1A

CENTRE DE PHYSIQUE NUCLEAIRE

UNIVERSITE LIBRE DE BRUXELLES

Note n° 9

Juillet 1949

HIGH ENERGY PARTICLES IN COSMIC RAY STARS OBSERVED IN PHOTOGRAPHIC EMULSIONS

M.G.E. COSYNS , Mlle C.C,DILWORTH , Y. GOLDSCHMIDT-CLERMONT,
G.P.S. OCCHIALINI , M. SCHÖNBERG(x), L.VERMAESEN(xx)

(x) Université de S. Paulo,Brésil,séjournant actuellement à l'Université Libre de Bruxelles

(xx) Université de Gand,séjournant actuellement à l'Université Libre de Bruxelles

HIGH ENERGY PARTICLES IN COSMIC RAY STARS OBSERVED IN PHOTOGRAPHIC EMULSIONS

The Bristol group has shown recently (1) the existence of particles of ionisation close to the minimum in cosmic ray stars detected in photographic emulsions. They suggested that a part of them could be mesons created in collisions of nucleons. In most cases the observed disintegrations are very complex; large numbers of particles of low and high energy are produced and it is very difficult, often impossible, to determine the nature of the individual particles, particularly in the high energy region. In this note we shall give a preliminary survey of the different types of such phenomena we have observed in plates Kodak NT 4 and Ilford G5 of 400 and 600 microm exposed at Pic du Midi (2800M) and present a summary of the conclusions which up to now we have been able to draw.

The simplest phenomena of that kind are those described in a recent paper (2) by some of the authors of this note, in which a slow mesons is associated with a relativistic particle. We have also observed several two branch stars in which one branch has ionisation close to the minimum. Both branches leave the emulsion and the nature of the particles could not be determined. The interpretation given in reference 2 that there was the transformation of a neutron into a proton with the emisson of a meson could eventually be also applied to these two branch stars. We have also observed two branch stars in which both branches have ionisation close to the minimum (Photo 1). These must include pairs of electrons produced by gamma rays.

The next simplest example we have observed in which there are only relativistic particles is shown in photo 2. Here there is a central track of sparse grain density 7 cm long with two other tracks, also of low grain density, diverging from it, the angles with the central track being of 4°15' and 6°40'. This phenomenon can be interpretated either as a particle which gives rise to three other particles, one of them in continuation with the primary, or to a single particle which throws off two secondaries at one point of its track. If this event was recorded during the exposure at Pic du Midi, the orientation of the tracks in the plate is such that either the primary was travelling upwards against the main cosmic ray stream and the secondaries were thrown forwards or the primary was travelling downwards and the two secondaries were thrown backwards. In considering mechanisms to explain this event both possibilities of emission forwards and backwards were envisaged, We cannot exclude that the event was recorded before or after the exposure at Pic du Midi when the orientation of the plate was not known .

The nature of the secondaries can be established by the measurement of their scattering and grain density. Theoretical relations between scattering and ionisation were checked by direct measurement on mesons and electrons up to regions where the scattering becomes equal to that of the diverging secondaries.

The two secondaries have a scattering corresponding to electrons of 40 ± 3,5 Mev and 15 ± 1,8 Mev (long and short track respectively), the grain density is correspondingly less than 1,1 the minimum. It is extremely unlikely that the diverging secondaries are mesons, because their scattering indicates an energy of 23 ± 2 Mev and 8,5 ± 1 Mev (long and short tracks respectively) which should correspond to an ionisation at least three times the minimum. Besides the proof that the charge is unity, no other conclusion can be drawn as to the nature of the primary and the secondary emitted in continuity with it from scattering and ionisation. No difference in ionisation was found by grain counting and both of them do not show any observable scattering (less than 0,1 degree per cm.) so that they must have more than 2.10^9 ev. kinetic energies. Various mechanisms can be considered:

(1)- Decay in flight of some unstable heavy meson ~~unstable particle~~. Two possible modes of disintegration into known particles can be discussed:

a) Disintegration into three particles with nearly equal mass. Evidence for such a type of disintegration has been given by the Bristol group(1), the three particles having masses of the order of 200-300 electron masses. Such a type of disintegration is not likely in our case since the two diverging secondaries are very probably electrons. Moreover, using the laws of conservation of energy and momentum and the Lorentz transformation it can be seen that photo 2 can not correspond to such a type of disintegration, given the condition that the energy of one of the secondaries is very much larger than the energies of the other two.

b) Decay into two electrons and one heavy secondary. Such a decay would not be in contradiction with the conservation laws and the Lorentz transformation in our case. It would be analogous to the transformation of a neutron into a proton with the emission of a pair electron-neutrino.

Types of decay involving neutral particles, besides the three ionising ones can also be considered.

(2) - Production of pairs of electrons. Four modes of pair production can be envisaged.

a) Pair production by a photon.

The cross section of pair production by a photon of energy much larger than 137 mc^2 $Z^{-1/3}$ (complete screening of the Coulomb field of the nucleus)

$$\phi_{pair} = \frac{Z^2 r_0^2}{137}\left[\frac{28}{9}\log\left(183 Z^{-1/3}\right) - \frac{2}{27}\right]$$

$$r_0 = \frac{e^2}{mc^2}$$ (m - mass of the electron)

(see W. Heitler, Quantum theory of radiation, pg. 200, Oxford, 1944) gives for the material of the emulsion an averaged cross- section of about 3.10^{-24} cm^2 . Therefore the creation of a pair in the emulsion by a photon is not an unlikely event, if the photon has a path of the order of 1 cm. The photon could have been emitted by the primary outside the plate and followed its track or in the emulsion. The cross - section for radiation loss of an electron of energy much larger than 137 mc^2 $Z^{-1/3}$ is

$$\phi_{rad} = \frac{Z^2 r^2}{137}\left[4\log\left(183 Z^{-1/3}\right) + \frac{2}{9}\right]$$

(see Heitler, loc. cit. pg. 172). In the case of the emulsion this cross section is about 4.10^{-24} cm^2. Therefore the emission of a high energy quantum in the emulsion will be likely, in our case, if the primary is an electron. Since the photon would be emitted at a very small angle (of the order of 0.01°) the secondary electrons would appear to come from the track of the primary (within 2 microns). We cannot exclude the possibility of the primary being an electron of energy much larger than 2.10^9 ev. since in this case it would still not show any observable scattering even after losing a very considerable part of its energy by emission of photons.

There is some difficulty in assuming that the two diverging secondaries are a pair of electrons created by a photon since the energy of the photon would be of about 56 Mev and we should expect a smaller angle of the pair (2° - 3°). In the case of the creation of a pair by a photon the masses of the two secondaries could be expected to be larger than that of the electron by a factor of about 4. The eventual existence of such heavy electrons was already considered(3).

b) Direct pair production by an electron;

The cross section for this process is

$$\phi \sim \frac{Z^2 r_0^2}{137^2} \frac{28}{27\pi} \left(\log 137\, Z^{-1/3} \right)^3$$

(see Heitler, loc. cit. pg. 203; the formula given in Heitler's book does not take into account the screening, the effect of screening was given by L. Nordheim, Jour. de Phys. 6, 135, (1935)).

This expression of the cross section is rough but it shows that the direct pair creation by an electron is less probable than the pair creation by a photon by a factor of the order of 100. This is a rare phenomenon, moreover the angle of the diverging secondaries would be extremely unlikely if the primary were an electron.

c) Direct pair production by a meson or proton.

In this case we may neglect the screening and the cross section is that given in Heitler' s book (pg. 203)

$$\phi \sim \frac{Z^2 r_0^2}{137^2} \frac{28}{27\pi} \left(\log \frac{E}{Mc^2} \right)^3$$

E - energy of the primary.

M - mass of the primary.

ϕ is now of the order of 10^{-26} cm^2 or 10^{-27} cm^2 (meson or proton). This is an exceedingly rare phenomenon.

d) Pair production by an intermediate neutral meson.

The theory of nuclear forces indicates that nucleons may emit neutral mesons as well as charged ones. The cross section for such an emission in a collision of two high energy nucleons should be of the order of 10^{-25} cm^2 (4). The neutral meson can be expected to decay into two or three photons(5), with a lifetime of the order of 10^{-11} or 10^{-16} sec. according to the value of its spin (0 or 1). One of the photons arising from the decay of the neutretto can create a pair. In our case the energy of the photon would be of about 56 Mev (the total energy of the two diverging secondaries). Such an energy of the photon is satis -

factory if the neutral meson has a mass of the order of the masses of the known charged mesons. There is however a difficulty in assuming that the two diverging secondaries are electrons because their angle is somewhat too large for an energy of the photon of 56 Mev.

There is perhaps also the possibility of a direct disintegration of a neutral meson into a pair of electrons. If such a type of decay exists, we should expect it to correspond to a lifetime much larger than that corresponding to a decay into photons, perhaps of the order of 10^{-8} sec. If the neutral meson has travelled such a time it might have deviated considerably from the track of the primary proton.

Although there are some difficulties, the production of a pair by one of the mechanisms involving an intermediate neutral meson can not be excluded, specially if the articles of the pair are assumed to be somewhat heavier than electrons.

3) Production of charged mesons.

Although it seems very improbable that the two diverging secondaries could be mesons, we shall not rule it out entirely.

It is not yet clear whether the meson production by high energy nucleons is single or multiple. The multiple production of mesons has been considered more probable by some authors (6), whereas Heitler and his collaborators (7) consider more probable the single emission of a meson in a collision between two nucleons. The available experimental evidence does not allow to settle this point up to now, although there are some facts which seem to exclude a high multiplicity of production as we shall see later.

The cross section for the creation of a single charged meson at high energies is of the order of 10^{-25} cm^2 in a collision between two nucleons, according to Heitler and Walsh (4). The production of two mesons could be due to two successive collisions in the same nucleus in the model of single production, and would have almost the same probability as the production of a single meson in a collision between two nucleons, as it was pointed out by Janossy (8), since the cross section of 10^{-25} cm^2 is of the order of magnitude of the area occupied by a nucleon in the nucleus.

The production of the two mesons in a single act would perhaps fit better our experimental evidence than a successive production, since a smaller excitation of the nucleus would be expected in the case of a single collision with a nucleon at the boundary of the nucleus and this would explain the absence of low energy particles in photo 2. A law of energy loss of the type introduced by Heisenberg (6) would lead to the emission of two mesons in a collision between an incoming nucleon of 2.10^9 ev with a nucleon at rest. If the production of mesons is multiple rather than plural the cross section will probably also be of the same order as that given by the theory of Heitler and Walsh, since the experimental results on the absorption of penetrating showers give an absorption coefficient of about 100 gr/cm^2 for the primaries (9).

::::::::::::::::::::::::::::::

The various types of stars observed in this investigation can be classified in a rough grouping demonstrating the existence of several distinct ways of disintegration.

1) Stars which have only high grain density branches i.e. branches of grain density more than about twice the minimum. They are 85% of the total.

These stars may be ascribed to nuclear evaporations produced mostly by neutrons of relatively low energy. We shall not discuss more in detail this kind of stars which were extensively examined in the old less sensitive plates$^{(10)}$.

2) Stars which have a single low ionisation track, besides the high grain density ones. They are 7% of the total.

The single high energy particle may be in some cases the primary, most probably a proton and exceptionally a meson, giving rise to a normal evaporation star(see secondary star in photo 3). In other cases, particularly when the orientation of the tracks in the plate is such that the low ionisation track is directed downwards from the centre of the star, it could be a secondary particle carrying a large part of the energy of the neutral primary and leaving the nucleus in an excited state followed by evaporation.

3) Stars in which there are several low grain density branches. These are 8% of the total.

The low grain density particles are often emitted as a shower within a limited solid angle, nearly always directed downwards, with an axis of symmetry at a relatively small angle to the vertical. For a group of 18 stars with showers of more than 4 particles with grain density less than 4 times the minimum, 9 of the stars showed an angle of less than 27° between the axis of symmetry of the shower and the vertical

In 16 of these stars the particles in the shower had less than about twice the minimum of ionisation.

In 8 of these stars there are low ionisation branches going backwards but these can not include an ionising primary in more than 4 of the stars because they have either less energy than secondaries thrown forwards or make too large angles with the axis of symetry. Therefore we may conclude that at least 14 of these stars are produced by neutral primaries, most likely high energy neutrons. We were not able to find any correlation between the number of the low ionisation branches and the opening of the shower. 50% of the particles with less than twice the minimum grain density make angles smaller than 27° with the axis of symetry. The ratio between the number of high and low ionisation branches in a star varies considerably. There are stars in which there are more low ionisation branches than high ionisation ones, stars in which both kinds are present in equal numbers and stars in which there are very few low ionisation branches although the number of high ionisation branches is considerable. The average numbers of low and high ionisation branches are respectively 5 and 14. In 50% of the stars which we observed the ratio of the numbers of high and low ionisation branches was larger than 2 ; in 75% there are more high ionisation branches than low ionisation ones.

Photo 4 shows a small angle shower with rather few low energy particles. This we can expect to occur when the shower is produced in one or a few collisions in the nucleus and therefore little energy is given up to heat the nucleus.

A typical example of an energetic shower associated to several low energy particles is shown in photo 5. Here there is a shower of 8 high energy (low grain density) particles accompanied by 10 low energy ones, of which one has certainly a charge larger than 2, and one which is sent backwards ends with the emission of an electron. This latter heavy particle could be possibly the residue of the nucleus after the evaporation of many particles, which would remain in an excited state and would later emit a beta ray. The emission of such short range unstable particles is not unfrequent and was already observed (2). The* beta decay could occur when the residual nucleus is already at rest. The decay electron will appear as a low ionisation branch which may be either inside or outside the cone of the high energy shower.

In photo 5 there is a track of 2.7 the minimum grain density, lying inside the cone of the shower, which gives rise to a secondary star . The grain density of this track corresponds to a meson of 22 Mev or to a proton of 150 Mev.; the scattering of the track is of the order of 0.2° per 100 microns, which is much less than would correspond to a meson with 22 Mev, but fits well to the scattering of a proton with an energy of 150 Mev. We can therefore conclude that the particle which produces the secondary star is a proton.

It is important to emphasise the difficulties which in most cases presents the identification of particles with less than twice the minimum of ionisation. Although it is established that in these emulsions particles of minimum ionisation are recorded, it has not yet been proved that in this region there is a proportionality between grain density and specific ionisation.

The measurement of the scattering (11) is done by dividing the track in cells and determining the angles between the successive cells. The length of the cell has to be chosen by considering the effect of the spurious scattering due to the finite dimension of the grains and the necessity of obtaining a good statistical accuracy. The spurious scattering is reduced by increasing the length of the cell, but since the length of the track is finite this leads to a decrease of the statistical accuracy. The length of the cell must be chosen in each case, taking into account the magnitude of the scattering and the length of track available , in such a way that the combined errors due to spurious scattering and statistics be minimum.

As an example, the two diverging tracks of relatively low energy of photo 2 were divided in cells of 50 microns whereas the high energy tracks of the stars with showers were divided in cells of 200 microns or more.

The accuracy of a measurement of scattering depends on the nature and energy of the particle in consideration and also on the length of its track in the emulsion. In some cases, as shown in the preceding examples, we found high- energy particles for which it was possible to measure the value of the scattering with an accuracy sufficient to allow its identification by comparison of scattering and grain density.

In the group of 18 stars with showers of particles with grain densities less than 4 times the minimum, 16 had 4 to 9 particles in the shower but we observed also two large stars, shown in figs 1 and 2, which are of the same type as the smaller ones.

We observed also one star with a shower (not included in the group of 18), whose angular distribution is shown in fig.3 which presents very different characteristics. In this star the branches with less than three times the minimum grain density are distributed over an axtremely large solid angle and are more closely grouped in the neighbourhood of a plane perpendicular to the axis of symetry.

One of the big stars(fig.1) has 31 low ionisation branches(x) and 14 high ionisation branches. Photo 6 is of this star and shows a view at a single depth with a low power(40) dry objective. The close grouping of the low ionisation branches can be readily seen from this photograph. Photo. 7 shows a mosaic microphoto of the same star. The biggest star is shown in fig.2. It has 25 low ionisation branches and 26 of high ionisation. The angular distribution of the particles of the two stars is shown in the diagrams of fig.4A . The diagram 4AF shows the angular distribution of the particles with less than twice the minimum grain density. In both stars 80% of the low ionisation branches are inside cones with a total angle of about 110°. In the 45 branch star 50% are inside a cone of 50° total angle, whereas in the 51 branch star 50% of the low grain density branches are ~~out~~inside a cone of total angle of 76°. In the 51 branch star there are two low ionisation particles thrown backwards, neither of them lying close to the axis of symetry of the shower. Both of these particles have a scattering of the order of 0,5° per 100 microns and are either electrons or mesons

---

(x) In fig.1 the branchn° 17 may not belong to the star and was not counted in the statistics.

of about 50 Mev. The low energy of these particles excludes them as possible primaries. Therefore it is quite probable that the two big stars are produced by neutral primaries. It was possible to establish by measurement of scattering and grain counting that many particles of this group(low grain density) are mesons or electrons.

If all the low grain density particles in a star were produced in a single collision between two nucleons the angular distribution in the shower would result from the Lorentz transformation of a roughly spherically symmetrical distribution in the baricentric system of the two colliding nucleon (the incoming nucleon and the other practically at rest with respect to the plate). The kinetic energy of the primary E_p would then be given approximately by the formula

$$E_p \sim 2Mc^2 \cot^2 \frac{\alpha}{2}$$

M being the mass of a nucleon and the angle of the cone of the shower. In the case of the big stars we would get an E_p of the order of 10^9 ev. A primary with such a low energy could not create a large number of protons or mesons with low ionisation tracks. It probably could not have created all the fast secondaries even if they were electrons since no electrons with energiy less than 50 Mev were found, in the measurements of scattering in the two big stars. It would not be possible to explain the big angles of the showers by a scattering of the created particles inside the nucleus. If we assume that most of the created particles are π mesons, which seems quite reasonable since the creation of electrons in large numbers would require the existence of a decay of mesons into electrons with a very short lifetime, the cross section for the scattering of a meson by a nucleon being much smaller than $10^{-25}cm^2$ (cross-section for meson creation in collisions of high energy nucleons) the probability of a collision between a meson created inside the nucleus and the nucleons would be small. We may therefore rule out the creation of all or most of the low ionisation secondaries in a single act.

The diagram M of fig. 4A shows the angular distribution of the particles with intermediate grain density- between 2 and 4 times the minimum- in the two big stars. Several particles in this group could be identified as protons. There is a cut-off in the angular distribution of these particles at about 70° which can be explained by assuming that most of the particles in this group are protons ejected in elastic collisions with fast nucleons.

The diagram S of fig.4A shows the angular distribution of particles with more than 4 times the minimum grain density. All the particles in this group have masses equal or larger than that of the proton. The observed angular distribution can be interpretated as the superposition of a spherically symmetrical one, presumably due to the evaporated particles, and a distribution with a rather sharp maximum at 90° due to slow recoil particles from collisions with fast nucleons travelling approximately in the direction of the axis of symmetry of the shower.

The diagrams of fig. 4B show the angular distribution of all the particles of the group of 18 normal stars, including the two big ones but not the exceptional star of fig. 3. These angular distributions are almost of the same type as those of the diagrams of fig. 4A, with minor differences. Thus, for instance, there is a second maximum in fig. 4BF which corresponds probably to fast recoil protons in the smaler stars travelling outside the cone of the fast mesons which probably give the first maximum. In the big stars the angular spread of the recoil protons would be smaller and the second maximum disappears. The maximum in fig. 4BM may corres pond to the existence of a considerable number of mesons with intermediate grain density in the smaller stars. The non existence of such a maximum in 4AM would then indicate that there are few mesons with intermediate grain density in the two big stars. The first maximum in the diagram of fig. 4BS indicates the existence of a group of recoil protons with low energies in the smaller stars.

In photo 6, the grouping of the tracks at a large distance from the centre of the star shows clearly the existence of an association effect between pairs of low ionisation tracks. The same association was found in most of the 18 stars of the group.36% of the particles with less than twice the minimum grain density are associated in pairs with angles less than 9°, one half of these pairs have angles less than 3.5° and their mean angle with the axis of symmetry is 17°. The pairs with angles larger than 3.5° lie farther away from the axis of symmetry ,the mean angle being 26°. The high density of the low ionisation tracks does not allow in most cases to establish whether there are associated pairs of angles larger than 9°, but the two fast secondaries of the 51 branch star thrown backwardmay be considered as an associated pair with an angle larger than 9°. It is probable that far more than 36 % of the low density tracks are associated in pairs. The existence of such a high percentage of particles associated in pairs indicates that mesons are largely produced in pairs or singly. In the group of 18 normal stars it was also possible to establish the existence of 10 pairs of particles with grain density more than twice the minimum.

The anormal star shown in fig. 3 has 10 branches of low grain density, 4 branches of grain density between two and three times the minimum and 24 branches with more than four times the minimum. 9 of the tracks of grain density less than three times the minimum make with the axis of symmetry angles between 54° and 90° with a rather sharp maximum in the neighbourhood of 70°. Two of them can be attributed to protons and one to a meson or electron by measurement of grain density and scattering. Two fast particles are thrown backwards with angles of 109° and 115°. one of them is a proton of 250 ± 70 Mev and the other is a meson or lighter particle of 300± 150 Mev. The angular distribution of the high grain density particles presents three maxima- in the forward direction, at 70° and 120°.

This star seems to be produced by a mechanism different from that of the normal stars with low grain density tracks. The very large angular dispersion of the low grain density tracks indicates that the velocity of the primary is much smaller than in the case of a normal star of comparable size, the excitation of the nucleus being probably of the same order. Therefore the mass of the primary is larger than in the normal stars. The primary could perhaps be a heavy nuclear fragment or a very heavy elementary particle scattered or absorbed by a nucleus in the emulsion. It is difficult to understand how a high energy nuclear fragment could arrive at such a depth in the athmosphere. The primary may eventually be a ~~charged~~ neutral particle of the type found by Alichanian, Alichanow and Weissenberg(12) ~~or a related neutral particle.~~

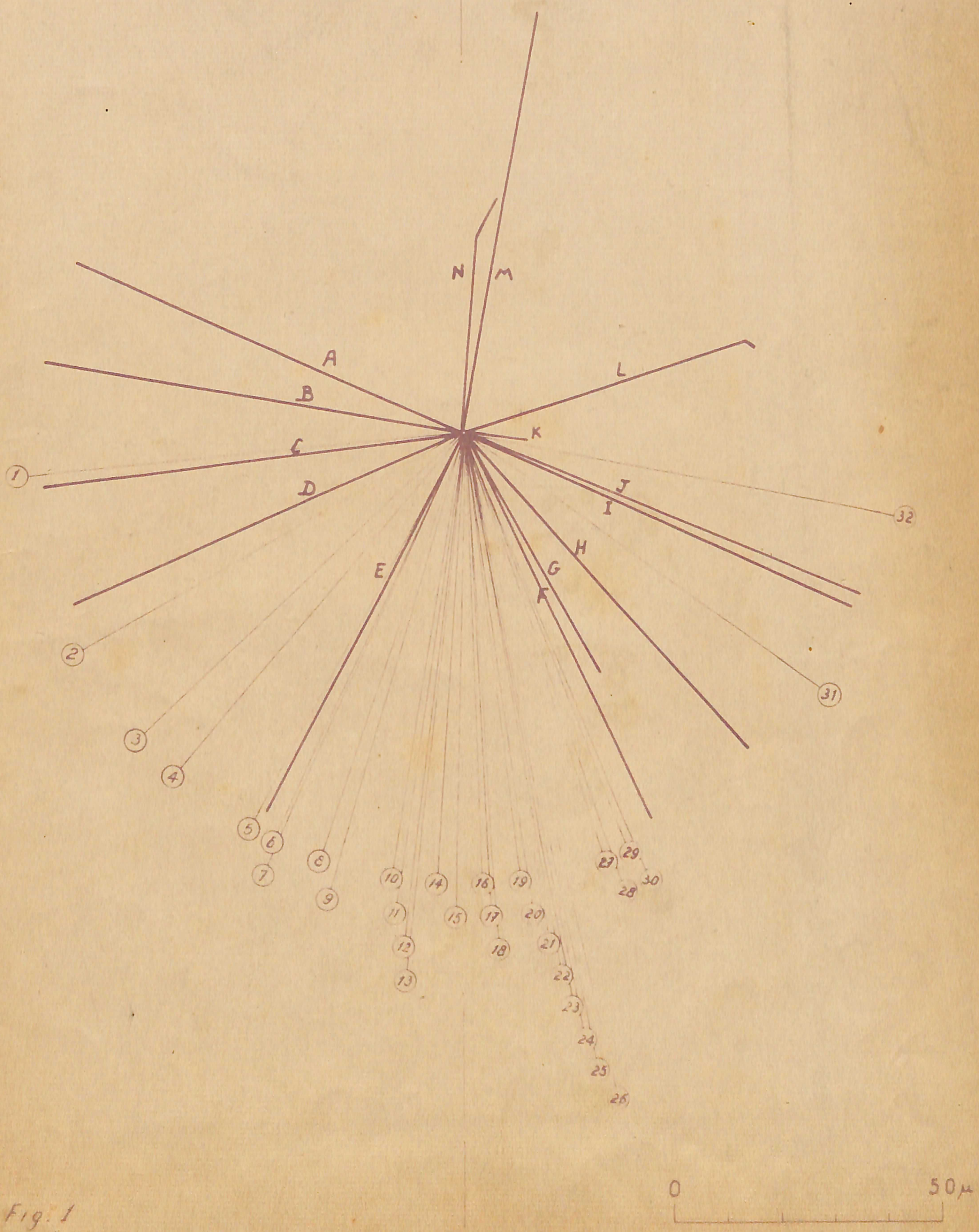

N
M
A
B
L
K
C
D
J
I
H
G
F
E
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
0
50μ

Fig. 1

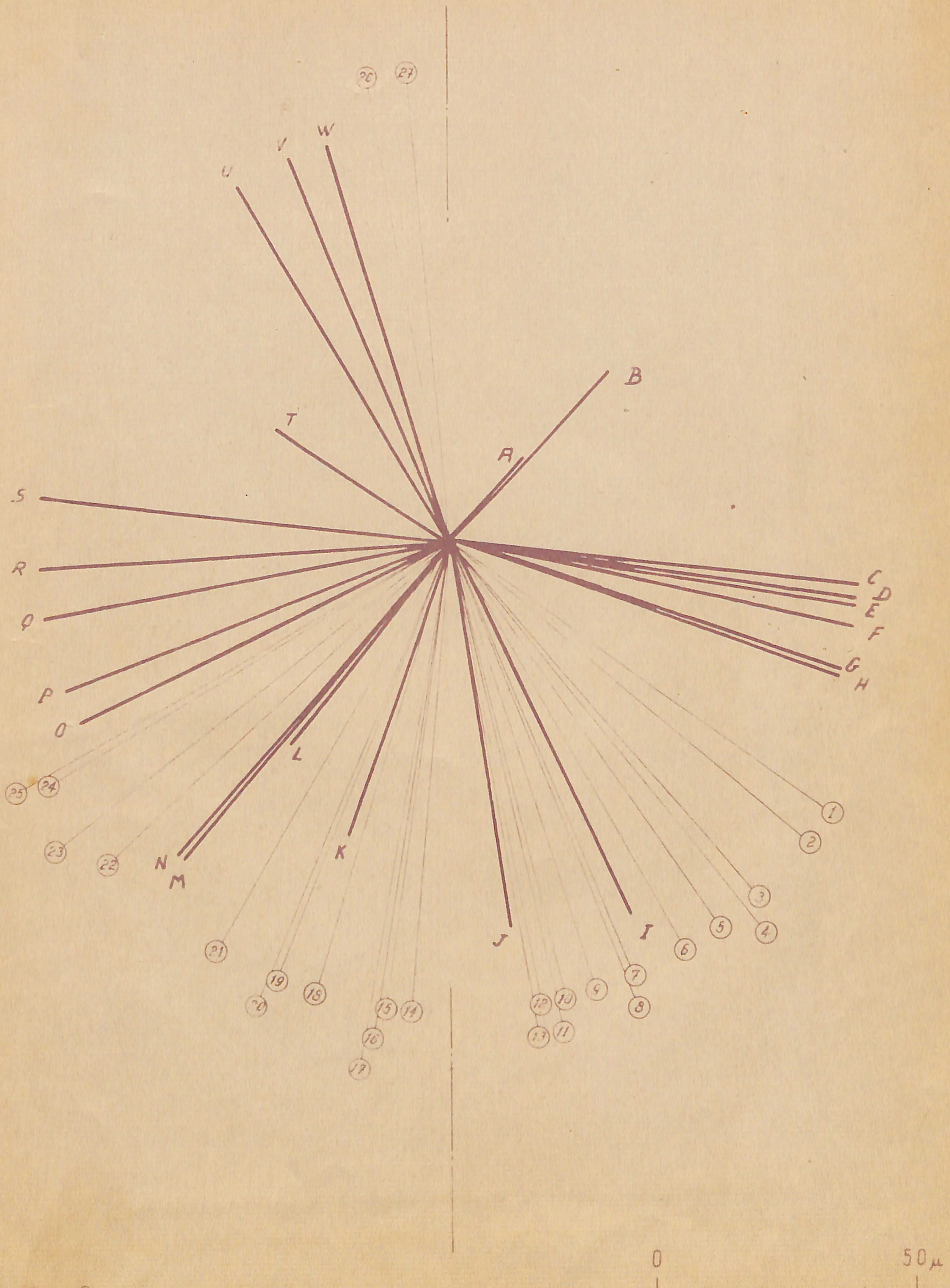
㉖
㉗
W
V
U
B
T
A
S
R
Q
P
O
C
D
E
F
G
H
L
㉕
㉔
㉓
㉒
N
M
K
J
I
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
⑬
⑭
⑮
⑯
⑰
⑱
⑲
⑳
㉑
0
50μ

Fig. 2


Ordinates are in number of particles per 1/40th of sphere
B
30
20
10
0
Fast
5
0
Medium
5
0
Slow
Evap.
0°
90°
180°
A
5
0
Fast
1
0
Medium
1
0
Slow
Evap.
0°
90°
180°

Fig.4

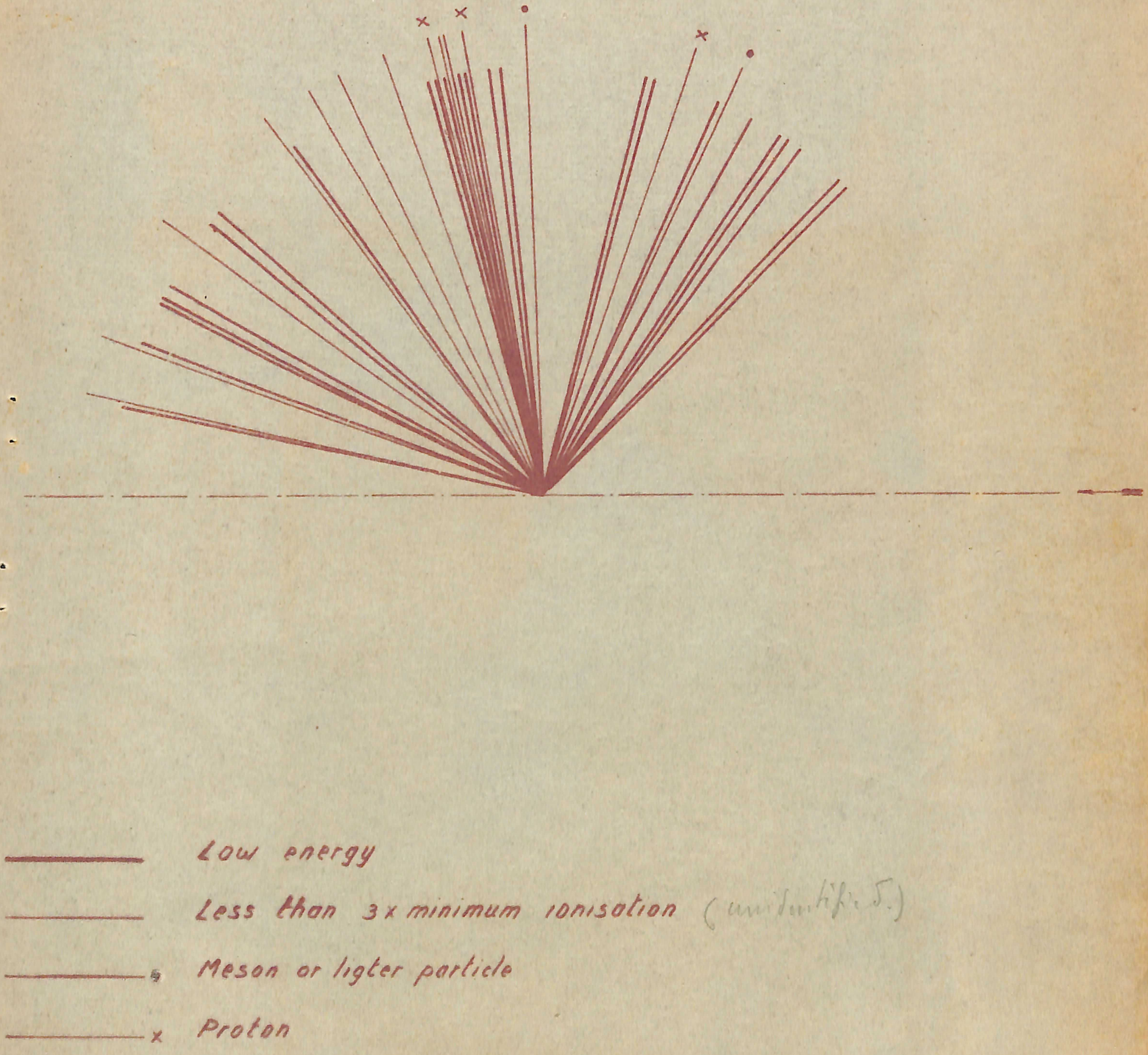

× × ●
× ●
Low energy
Less than 3 x minimum ionisation (unidentified.)
● Meson or ligter particle
× Proton

Fig. 3

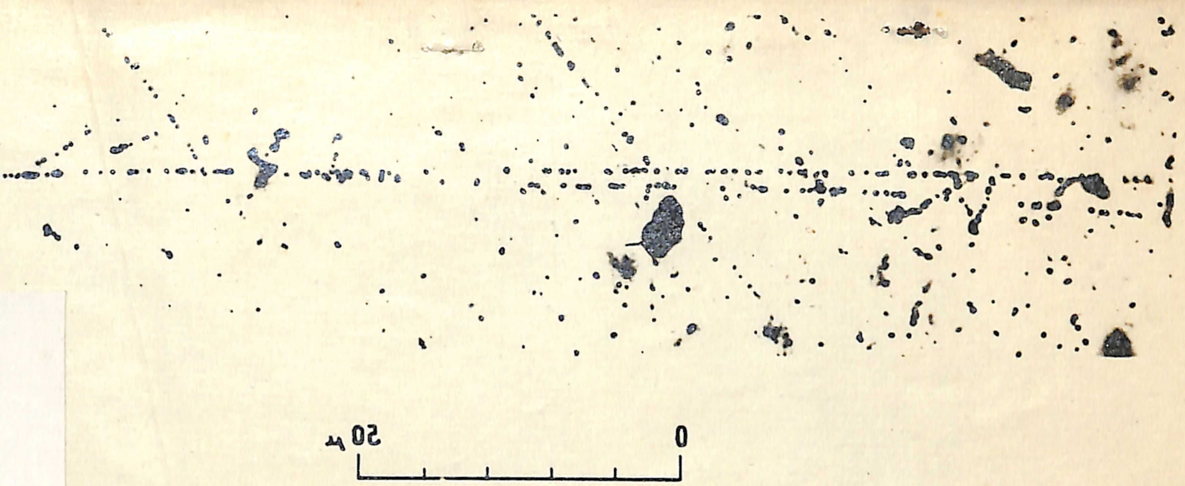


Photo 1

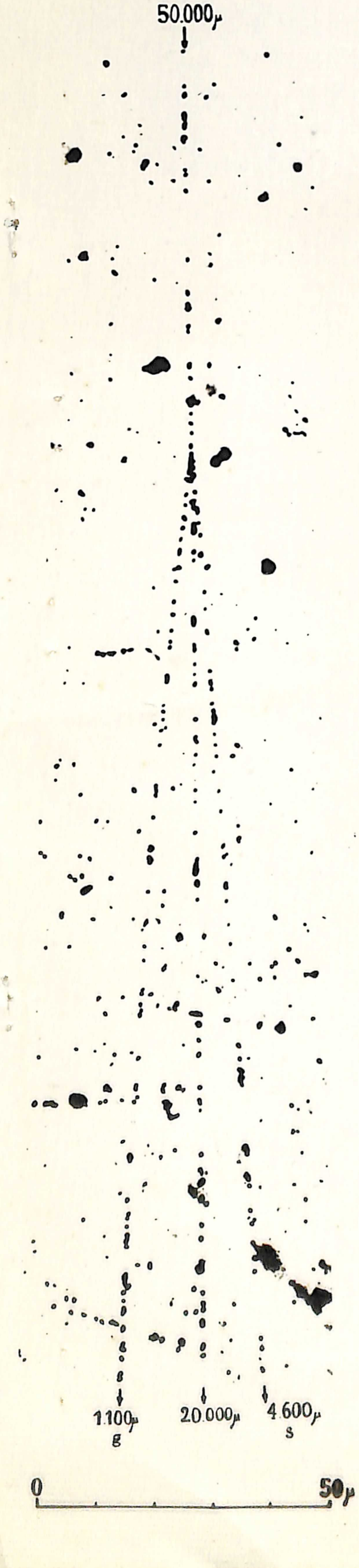


Photo 2

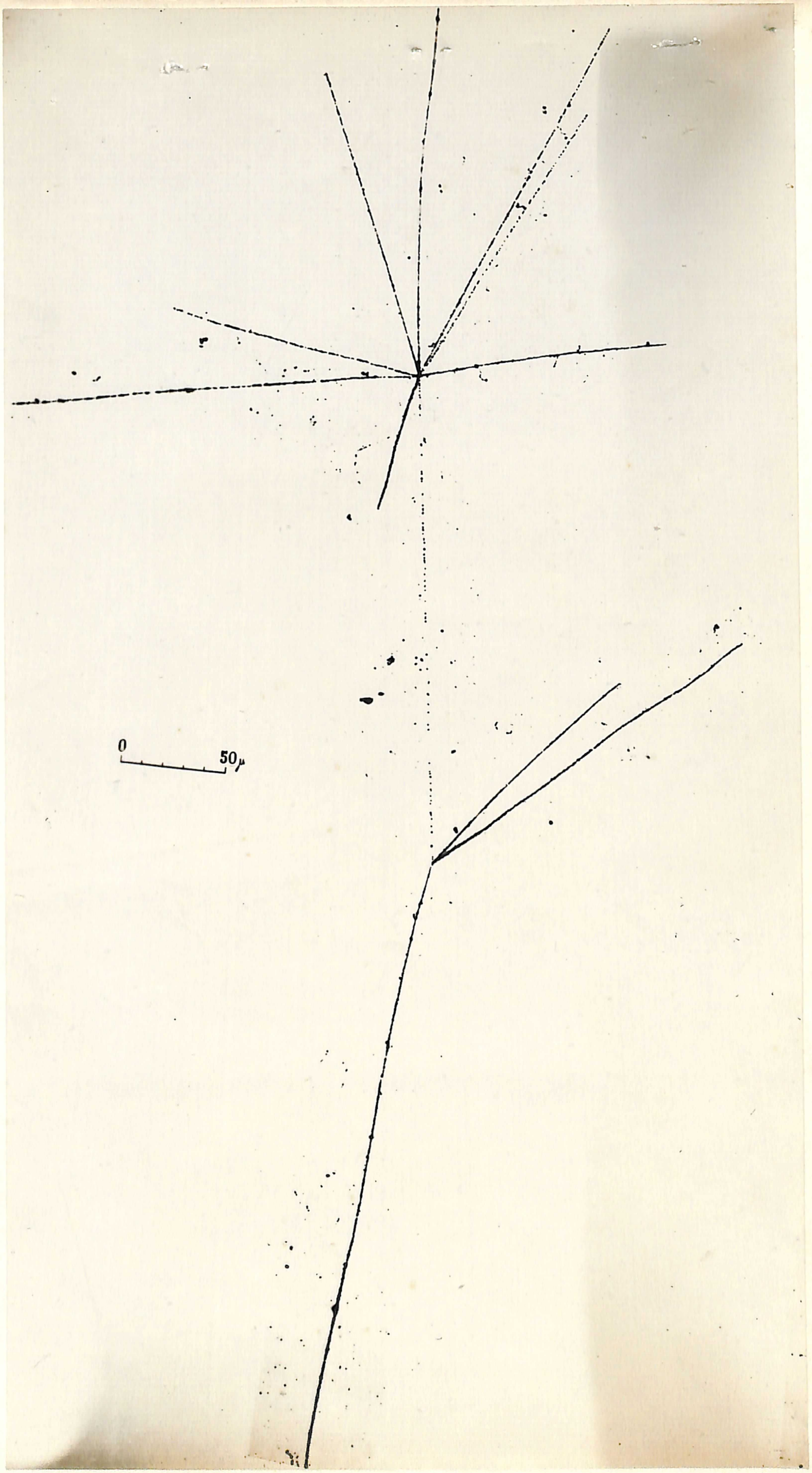


Photo 3

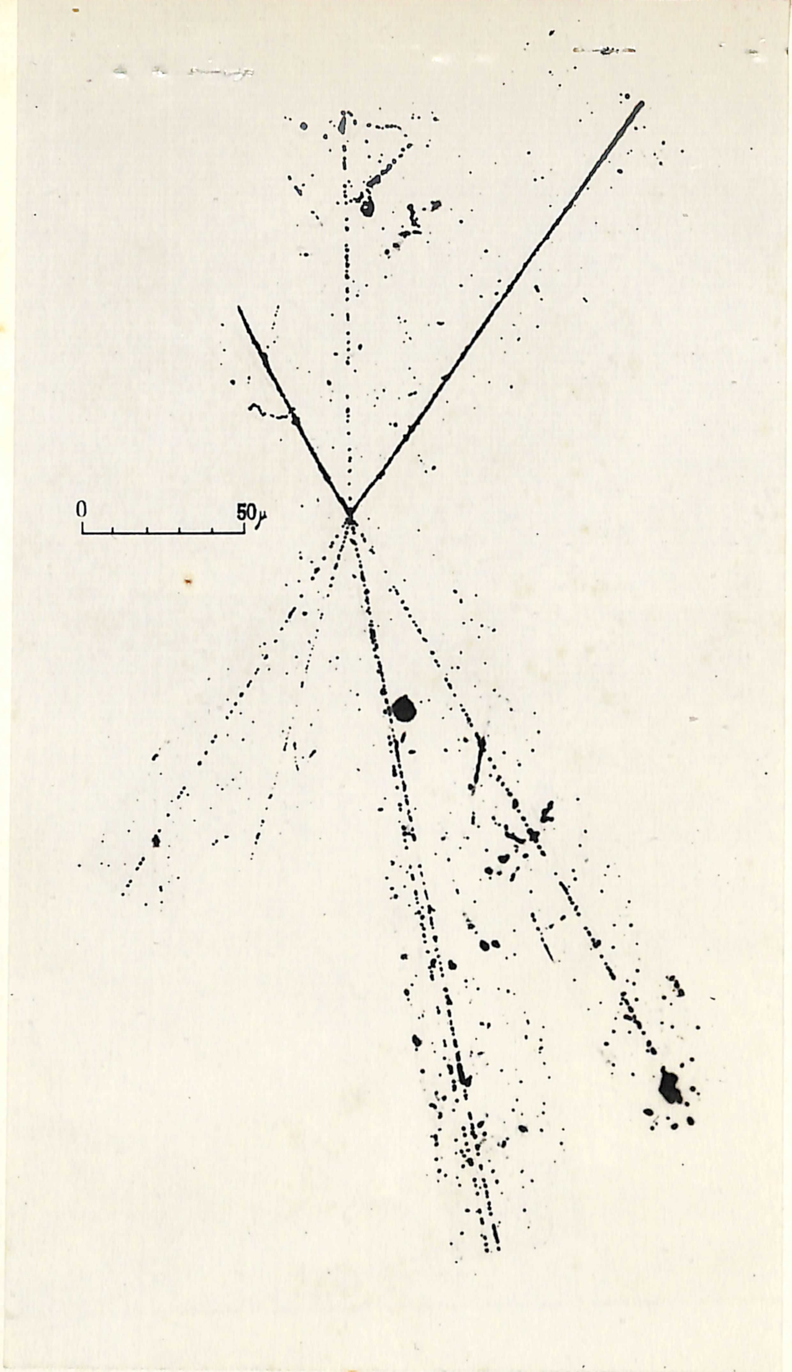
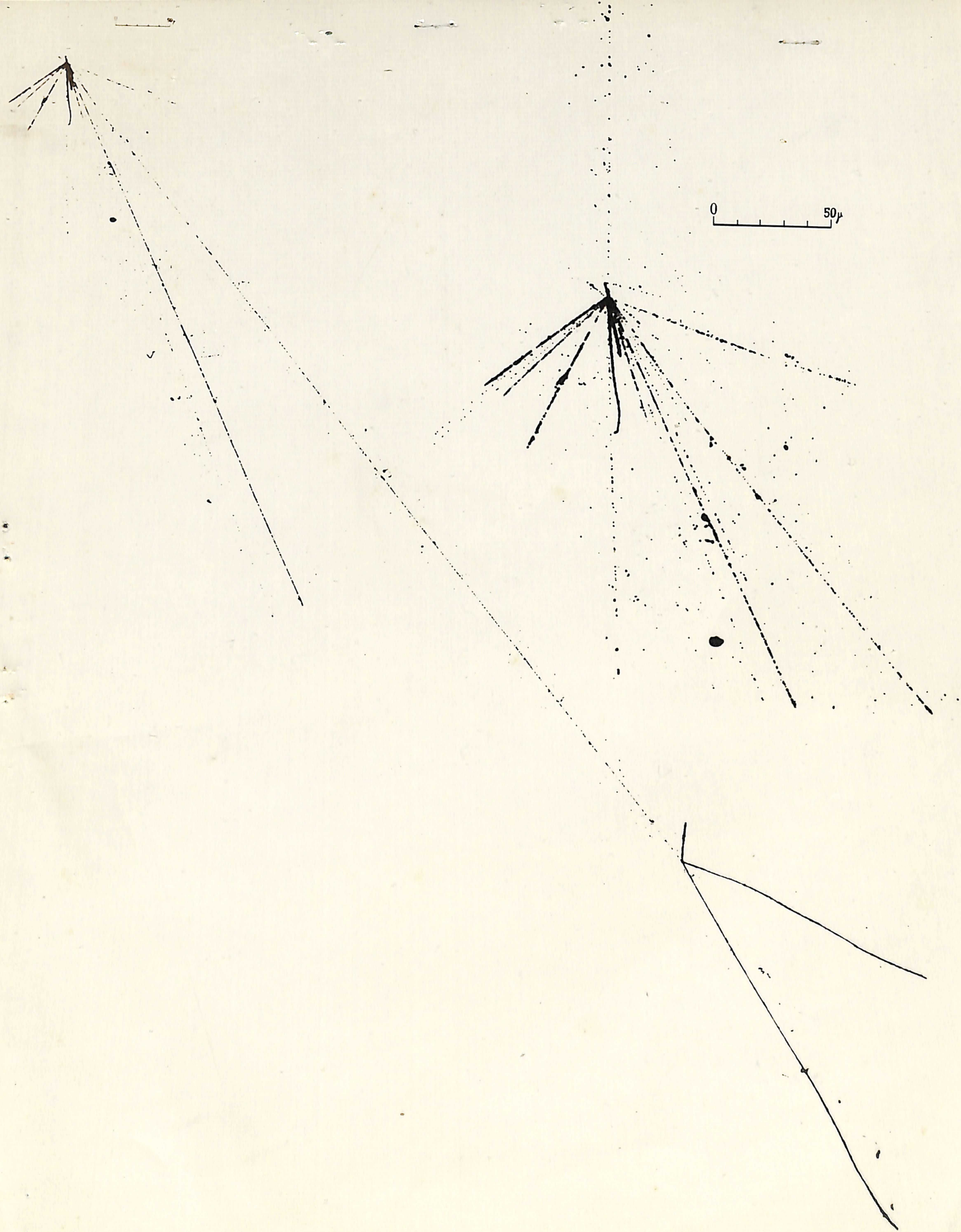
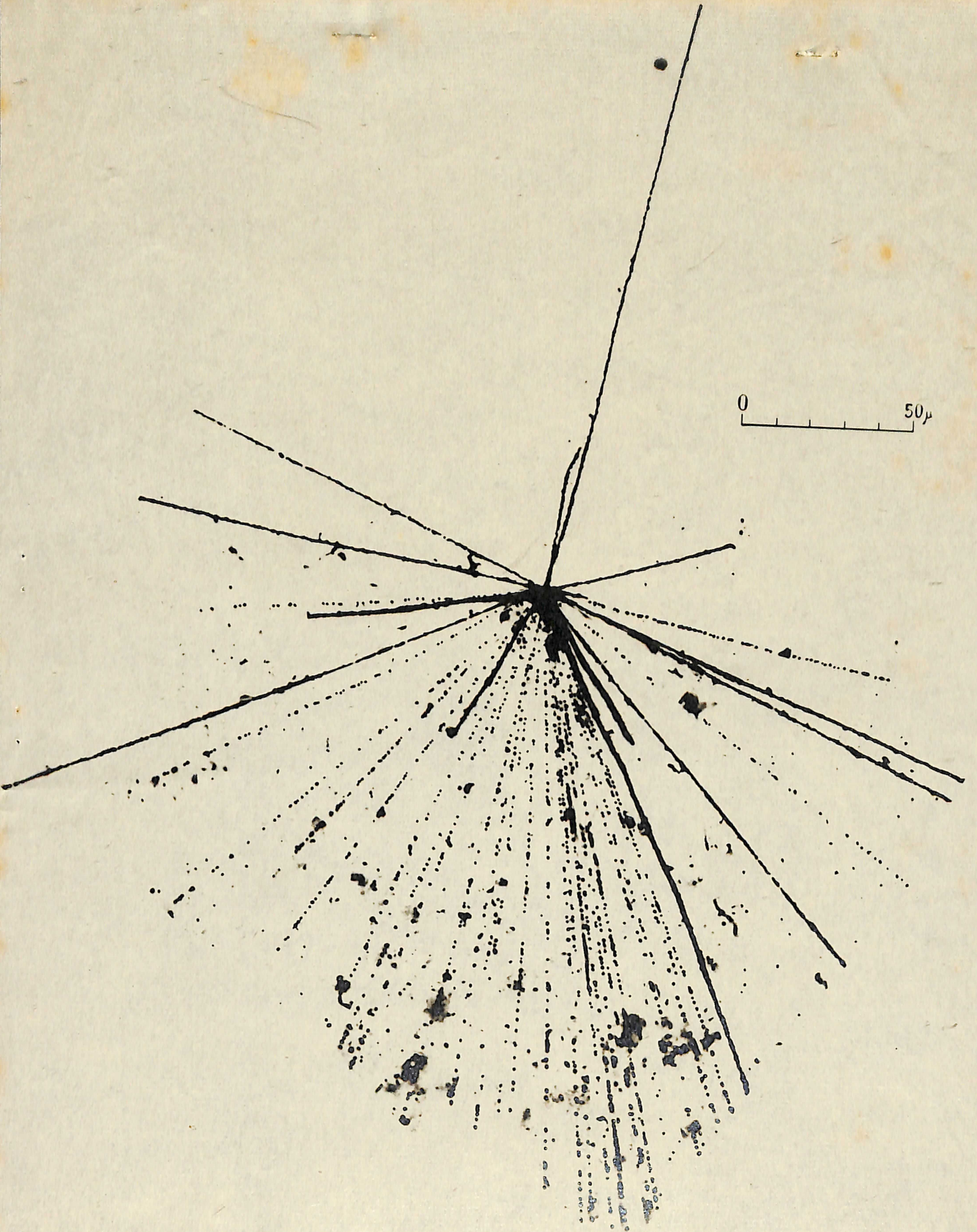


Photo 4


0
50μ


0
50μ