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Title	The Effect of an Electric Field on the Growth of Frost
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Citation	北海道大學理學部紀要, 4(6), 359-368
Issue Date	1955-12
Doc URL	http://hdl.handle.net/2115/34223
Type	bulletin (article)
File Information	4_P359-368.pdf

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[Journal of the Faculty of Science, Hokkaidô University, Japan, Ser. II, Vol. IV, No. 5, 1955]

The Effect of an Electric Field on the Growth of Frost

Chôji MAGONO and Setsuo SEKIYA*

(Received November 7, 1955)

The frost insulated electrically was produced in an electric field and the measurement of the charge on the frost was attempted by HANKEL's electrometer method. The attempt, however, failed owing to COULOMB's force between positive and negative charges induced by the polarization on the frost. It was quantitatively observed by successive photographs that the growth of frost developed along the line of force. Through the experiments, it was considered that the acceleration of growth of frost and development along the line of force was resulted from the attraction of super-cooled water droplets polarized by the electric field.

§ 1. Introdution

It was found by WORKMAN and REYNOLDS[1] that an electric charge was separated between an ice and unfrozen water during the freezing of dilute aqueous solution. They applied this phenomenon to explain the mechanism of charge separation in thunderstorms by the following model. When super-cooled water drops impinge upon a rimed ice pellet or graupel, a portion of the water of the drops freezes to the surface of the ice and the remaining portion of the water, because of splash effects, will become detached in small drops carring positive charges. If this is the case, the rimed snow crystals or graupel must be charged negatively during the growth. It may be a proper method for the decision of the propriety of their opinon to observe the sign of the charge on rimed snow crystals. The charge, however, will leak sooner or later and be affected by a selective ion capture under an atmospheric electric field. The electric sign during the growth may be common to the frost and snow if the frost is electrically insulated. In place of snow crystals, therefore, the sign of frost crystals was observed in a cold chamber by the method of HANKEL's electrometer.

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If an electric potential takes place between an ice aud water during the freezing of dilute aqueous solution, it is also supposed that in an electric field the development of the crystal to one direction is accelerated and that to the opposite direction is restrained. From this point of view, the process of growth of frost in an electric field was observed by taking successive photographs. If the form and growth of frost are affected by the external field, it may be possible to presume the atmospheric electric field by examining the form of falling snow crystal. SCHAEFER's paper[2] on the effect of an electric field in the continuous cloud chamber was very suggestive to our work.

§ 2. The Apparatus

The apparatus used for producing the frost is similar to NAKAYA's apparatus[3] for the artificial production of snow crystals except the cooling method. Our cold chamber was cooled below the freezing temperature, say, $-20°C$ from the upper side using dry ice. The vertical section of the chamber is shown in Fig. 1. The water in a beaker which was placed at the bottom was heated electrically, and warm vapor was driven by convection to the upper part where frost crystals were produced. The city water was used. The details of the upper part of the chamber is shown in Fig. 2. The thick solid lines show the section of metallic portion of the chamber. A sharpened stick of a match was sustained at the lower end of a candle which was set vertically at the center of the cooling box. Frost crystals were produced at the lower end of the stick. Two parallel plate electrodes ($1 \times 2\,cm^2$) were vertically on the both side of the stick in order to apply an uniform horizontal field to the frost. The stick which suspended the frost was insulated with the candle through which a thin lead wire passed. The wire was used to connect the frost electrically to the earth or to examine the insulation of the frost system. The examination of insulation was carried out by an ordinary aluminum leaf electrometer. The two electrodes were also insulated by candles which had the character to repel water. The insulation by the candles was very effective.

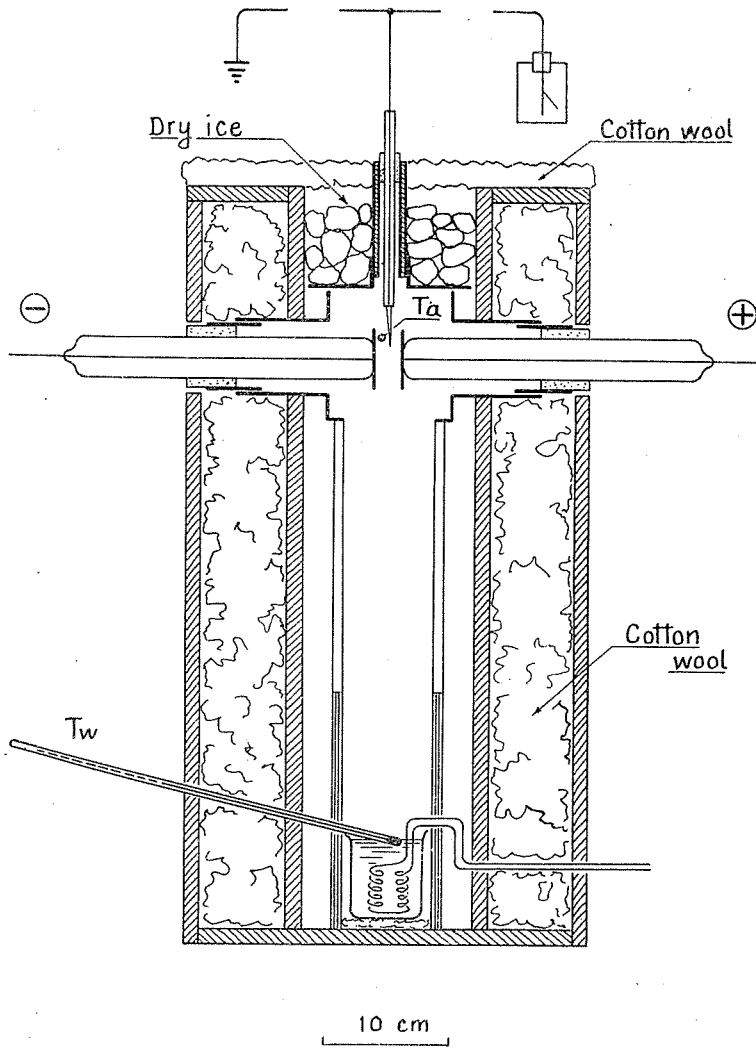

Fig. 1.

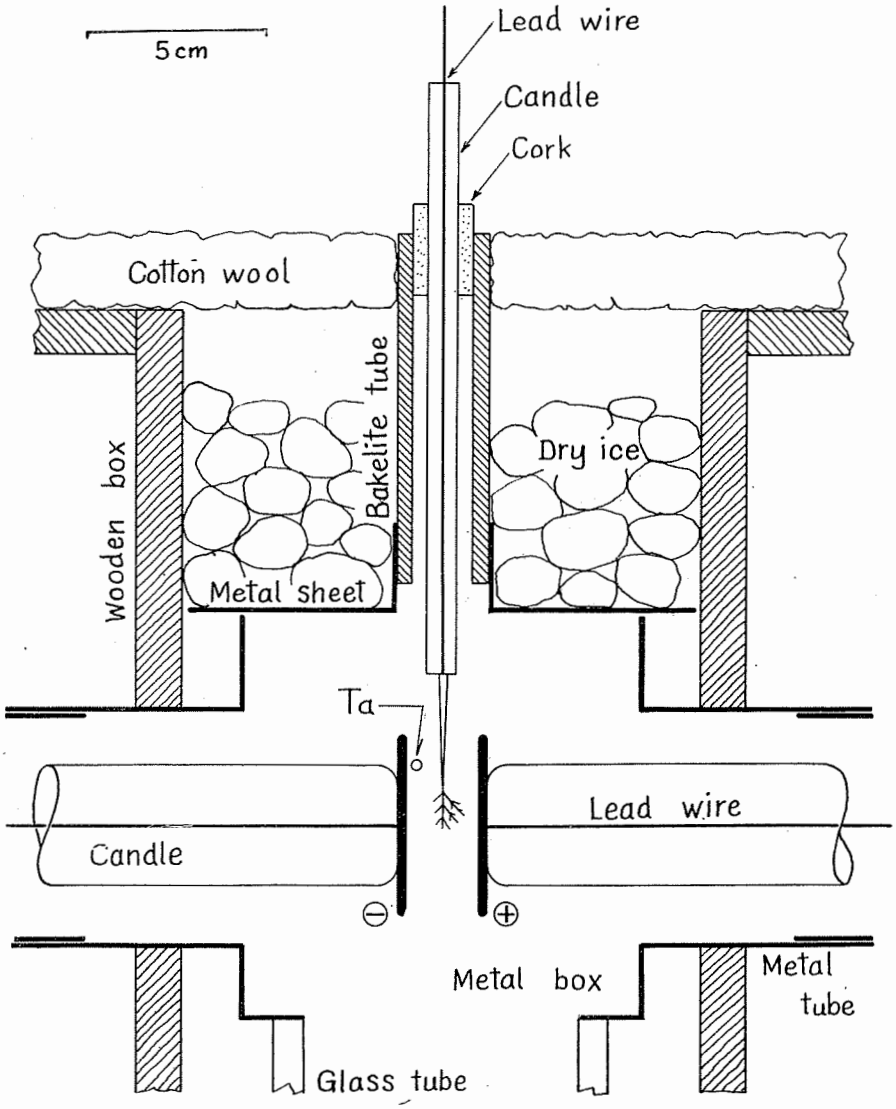
5 cm
Lead wire
Candle
Cork
Cotton wool
Bakelite tube
Wooden box
Dry ice
Metal sheet
Ta
Lead wire
Candle
Metal box
Metal tube
Glass tube

Fig. 2.

§ 3. The Measurements and Results

When negative charge of several hundreds volts was given to the stick which was insulated, the frost at the end of the stick grew rapidly as shown in Photos. a_1, a_2 and a_3, Pl. I, the electrodes having been earthed. The frost was instantaneously attracted to the right side (positive electrode) when an external field was applied, and then grew to that direction as represented in Photo. a_4. The Photos. b_1 and b_2 show the process of growth of frost in the same field as a series, when positive charge (320 volts) was given to the stick. The direction of attraction of frost was inverted to the opposite side when the field was reversed, as shown by Photos. b_3 and b_4. By the preliminary experiments, it was confirmed that the direction of attraction of frost in an external field showed the sign of the charge on the frost in our apparatus.

Hereafter, the experiments were carried out by the following procedures. At the beginning of experiments, the stick system was connected to the earth for a time, then it was insulated. If the frost which grew on the stick carries some charges, it will be attracted to one side according to the sign of its charge, when a field was applied. The pictures of c series in Pl. I show the frost produced in an external field. Photos. c_1 and c_2 shows the state of frost 3 and 11 minutes after applying the field of 550 volt/cm (left positive) respectively. It is clearly seen that the frost grows to the left side (positive electrode). When the field is switched off, the frost hangs down as shown in Photo. c_3. The frost grows not only towards the positive electrode but also it is attracted to the electrode. The frost is again attracted to the same side when the field is reversed, c_4. Repeating the experiments, the same result was always obtained. The phenomenon that the frost grows predominantly to one side, irrespective to the direction of the electric field, shows that this is not the problem of sign of charge of the frost but it must be due to the habit of our apparatus.

It is not likely that the vapor is supplied much more to the left side. The inclination of the frost did not change when the stick was rotated around its vertical axis. While moving the stick, it was found that the position of stick was an important factor.

The stick was purposely put nearer to the left electrode, the frost grew towards the left side ; d_1, Pl. II. After full growth, it touched to the frost which developed from the left electrode; d_2. Pl. II. When the stick was set nearer to the right electrode, it grew towards the right side; e_1 Pl. II. After the frost touched to the frost from the right electrode, it began to grow towards the left side ; e_2, Pl. II. It is now clear that the habit of frost growing towards the left electrode was due to the position of the stick, which was set somewhat nearer to the left electrode. The exactly neutral position, however, could not be determined because the two electrodes were neither exactly symmetrically set, nor had the exactly same dimension. The neutral position was determined tentatively by displacing the position of the stick slightly to left or right side. The example of this adjustment is shown in the pictures of f series, Pl. II. As the frost grew prevaillingly towards the left side, f_1, the stick was moved slightly towards the right side, and the frost grew uniformly towards both sides, as shown in Photo. f_2.

If the electrode plates are set exactly parallel, the field strength between them is independent of the distance from the electrode surface except near to the ends of the plates. From the fact that the position of the stick influenced the growth of frost, it was suggested that the electrostatic induction or polarization of frost was one of the factors. If this is the case, in other words, the polarization plays a main role, a similar phenomenon will be also seen when the stick is connected to the earth. In this case, the charge of the frost will exert no influence on the phenomena. Photos. g and h, Pl. II. show the frost grew in the field of 500 volt/cm, the stick being connected to the earth. The branches of frost stretched roughly perpendicularily from the surface of the stick towards the both electrodes. When the stick came nearer to the left electrode, the frost grew towards the electrode as expected; h, Pl. II. From these experimnts, it was found that we can not distinguish the sign of the charge of frost by HANKEL's electrometer method.

§ 4. The Field Strength and the Rate of Growth

In the process of the experiments, it was observed that the

rate of growth of frost was accelerated by the electric field. In order to find the relation between the field strength and the rate of growth, we observed the frost which grew from two parallel electrodes. The field strength between the electrodes was varied in the range between 200 and 1000 volt/cm, while the distance between them was kept constant at 1 cm. The air temperature near the frost was kept at approximately −20°C. The growth of frost at each of the field strengths was measured by the mean length of many frost branches sprouted from the surfaces of the electrodes. The relation between the field strength and the rate of growth is shown in Fig. 3. It was somewhat difficult to keep

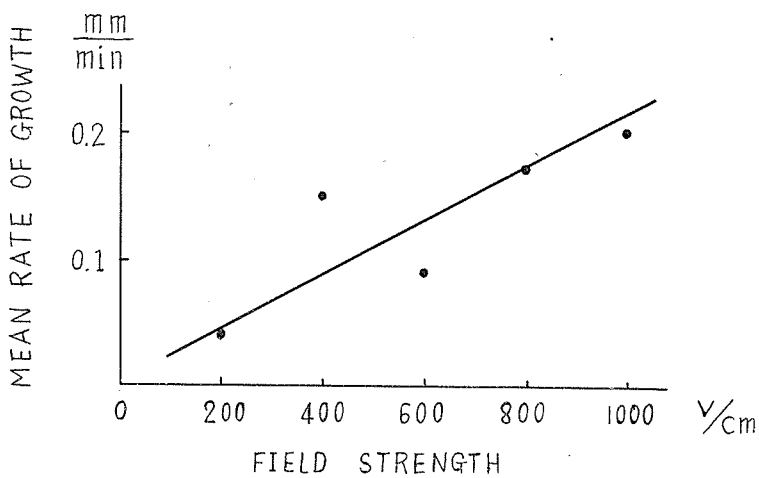

Fig. 3.

the air at a constant condition throughout these five experiments. In the case of field strength 400 volt/cm, the air temperature rose accidently from −20°C to −18°C. At the temperature −18°C, the formation of ice is considered to be more favorable than at the lower temperature, say, −20°C. Except this point, the rate of growth is nearly proportional to the field strength. Above the field strength 1000 volt/cm, a part of the frost were often torn off from the electrode surface, therefore, the maximum rate of growth may exist near the strength 1000 volt/cm as suggested by Schaefer[2]. Photos. i_1, i_2 and i_3, Pl. II show the growth of frost, 8 minutes after the field is applied. The field strengths were 200,

600 and 1000 volt/cm respectively. In this series the field was always towards the left side. All the frosts stretched perpendicularily from the surface of the electrode.

§ 5. The Line of Force and the Shape of Frost

From the pictures shown above, it is noticed that the branches of frost develop apparently along the line of force. When two needle electrodes were used, the frost developed as shown in the pictures of j series in Pl. III. The shape of frost shows a close resemblance to the figures of preliminary discharge in electric spark formation. When the branches of frosts from two electrodes come in contact with each other, the electric field is partly neutralized and the frost hungs down by gravity, j_4, Pl. III.

Twenty years ago, NAKAYA and YAMAZAKI[4] published the photographs of preliminary stage of spark formation between two electrodes of plate and needle, which were taken in a cloud chamber. Photos. k_1 and k_3, Pl. III are the reproduction of their photographs of preliminary discharge taking place in CO_2 atmosphere. Photos. k_2 and k_4 show the frosts which grow between plate and needle electrodes. It is remarkable that the shape of frosts and that of preliminary discharge of spark formation show such a resemblance with each other. The development of the branches of forst agrees fairly well with the course of ionization before the spark formation, except the effect of gravity and crystal habit of hexagonal type.

§ 6. The Discussions

The results obtained in this series of experiments are summarized as follows. i) The frosts grow along the line of force in the electric field. ii) The growth of frost is accelerated by the field and the rate of growth is approximately proportional to the field strength in the range smaller than 1000 volt/cm.

i) *The Growth of Frost and the Line of Force.*

COULOMB'S force on the tip of branch sometimes becomes so strong that the end of branch is torn off from the frost. In one experiment a drop of alcohol was left on the needle electrode, as shown in Fig. 4. When the field was applied, the drop was instantaneously drawn to the tip of the electrode.

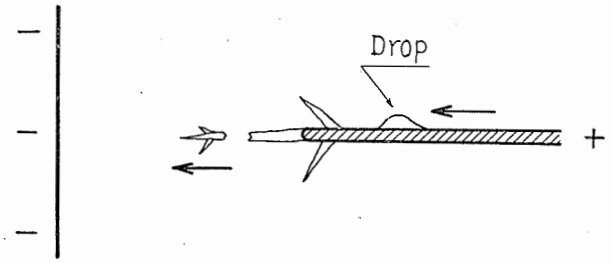

Fig. 4.

It is considered that the surface of snow or frost crystal is covered with thin layer of liquid-like film during the growth. The frost was almost rimed in our experiment, in other words, attached with numerous frozen droplets. Considering these facts, it may be accepted that a portion of the unfrozen water of the droplets attached to the frost surface is accumulated to a tip of the branch. The force is along the line of force, then the frost developes along the line of force.

ii) *The Acceleration of the Growth of Frost by an External Field.*

Schaefer reported that at a critical voltage the frost crystal grew at a rate nearly a millimeter per second. In our experiments also, the rate of a few millimeters per minute was not

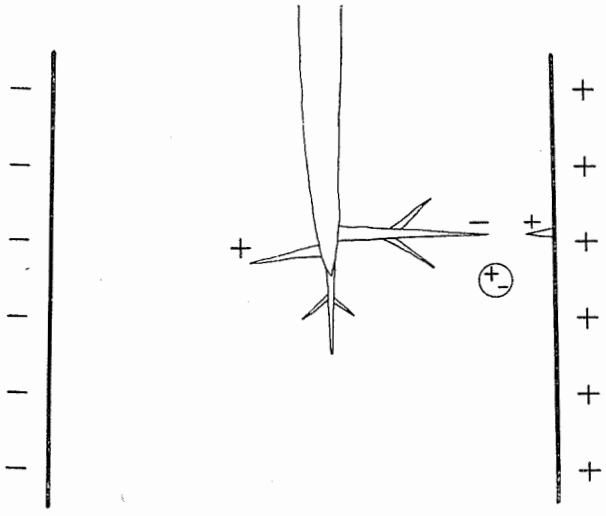

Fig. 5.

rarely observed. For explaining such a large acceleration of the rate of growth of frost by the electric field, the following consideration was made. Numerous super-cooled water droplets of diameter smaller than a hundred microns were seen near the growing frost in our cold chamber, as seen in Photo. *l*, Pl. III. These droplets are considered to be an important source for the growth of frost, because the frosts are always rimed. As pointed out by SARTOR[5], the droplets come nearer to the end of the branch of frost where the field gradient is strong, they are drawn by the force proportional to $\nabla E^2 = 2E\nabla E$ to the tip of the branch and accumulated there. The state of the polarization is schematically shown in Fig. 5. Thus the total water content in the air has the tendency to accumulate always to the tip of the branch, and the growth is accelerated.

This work was done when one of the authors at Yokohama National University. A part of the expense of the resarch was defrayed from the Special Fund for Scientific Research of Educational Ministry of Japan.

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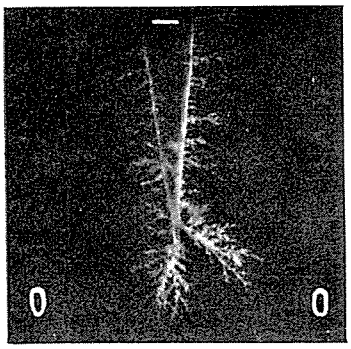
4) U. NAKAYA and F. YAMAZAKI, *Proc. Roy. Soc.* London A 153 (1936), 542.
5) D. SARTOR, *Jour. Met. Amer.*, 11 (1954), 91.



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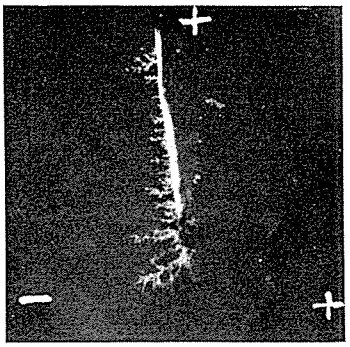

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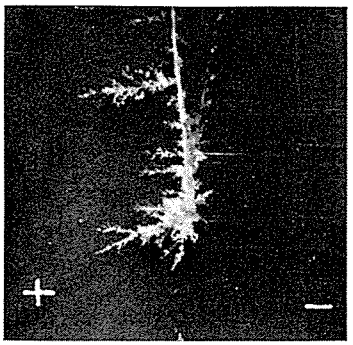

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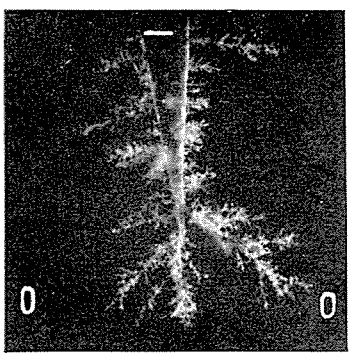

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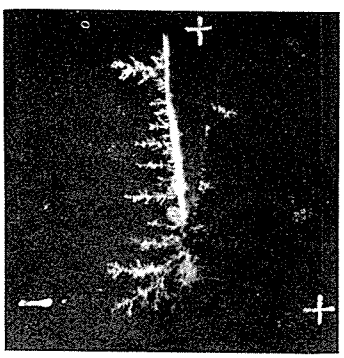

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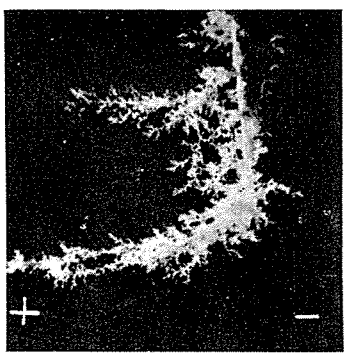

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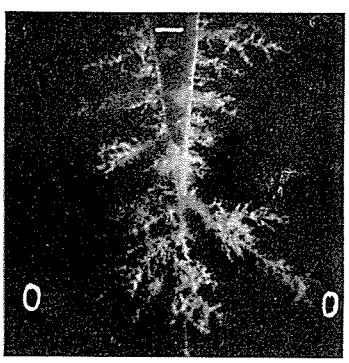

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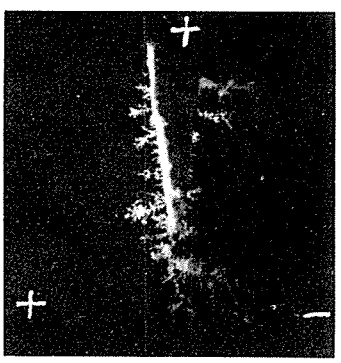

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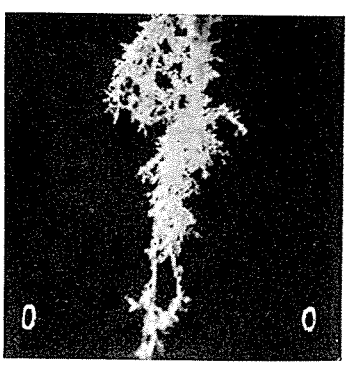

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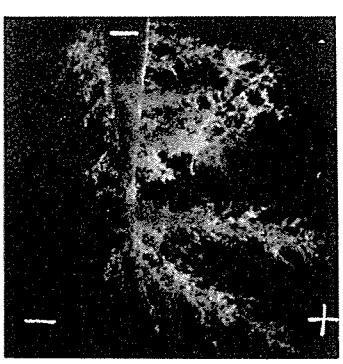

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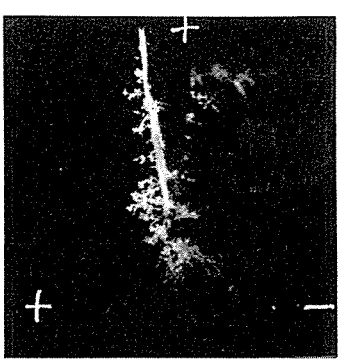

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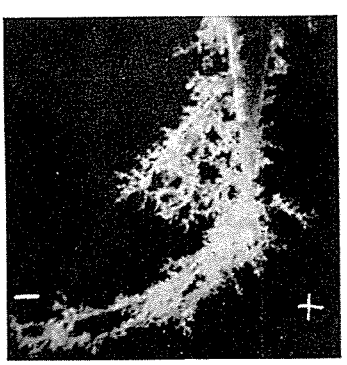

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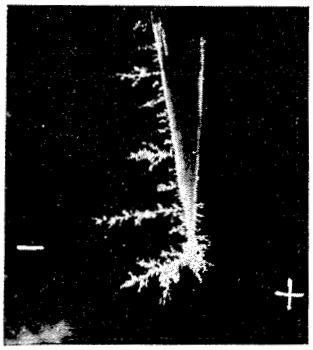

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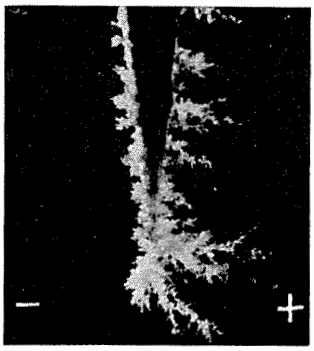

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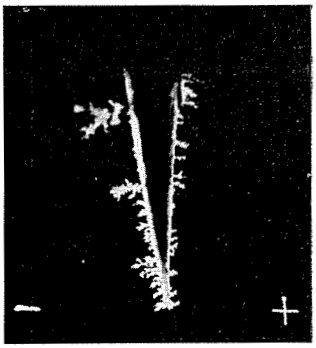

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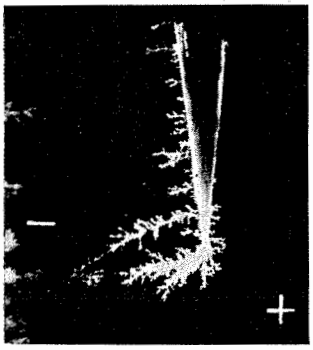

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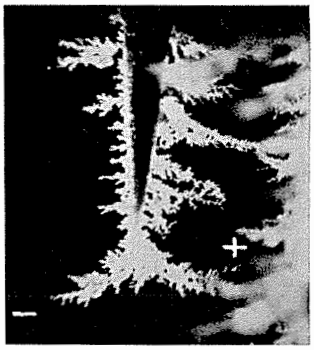

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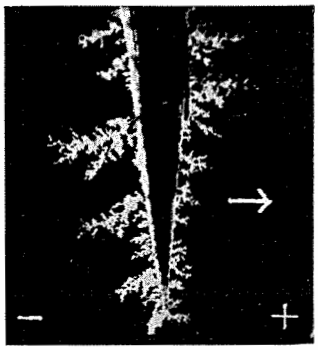

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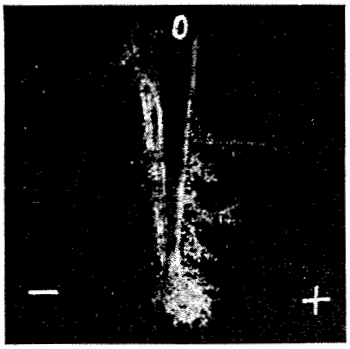

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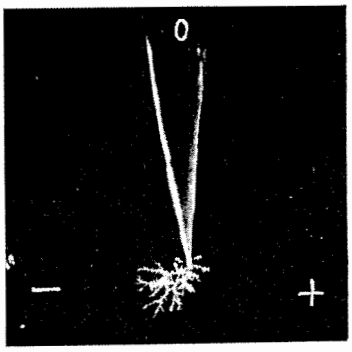

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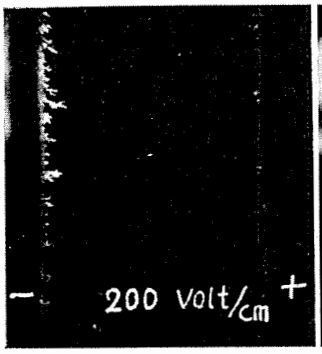

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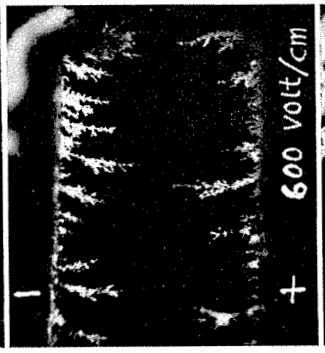

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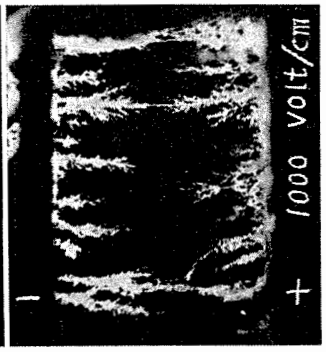

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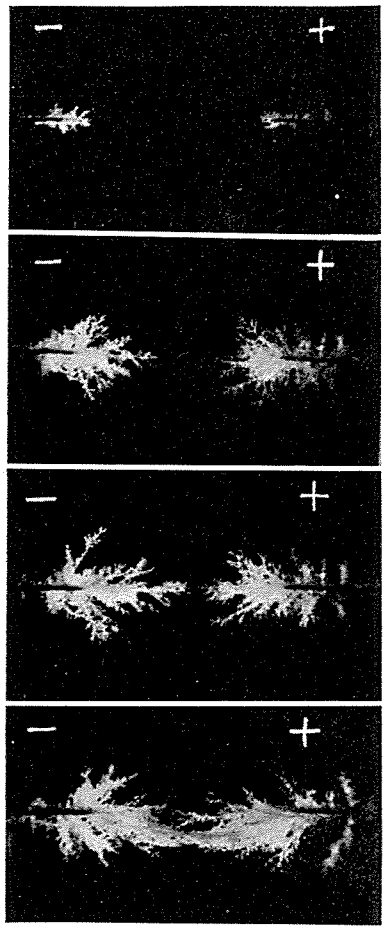

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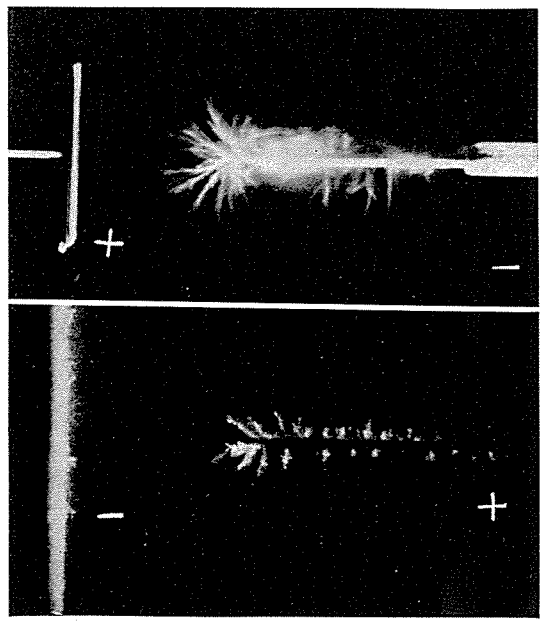

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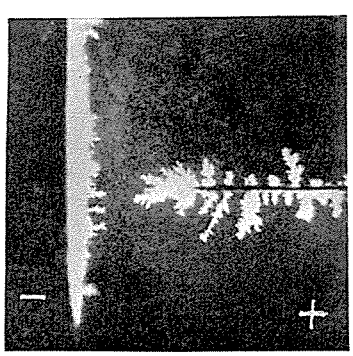

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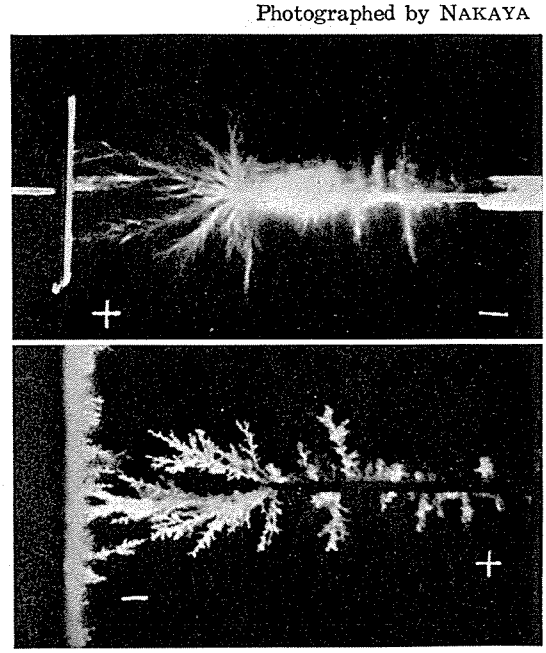

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