained by Jagoda (**10, 11**), who estimated it as 10 stars/cc./day for the radioactive stars with 2~5 prongs found in the Ilford C_2 plates.

TABLE III.

Number of prongs	Number of stars in 2.3 sheets of plates
2	70
3	149
4	124
5	72
6	3

The quantity of natural radioactive substances in the glass is expected to be larger than that in the emulsion. In fact we found many stars which had their origin in the glass, but we neglected these stars, because we could distinguish them easily.

3. Single tracks

Besides cosmic-ray stars there can be found a good number of single tracks in the emulsion. Among these there were about thirty tracks in one sheet of plate which had the ends of their ranges longer than

200 microns in the emulsion. The greater part of them seems to be protons and some to be mesons. On scores of tracks we examined the relations between their residual ranges and the total number of silver grains contained in residual ranges in order to estimate the masses of these particles (**12**). And on some of tracks we used the method of scattering (**13**) for the same purpose.

In estimating the masses of the particles, the uniformity of the development and the fading of the latent images present a serious problem: but the former is out of the question, because the emulsions used are 50 microns in thickness. The extent of the latter, however, being uncertain, though a few reports (**10, 11, 14, 15**) have been published on the fading of alpha-particles and protons, we tried the grain counting. The results are presented in Fig. 3.

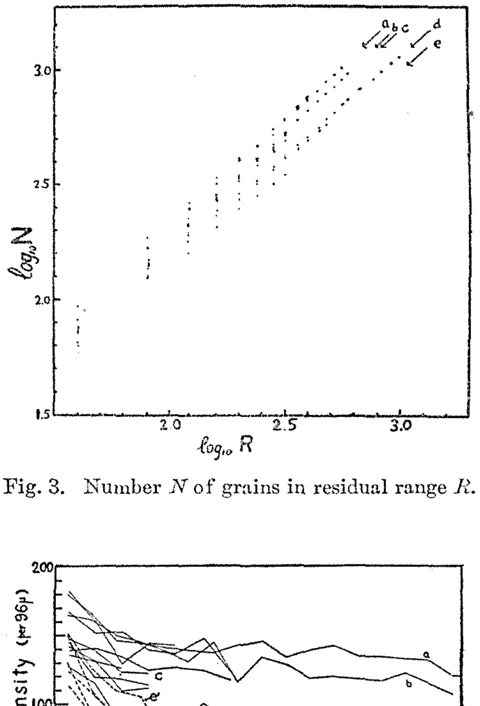

Fig. 3. Number N of grains in residual range R.

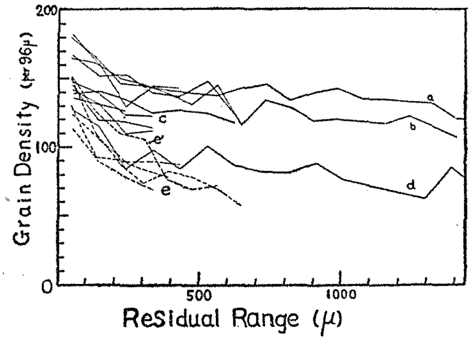

Fig. 4. Grain density *versus* residual range.

From Fig. 3 one might first be tempted to conclude that there are some different groups of particles. Assuming the group *c* to be proton, we estimated the mass of each groups *a*, *b*, *d* and *e* as shown in the figure by the method taken by Lattes et al. and the mass of group *a* particle is found to be 3∼5 times that of proton, group *b* 2 times, group *d* $\frac{1}{2}\sim\frac{1}{5}$ and group *e* $\frac{1}{10}\sim\frac{1}{20}$. Though the results may show the existence of various particles with various masses, i.e. varitrons, we must be careful to obtain the conclusion, for the effect of the fading of the latent images plays an important role in grain density. So we rewrote the above results to the relation between grain density and residual range, which is shown in Fig. 4. If we regard all the particles illustrated by full lines in Fig. 4 to be protons and consider that the extention of the grain density is due to the effect of fading, the ratio of the mass of particles with maximum grain density to that of those with minimum grain density will be about 0.6. The results are found nearly equal to Mather's experiment (**14**) which investigated the fading of the proton track in NTB emulsions. In his experiment the order of fading was 70 per cent after 47 days since latent images were formed. Therefore, from our results it will be adequate to consider that the extension of grain density is rather due to the effect of fading than due to the existence of various particles with various masses.

In the next place, judging from the shape of their curves, it seems clear that the particles shown by dotted lines are different particles. They also show the extension in grain density. From the relation of the mean grain density and the range of each group, we estimated the ratio of the mass of the former group to that of the latter group, and it was found to be 9∼10. Therefore, the latters are considered to be μ-mesons. We estimated the mass of these particles by the method of scattering taken by Latimore (**13**) and found it to be 211 ± 13. So the above consideration seems to be reasonable.

In addition, in order to testify the existence of the varitrons the effect of the fading of emulsion has the important relation as discussed above. So it would be very difficult unless much care is taken of for the effect.

In conclusion the authors express their heartfelt gratitude to Dr. Webb and Mr. Knapp of Eastman Kodak Co. for their kind offer of the nuclear emulsions, to Professor Dr. B. Arakatsu for his advice, to Mr. H. Morishita for his kind help at the Meteorological Observatory on Mt. Norikura, and Miss. K. Ishii for her aid in this work.

Appendix

Some Peculiar Aspects of Stars

By careful investigations of stars found in the photographic emulsions, we noticed that a good number of stars are followed by a few

TABLE IV.

Number of prongs	2	3	4	5
Percentage	29	57	24	0

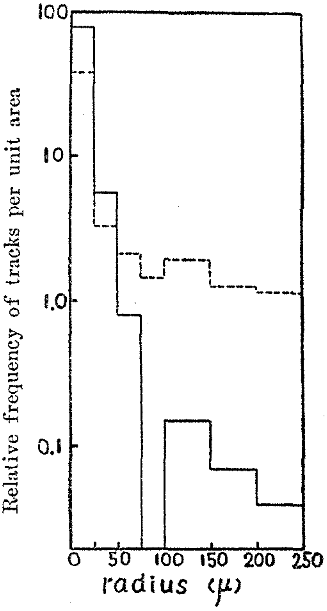

Fig. 5. Distribution of single tracks. Tracks which have both ends in the emulsions in full lines, and one end in dotted lines.

single tracks of short ranges in the neighbourhood of them. Further studies showed that these stars found together with single tracks had prongs of 20～40 microns in length, which were nearly equal to the ranges of natural alpha-rays from radioactive substances. Among the stars which have prongs of 20～40 microns length, the proportion of those which are accompanied by single tracks to the total number of stars of given prong number is shown in Table IV.

At first, we investigated whether these single tracks had relations with stars, or they fell on the star by chance. Suppose circles with their centers on the centers of stars, and with radii of 25, 50 microns and so on. Thus we counted the number of single tracks contained in each zone on 251 stars, (tracks stretching over two zones are regarded as in the zone in which the center of the track lies) and the results are shown in Table V. Also in Fig. 5 the number per unit area is shown in histogram. The counting was done respectively in the tracks having both ends in the emulsion, and only one end in the emulsion. Tracks with no end in the emulsion (these tracks are larger than 50 microns) were neglected. The tendency is very remarkable that short tracks are found near the center of stars. The range of those tracks with each end in the emulsion is shown in Fig. 6.

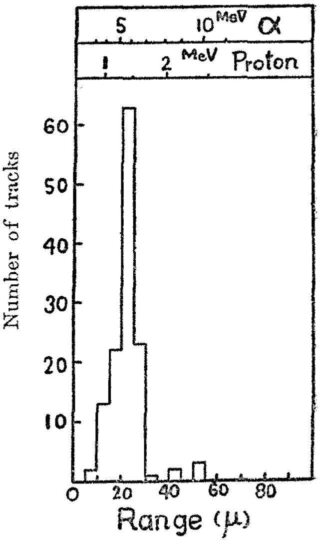

Fig. 6. Number-range histogram.

The mass and the charge of the particles were also investigated, but we got no conclusion because they were too short to give clear informations. Some microphotographs

Fig. 7 (a). Microphotograph of three pronged star with two single tracks.

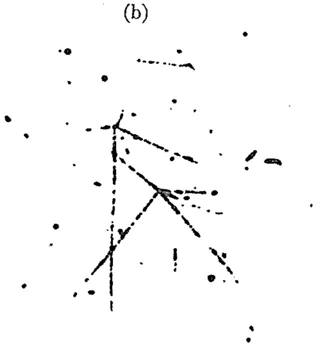

Fig. 7 (b). Microphotograph of Thorium star.

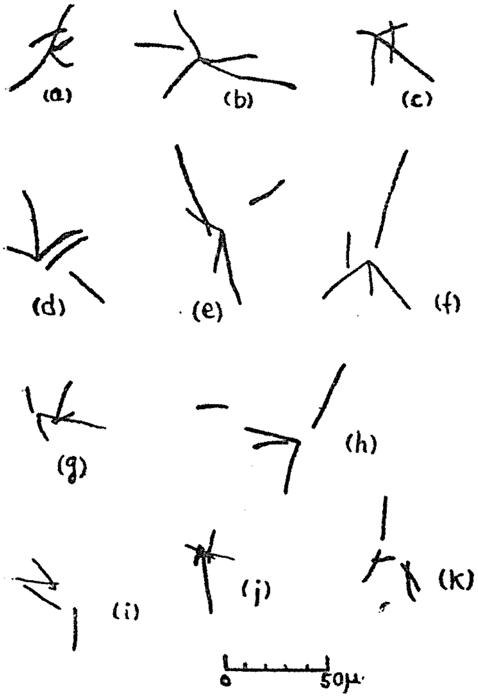

Fig. 8. Sketches of stars accompanied by single tracks.

and sketches of these stars are shown in Fig. 7 (a) and Fig. 8 (a)~(k). A microphotograph of RdTh star is also presented for comparison in Fig. 7 (b).

As easily found in the sketches, they are of various sorts. In Table VI the statistics about the prong number of the stars and the number of single tracks which were found together is shown.

In this table, "prong number 0, single track 5" for example, means an event that five single tracks are found together as shown in Fig. 8 (k). The histogram in Fig. 9 shows the distribution about the sum of number of single tracks and the number of prongs of stars found together, and we find that the majority have five or four tracks in all.

From these results, we attempted to give an explanation as follows: these stars would be RdTh or Ra stars, and though they are five or four pronged stars in nature, their origin moved during the formation of the stars by the diffusion of the atoms in the radioactive series.

TABLE V.

Radius in microns	Area (ratio)	Tracks with both ends in emulsion	The same per unit area	Tracks with one end in emulsion	The same per unit area
0~25	1	69	69	38	38
25~50	3	17	5.6	10	3.3
50~75	5	4	0.8	11	2.2
75~100	7	0	0	10	1.43
100~150	20	3	0.15	39	1.95
150~200	28	2	0.07	36	1.28
200~250	36	1	0.03	41	1.14

TABLE VI.

Number of prongs \ Single track	0	1	2	3	4	5
2	45	0	6	12	0	0
3	62	43	38	2	0	0
4	85	25	1	0	0	0
5	71	0	0	0	0	0
0	0	0	0	0	0	3

For example, a four pronged star with one single track would be considered that after RdTh emitted an alpha-particle the resulted ThX moved before it decayed (the mean life of ThX is 5.26 days) and then formed the remaining a four pronged star there. The three pronged stars with one single track would be regarded as Ra star, in which Rn moved after Ra had decayed (the mean life of Rn is 5.53 days), and then continued to decay until RaD was formed.

If we suppose that the diffusion velocity of the atoms in the radioactive series are the same, the distance of the movement would be proportional to their lives (of course it is true in the statistic meaning.) Then some of ThB would move by noticeable distance, and the existence of three pronged star with two single tracks will be understood. But it will be a rare event for the other elements as Tn, ThA, ThC, ThC′, RaA, RaB, RaC and RaC′ to move by noticeable distance, so there are no good explanation for the abundance of other kinds of stars.

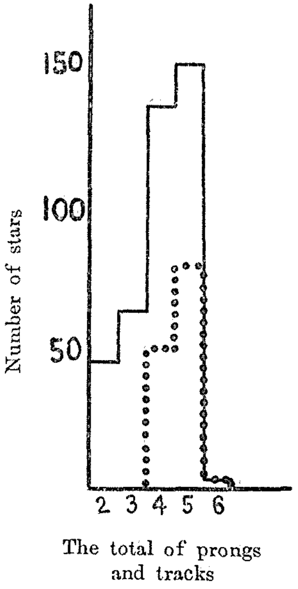

Fig. 9. Histogram of number of stars *versus* total number of prongs and single tracks.

We also considered whether or not the developer is mixed with Th, Ra contaminations during the procedure, but the situation is not important because the observable number of stars will not be formed in such a short time even with appreciable large quantity of radioactive substances. Therefore, we can consider that a neutral atom moves with mean velocity of about 10^{-9}cm/sec. in the emulsion.

Hence, we studied the aspects of RdTh stars. The experiments were done with some sheets of nuclear emulsion plates (Eastman Kodak NTA 25 microns in thickness) soaked in the thorium-nitrate solutions in 0.01 %～0.0005 % for several minutes. They were developed 1～3 weeks after the soakage. With the assumption that the elements are in radioactive equilibrium in the solution, the ratio of the number of stars is calculated. In our experimental results, however, the ratio was considerably different from the calculation, and the deviation had various tendencies.

The experimental result is shown in Table VII in comparison with the calculated ratio. In these results, the ratio of the five pronged star to the four pronged star is too large or too small, while the three and two pronged stars are very few and in this respect the result accords with the calculation. In the plates soaked in 0.01 % of thorium-nitrate solution, RdTh stars were found superposed one over the other, but in case of 0.0005 % they were well dispersed. We examined whether there were some stars followed by single tracks closely by them, but it seemed very few though they were covered by single tracks in the background. These results are somewhat unfavorable for the preceding assumption. We could not experiment with regard to the Ra star, but their nature will be analogous to the result with RdTh stars.

In spite of the resemblance of these stars with radioactive stars, we also assumed that they had relations to cosmic-rays. If these single tracks are recoil protons originated from neutrons emitted from the center of the star, the number of neutrons must be unreasonably large.

So there may be other unknown phenomena, but we abstain here from speculating about this problem until more sufficient ground are obtained to abandon the assumption of the radioactive origin.

TABLE VII.

Number of prongs		1	2	3	4	5	6
A	cal.	—	0	0	0.36	1	0
	obs.	—	0	0	1.29	1	0
B	cal.	7.45	0	0.12	1.35	1	0
	obs.	7.86	0	0.02	0.57	1	0

A: 0.0005 per cent 21 days. B: 0.01 per cent 7 days.

We excluded the stars with single tracks in the statistics of cosmic-ray stars in 2, considering that these stars are due to radioactive elements.

Since a definite conclusion, however, has not yet been reached, we intend to continue further studies.

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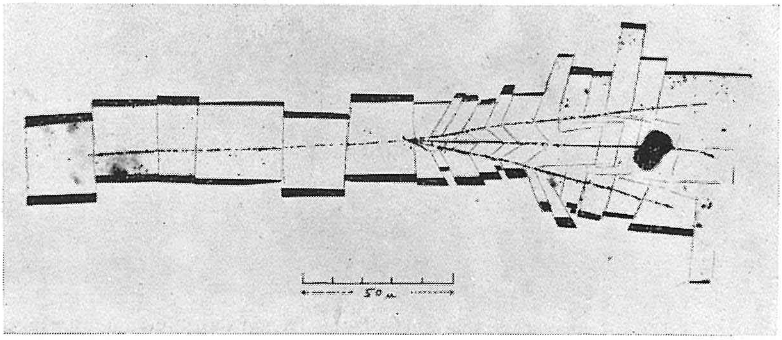
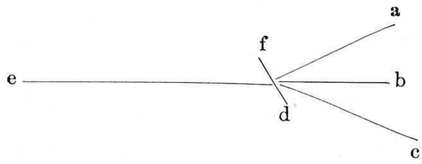
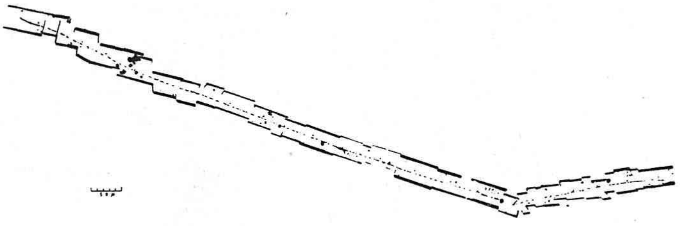
Plate I. Cosmic-ray star.



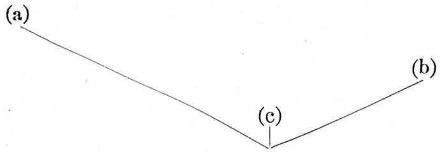
(a)



a, b, c, and d: alpha-particles f: heavier fragment e: proton

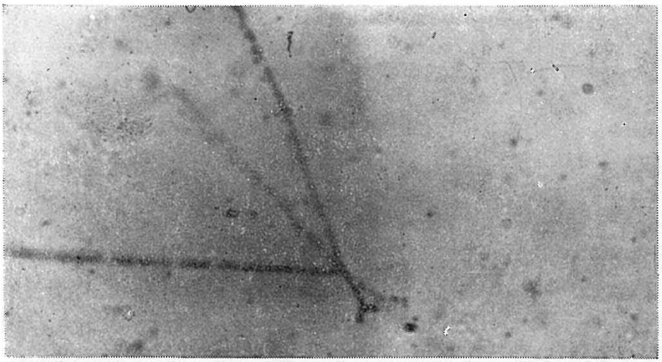


(b)

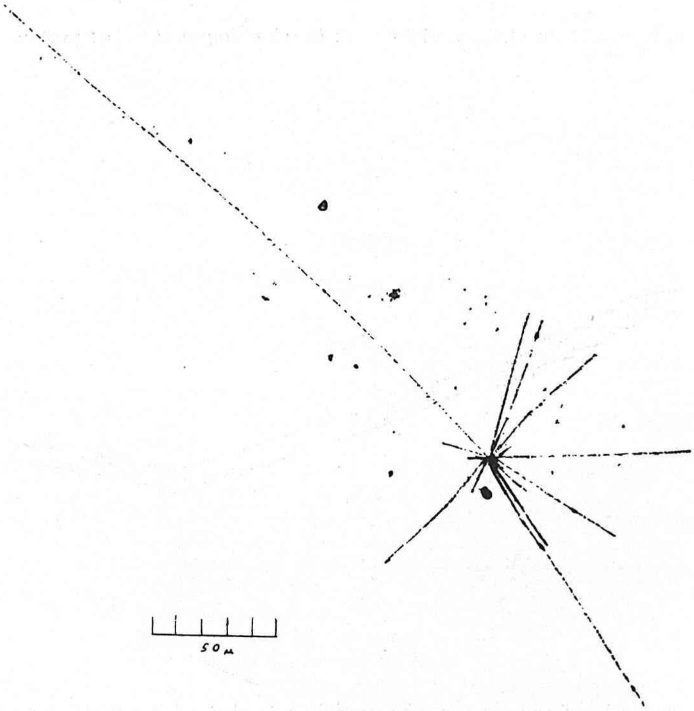


The ratio of the mass of the particle a to that of b was 2.8 from grain counting. The former seems to be triton, and the latter proton. The particle c is recoil nucleus.

a: 870 microns b: 250 microns.

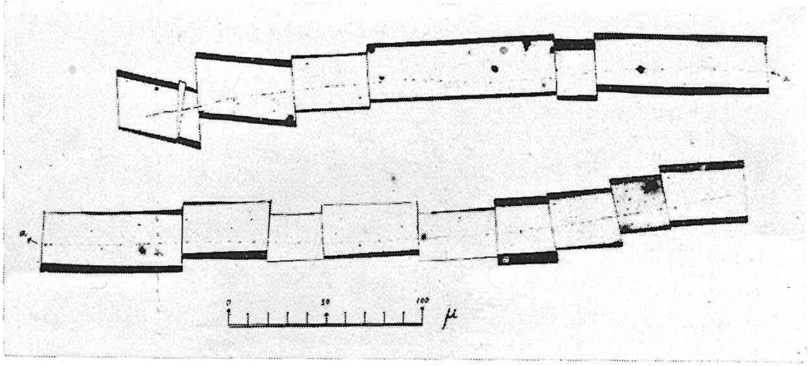


(c) The forked track shows that one of the fragments suffered scattering by the collision with a nucleus.



(d) Explosive disintegration of a nucleus (silver or bromine). The track of fourteen fragments can be seen including protons, alpha-particles and heavier nuclei.

Plate II. Track of μ–meson.



(The track continues from sign a to a.)