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Forcible Separations between Ice Crystal Charges and Their Surrounding Space Charge Densities

(Electrification Mechanisms of Snow Crystals: Part I)

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Abstract

In the laboratory, some experiments were carried out to investigate the electrification processes of ice crystals in the atmosphere. Ice crystals were separated forcibly from the atmosphere and the electric charges on ice crystals and space charge densities in the residual atmosphere were measured simultaneously.

They invariably had the opposite signs of electric charge from each other. It is noted that the signs of electric charge on ice crystals depended on the time of their life cycles in the cloud chamber, the feature of ice crystals and the seeding procedure.

However, it may be concluded by some considerations that the signs of the electric charge on ice crystals depend essentially on the humidity. When the humidity is sufficiently high, ice crystals grow vigorously and preferentially carry positive electric charges. On the other hand, when the humidity is not high, ice crystals carry negative electric charges during their slow growth and/or evaporation.

1. Introduction

It is widely accepted that precipitation elements have an important role in thunderstorm electrification. The most important elements are considered to be graupel or soft hail, which have been investigated by many workers (Reynolds, Brook and Gourley, 1957; Küttner and Lavoie, 1958; Latham and Mason, 1961; Magono and Takahashi, 1963a, 1963b) because of the strongly effective electrification in association with the riming process.

However, the electrification mechanism of snow crystals have not been investigated although it is considered that snow crystals occupy a large volume of winter thunderclouds and their electric charges contribute essentially to the electrical structure of such clouds.

Some early investigations in measuring the electric charge of natural snow crystals were done by Nakaya and Terada (1934) and Schaefer (1947).

They reported that, when non-rimed snow crystals alone fell, they carried a negative charge and as rimed crystals began to be mixed in the snowfall, a certain fraction of positively charged snow crystals were observed among negative charged snow crystals.

Magono and Orikasa (1966) carried out many simultaneous observations of electric charge of precipitation particles and atmospheric electric potential gradient on the earth surface. They concluded that clean snow crystals without riming almost always carried negative charges and then the potential gradient showed positive values in several times of fair weather values, and that generally, there was an inverse relation between the sign of precipitation charge and atmospheric electric potential graident.

Recently, Kikuchi (1975) reported that rimed snow crystals and flakes carried positive charges and clean snow crystals without riming also carried negative charges, and set forth numerous evidences with snow crystals replicas obtained for individual cases.

.Magono and Orikasa (1966) considered that the inverse relation could be explained qualitatively by Wilson's ion capture theory but which was not sufficient as a quantitative explanation.

Magono and Iwabuchi (1972) measured the electric charge on individual ice crystals in a cold room and reported that although, on the average, ice crystals carried negative electric charge predominantly, the carried positive electric charge in the temperature ranges where columnar type crystals predominated, and generally the signs of electric charge on ice crystals were found to have a temperature dependence.

Electrification mechanisms of natural snow crystals are considered the same as that of ice crystals produced in the laboratory, in spite of the difference in size between them.

It may be expected that there are some mechanisms of preferential electrification of snow crystals. The main purpose of the present study is to look for such conditions which control the electrification of ice crystals among the results of laboratory experiments.

2. Experimental Methods

The quantities of electric charge of individual ice crystals are too small to be measured and are considered to decrease because of recombination loss in the relaxation time for several tens of seconds to a few hundred seconds.

To measure the predominant electric charge of total ice crystals and to avoid the recombination loss with opposite charges between ice crystals and their surrounding atmosphere, a method of forcible separation between total ice crystal charge and total space charge except for ice crystal charge and simultaneous measurements of them were performed. The apparatus utilized is shown in Fig. 1. The apparatus was set up in a cold room. A cloud was made in left side tower in the figure with horizontal areas of 40 cm×40 cm and a height of 240 cm, by introduction of droplets from a steam supplier (A in the figure) by means of the method of warming by a double beaker used by Magono and Takahashi (1959) to avoid any charge generations.

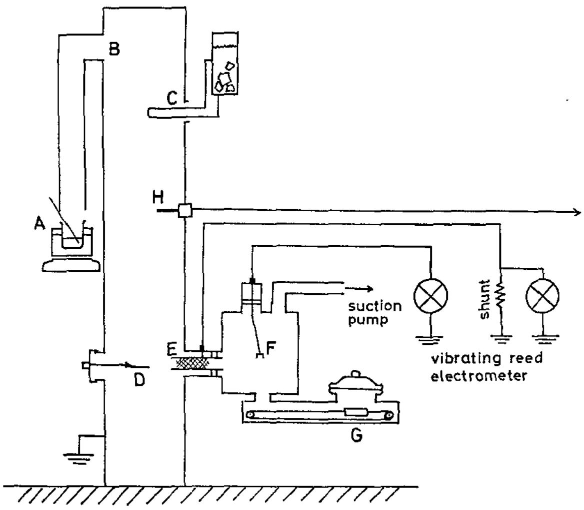


Fig. 1 Separating and measuring apparatus for electric charge of ice crystals and electric space charge of its atmosphere.
A: steam supply C: seeding point D, G: slide glass holder E: steel wool filter F: radioactive equalizer: Am^{241} H: thermometer.

When the tower was filled densely with cloud, the supplier was removed and inlet was left open.

As soon as the air temperature in the tower became nearly the same as that of the cold room and the droplets were supercooled there, seeding was done by cooling the air with a copper pipe (C in the figure) in which ethyl alcohol cooled by dry ice was circulated to prevent unexpected disturbances arising from dry ice as charge generators selected by Magono, Endoh and Inoue (1971). Then a large number of ice crystals appeared and were suspended in the air of the tower.

All ice crystals and suspended air were sucked forcibly by a suction pump and ice crystals alone were trapped by a steel wool filter, which was electrically isolated from the ground and connected to an vibrating reed electrometer for measuring of electric current due to the flow of ice crystal charge (F.i. in the figures). The adjacent metal box placed after the filter is electrically connected to the ground. At the center of the box, a piece of radioactive equalizer ^{241}Am was fixed, isolated from the ground and connected to another vibrating reed electrometer for the measurement of electric voltage due to the space charge through the box (S.C. in the figures).

These space charges are considered to be carried by small particles contained in the filtrated air with the exception of ice crystals.

Outputs from these two electrometers were connected to inputs of a dual pen recorder and simultaneously recorded. A small part of ice crystals were sampled simultaneously at the lower part of the tower (D in the figure), and photographed by a microscope during each experiment.

3. Results

It was sometimes revealed that no ice crystal passed through the filter by means of sampling slide glasses covered with silicon oil set in G of Fig. 1. Some blank tests were performed prior to measurements. The results are shown in Fig. 2, a and b. In the case of a and b, dry air alone in the cold room and supercooled droplets alone were sucked and measured respectively. It appears that no significant charge separation occurred and the values of filter currents (F. i. in the figure) and space charge densities (S. C. in the figure) were relatively small and leaned slightly toward positive sign. On the contrary, when ice crystals produced by seeding were introduced in the volume of specimen, even at the beginning of measurement, they shifted at the same time to the opposite direction to considerable large values. It is considered that a clear large charge separation occurred between ice crystals and their surrounding space. It is noted that the peak values of space charge (S.C.) in the case of c is larger by three hundred times of that in the case of a.

Two couples of typical results are shown in Figs. 3 and 4. These experiments were performed under nearly the same conditions of temperature, amount of droplets and seeding procedure except t: the time elapsed from the instant of seeding to the onset of suction and measurement. The signs of ice crystal charge in experiment 135 and 137 of Fig. 3 and experiment 149 and 147 of Fig. 4 are seen to be negative and positive respectively. It is

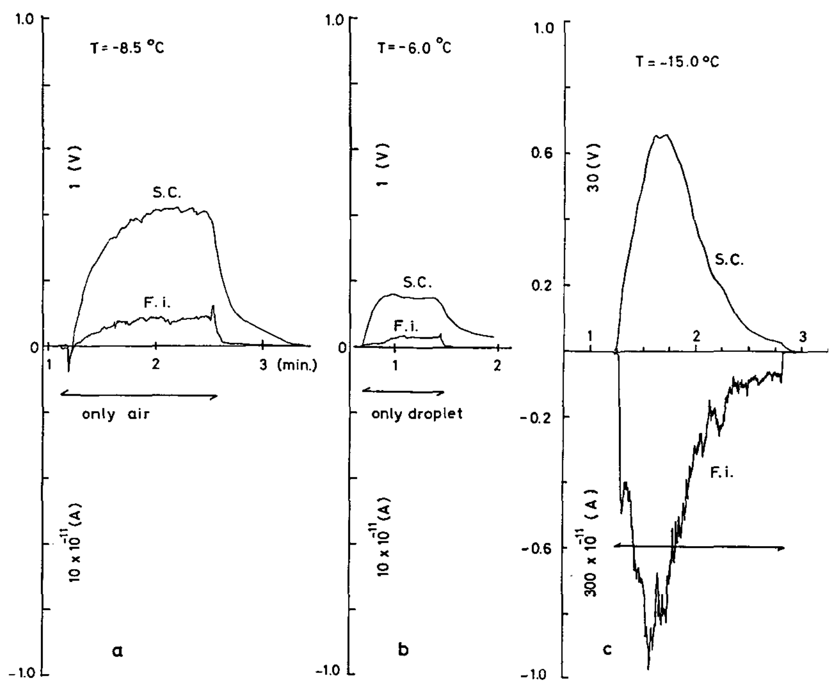
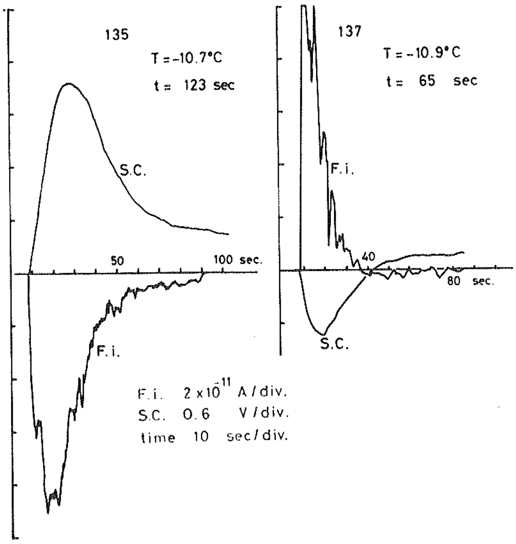


Fig. 2 Blank test and example of measurement.
F.i.: electric current from filter by electric charge of ice crystals.
S.C.: electric potential at the center of a Faraday cage by electric space charge in atmosphere around ice crystals. Arrow marks indicates the duration of suction by pump. a, b: blank test. c: measurement with ice crystals.

considered that these cases corresponded to the late and early stage of the period of ice crystal life time respectively. In both cases it was noted that the signs of ice crystal charge (F.i.) and its surrounding space charge (S.C.) were the opposite from each other. The pictures of ice crystals obtained at each experiment are shown in the lower half of these figures. In a comparison between these two couples of photographs, the size of ice crystals in experiment 137 and 147 (early stage) are larger than that in experiment 135 and 149 (late stage), and regarding the number of ice crystals, the former is less than the latter. Concerning the shape, ice crystals in 137 and 147, and 135 and 149 have clear sharp edges and rounded edges respectively.

All results of 73 experiments are classified into three types, and are summarized in frequency distribution histograms versus t as shown in Fig. 5.



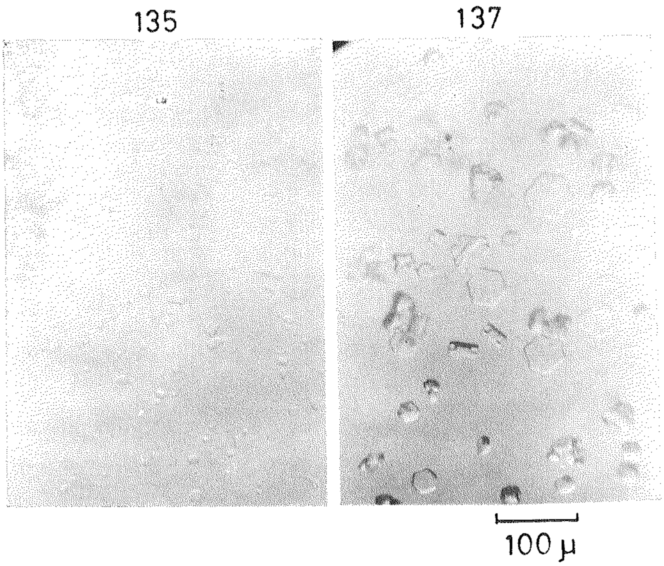


Fig. 3 Simultaneous measurement of electric charge of ice crystals (F.i.) and electric space charge of its atmosphere (S.C.).

F.i.: electric current from filter by electric charge of ice crystals.

S.C.: electric potential of the center of a Faraday cage by electric space charge in atmosphere around ice crystals.

t: waiting time for onset of measuring from seeding. Onset of measuring is early in 135 and late in 137.

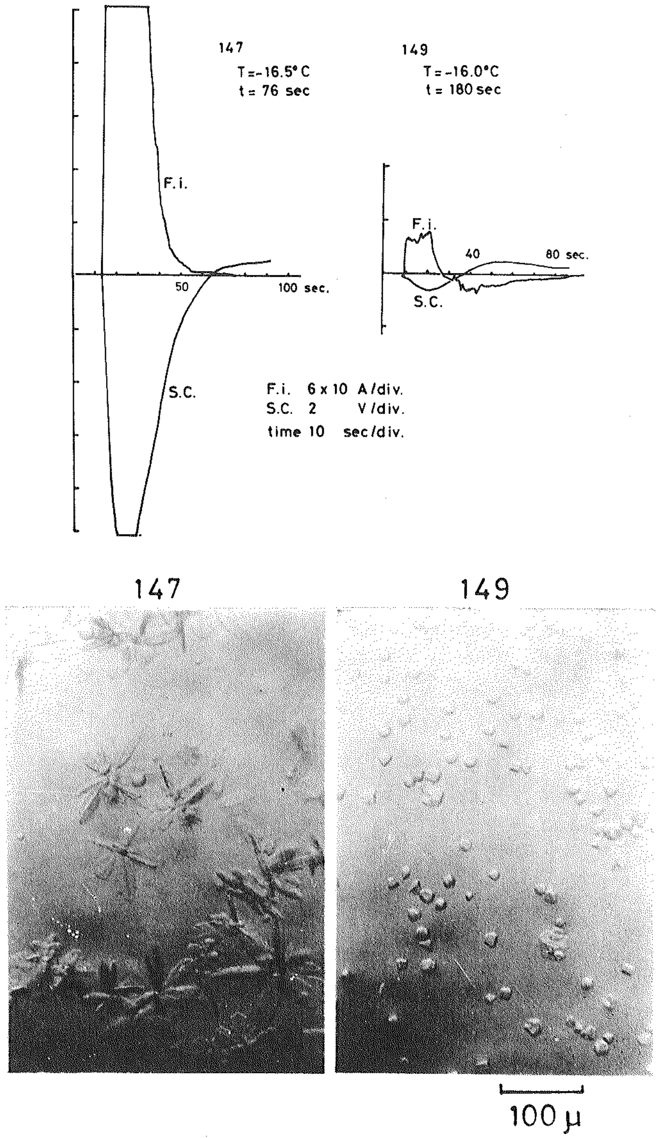


Fig. 4 Simultaneous measurement of electric charge of ice crystals (F.i.) and electric space charge of its atmosphere (S.C.).

F.i.: electric current from filter by electric charge of ice crystals.

S.C.: electric potential of the center of a Faraday cage by electric space charge in atmosphere around ice crystals.

t: waiting time for onset of measuring from seeding. Onset of measuring is early in 147 and late in 149.

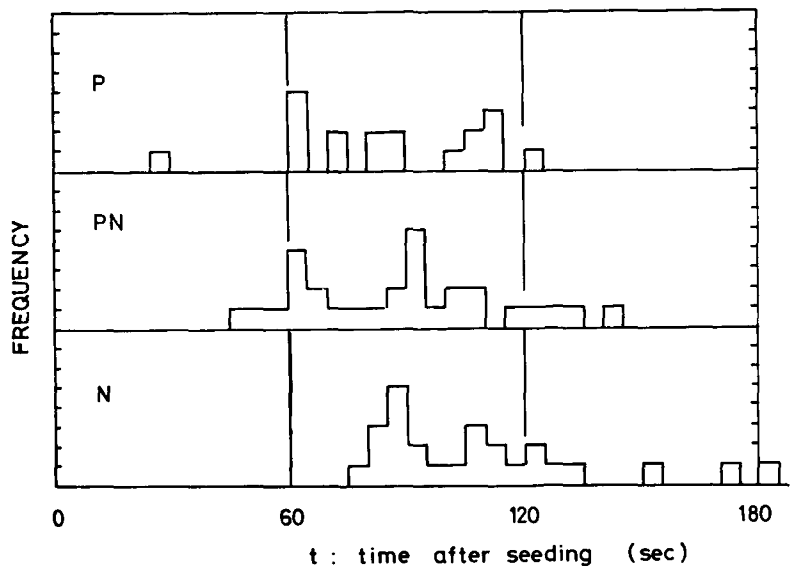


Fig. 5 Occurrence frequency of three types of time variation of F.i. versus time from seeding to onset of measuring. P and N: allover negative and positive respectively. PN: reversal from positive to negative.

Upper P and lower N in the figure show the cases in which ice crystals carried, allover positive and negative electric charges alone respectively. And middle PN shows the case in which the sign of ice crystal charge was positive at the beginning and changed to negative from the middle to the final of measuring duration.

Furthermore, some additional experiments were carried out by means of different procedures. Experiment 184 and 186 of Fig. 6 were performed in the intentional experiments of under seeding and over seeding. Although the air temperature was nearly the same and was −16°C or thereabouts in both cases, the duration of setting the seeding pipe in the tower (C in Fig. 1) were several seconds and several minutes in experiment 184 and 186 respectively. In the case of under seeding (184), ice crystals predominantly carried positive electric charges. On the other hand, in the case of over seeding (186), although ice crystals carried positive electric charge at the beginning, after that they continued to carry negative electric charges until the end of measurement. The feature of ice crystals in under and over seeding seems to correspond respectively to that of the early and late stage of the ice crystal life cycle previously mentioned.

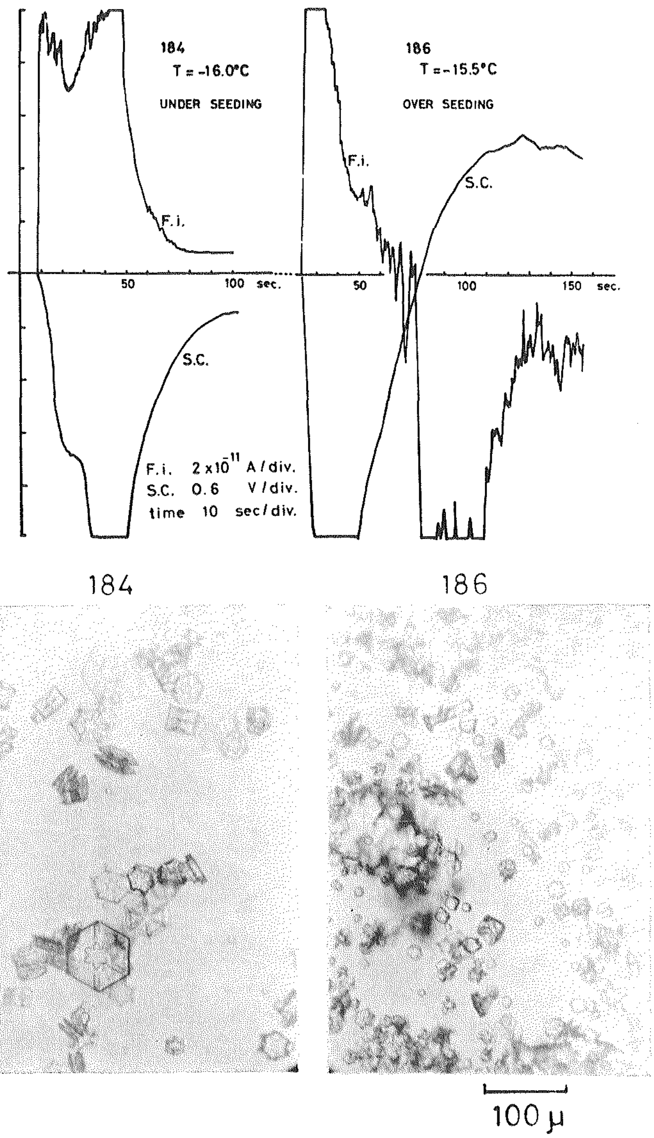


Fig. 6 Simultaneous measurement of electric charge of ice crystals (F.i.) and electric space charge of its atmosphere (S.C.).

F.i.: electric current from filter by electric charge of ice crystals.

S.C.: electric potential of the center of a Faraday cage by electric space charge in atmosphere around ice crystals.

t: waiting time for onset of measuring from seeding. 184: under-seeding, 186: over-seeding.

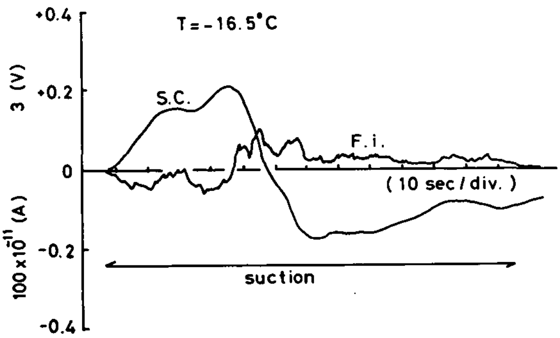


Fig. 7 Examination of reversal of sign of F.i. from negative (t=120 sec) to positive by means of late steam supply.

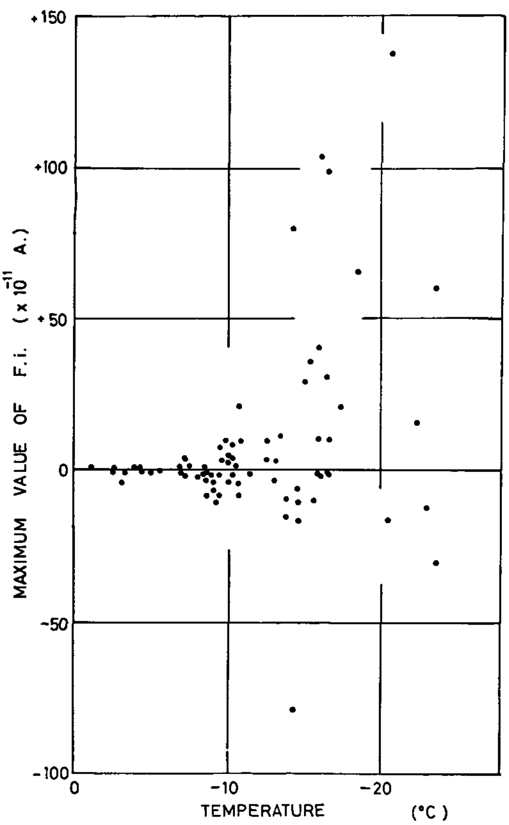


Fig. 8 Temperature dependence of electric charge of ice crystals.

Although the inlet of introduction of droplets (A in Fig. 1) was usually left open during the suction and measurement, droplets were deliberately supplied during suction and measurement, continuously in the experiment as shown in Fig. 7. There at the beginning filter currents (F.i.) were negative but changed to positive as freshly supplied droplets arrived at the filter and the space charge (S.C.) changed at the same time completely maintaining an inverse relation between them.

Maximum values of the time change in filter currents (F.i.) of all data obtained are plotted versus the condition of air temperature in Fig. 8. It appears that the quantities of electric charge on ice crystals clearly increased with the temperature decrease.

4. Consideration

It is noted that the features of ice crystals obtained in every experiment differed depending on the growing stages of their life cycle in the cloud chamber. In the early stage, ice crystals were relatively large in size, scarce in the number densities and showed sharp growing edges in their peripheries. On the contrary, in the late stage, ice crystals were small in size, numerous in the number densities and showed dull rounded peripheries. According to these feature of ice crystals and the time of their life cycles when they were sampled, the growth situation of ice crystals treated in the present experiment may be described as followings.

Generally, seeding tended to be somewhat in an over-seeding state. Therefore, in the early stages after seeding up to several tens of seconds, a number of minute crystals were generated and they were suspended at the upper part of the tower and did not begin to fall immediately. They merely formed ice crystal clouds alone and stagnated there. As a small amount of the lower part of the ice cloud descended into the zone of supercooled droplet clouds beneath them, they acquired abundant moisture from supercooled droplets, showed a sudden growth and began to fall downward. On their way down, they grew increasingly and spread out in almost all of the space of the tower except for a small volume of ice cloud in the upper part. Therefore a greater part inside of the tower was occupied by well-grown large ice crystals. On the other hand, in the later stage from several tens of seconds to a few hundred seconds after seeding, most of supercooled droplets were scavenged by the former ice crystals. And there were ice crystals alone which were minute in size but numerous in the number. The ice crystals left were considered to grow very slowly, or not to grow further or even begin evaporating.

Time changes of the signs of electric charge on ice crystals are summarized in Fig. 5 versus t: the time elapsed from the instant of seeding to the onset of suction and measurement which are considered to correspond to the time of growing stages of ice crystals in the apparatus above mentioned. In the figure, time changes of electric charge on ice crystals are divided into three types of P, PN and N. In every type, the distribution of occurrence versus t are seen to spread considerably. However, noting the distributed ranges of the case P, PN and N, they are seen to lie over 30–120 sec, 45–145 sec and 75–185 sec respectively. It appears that there are some appreciable tendencies of ice crystal charge depending on the time elapsed from seeding to the onset of suction and measurement.

It may be considered that ice crystals in the early and late stage of their life time, carried preferentially positive and negative electric charges respectively. In the former stage, since there was sufficient humidity, the ice crystals grew vigorously. On the other hand, in late stage, when the humidity was not abundant, it is considered that ice crystals grew slowly or stopped growing and that in some cases they began to evaporate. And the residual air except for the ice crystals always had the opposite signs of electric space charge against that of ice crystal charge. It is considered that the situation of under and over seeding corresponded exactly to that of the early and late stages of ice crystals respectively, according to the experimental results such as the feature of ice crystals, seeding procedures and the signs of electric charge on ice crystals.

The above-mentioned considerations may be reconfirmed by performing an intentional experiment as shown in Fig. 7. When residual ice crystal carrying negative charges in poor humidity were again supplied with sufficient humidity due to the overtaking droplets, ice crystal charges turned to positive.

These considerations are summarized in Table 1 in association with experimental results.

These experiments seem to have a questionable problem whether the filtration process may cause any secondary charge generations, namely the riming process or not, because the suction velocity was as high as 7 m/sec. In blank test, when droplets alone were sucked, no significant charge generations were observed. Furthermore, from the temperature dependence shown in Fig. 8, no electric effect of secondary ice production could be found around –6°C, which were observed by Hallett and Saunders (1980). Since ice crystals

Table 1 Summary of relation of experimental results and considerations.

Experimental results	Experimental procedure;	Measuring time Seeding	early under	late over
	Measured polarity of electric charge on ice crystals		positive	negative
	Feature of ice crystal;	Size Number Shape Existent droplets	larger moderate sharp, fragile a few	smaller too many round no
Consideration	Moisture around ice crystal		sufficient	insufficient
	Situation of ice crystal		growing	evaporating or slowly growing

observed were smaller than 100 μm in diameter, naturally no riming marks were seen on them. Since it seems to be difficult to examine the microphysical phenomena in the filtering process, it is desirable that these results will be verified by different methods.

5. Conclusions

Ice crystal charges and their surrounding space charge densities could be separated forcibly by means of a filter method and simultaneously measured successfully. Considerable amounts of electric charge separation were observed, as long as ice crystals were contained in the measured atmosphere. It is noted that these two charge separates always carried the opposite sign and had nearly equal quantities of electric charges as each other.

It was found that the sign of ice crystal charge depends on the time of ice crystal life cycle in the cloud chamber used. In the early and late stage, ice crystals carried predominantly positive and negative electric charge respectively, and the features of ice crystals depended on the same parameters. According to these conditions it may be considered that above-mentioned electrical properties of ice crystal depend essentially on the humidity conditions around them.

It may be concluded that ice crystals in their growing courses preferentially carry positive electric charges and when ice crystals grow slowly or stop growing or even begin to evaporate, they carry preferentially negative electric charges.

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