On the Mechanism of The Pure Electric Breakdown of The Solid And Liquid Insulators.*

By

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Contents.

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I.) Introduction.

In accordance with the enormous progress of high tension transmission, it is increasingly essential to study the electric breakdown of the solid and liquid insulators.

Unfortunately, however, knowledge on the electric breakdown of those materials is very meagre and theories on this subject put forward until now have given very little explanation on the phenomenon. In recent years, studies on the electric breakdown of gas, liquid and solid insulators, have been made by many experimentors. Study on gas insulator has been thoroughly performed, but studies on the liquid and the solid insulators have been as yet very imperfectly done.

Until now, it has not been distinctly known whether the solid and liquid insulators is broken down by thermal action or by electric. For instance, STEINMETZ & HAYDEN,(1) A. GEMANT(2) and H. EDLER(3) etc. considered that the breakdown of the liquid insulator is caused by the liquid vapour produced by the heat. H. EISLER(4) considered it may be caused by the electric action, but done by the static ion. W. O. SCHUMANN(5) and F. PEEK(6) thought the breakdown of the liquid insulator was the same as that of the air and that it was due to the ionization by collision of the electron.

According to A. NIKURADSE,(7) the breakdown of the liquid insulator may be due to the ionization by collision of the electron and there are two kinds of electric breakdown in the liquid, viz., the first is a direct breakdown of the liquid and is called "Ionization breakdown"; the second is the breakdown caused by the gas adsorbed on the electrodes or in the liquid and is called "Non-ionization breakdown", but it is not a thermal phenomena, as asserted by H. EDLER.(8)

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(1) STEINMETZ & HAYDEN: A. I. E. E. Jan. 1924, p. 36.
(2) A. GEMANT: Zeits. f. Techn. Phys., 9. 1928. p. 398.
(3) E. EDLER: Arch. f. Elektrot. 24. 1930. p. 37.
(4) H. EISLER: Zeits. f. Phys. 79. 1932. p. 366.
(5) W. O. SCHUMANN: Vertr. Ber. d. Studienges. f. Hochspannungsanlagen. 1926.
(6) F. PEEK: Dielectric Phenomena in High Voltage Engineering, 1930.
(7) A. NIKURADSE: E. u. M. 50. 1933. p. 465.
(8) H. EDLER: Arch. f. Elektrot. 24. 1930. p. 37.

Rather, it is due to the breakdown of the combined dielectrics, i.e. ionization by collision occurs at first in the absorbed gas film, and then the molecules of the liquid are ionized. Later, Y. TORIYAMA & S. SAWA(1) studied on the dust figure under a liquid and concluded that there are not two kinds of breakdown as A. NIKURADSE asserts, but only one. Recently, A. NIKURADSE(2) also concluded that the breakdown of the liquid is brought about only by the ionization of the liquid molecule itself. In short, it may be true that the breakdown of the liquid insulator may be cause by the pure electric action and moreover it seems due to the ionization by collision of the electron.

The most recent study, by Y. TORIYAMA and the present author,(3) on the breakdown of the liquid insulator from the spectroscopical point of view, has distinguished the pure electric breakdown and the pyro-electric or thermal one. In the pure electric breakdown of the liquid, the dissociation of the molecule due to ionization must be brought about, and it corresponds to the dust figure of twig-like form. But the pyro-electric or thermal breakdown may be caused without the dissociation of the molecule due to ionization and corresponds to the dust figure of leaf-like form which rather depends on the conductivity of the liquid and other factors. The space charge may be produced and the potential distribution near the electrode may be changed, but these have no direct relation to the pure electric breakdown. That is, the pure electric breakdown is due to the electronic phenomena, but the pyro-electric or thermal one is due to the ionic.

Next, on the breakdown of the solid insulator, there are at present, three kinds of theory, i.e. the thermal, the thermal-electric and the pure electric theory. On the thermal theory according to K. W. WAGNER,(4) the solid is broken down by the heat due to the current. But W. ROGOWSKI(5) modified this theory and stated

(1) Y. TORIYAMA and S. SAWA: Memo. of the Fac. of Eng. Hokkaido Imp. Univ. Japan. 3. 1933. p. 83.
(2) A. NIKURADSE: Zeits. f. Phys. 84. 1933. p. 701.
(3) Y. TORIYAMA and U. SHINOHARA: Denki-Hyoron (Electrical Review, published by Kyoto Imp. Univ., Japan,) Jan. 1934.
(4) K. W. WAGNER: J. A. I. E. E. 41. 1932. p. 1034.
(5) W. ROGOWSKI: Arch. f. Elektrot. 13. 1924. p. 153.

his belief that the specific resistance of the solid is the function of the temperature and the field strength. This theory is called the thermal-electric theory of the solid insulator. But those theories cannot explain thoroughly the experimental results secured with the impulse voltage. Hence, the solid insulator has been considered to be broken down only by purely electric action; this is the pure electric breakdown theory. On the pure electric breakdown theory, there are two kinds of opinion, viz., the first considers the solid to be broken down by the mechanical force due to the impressed voltage, while the second, by the ionization by collision of the electron. The former was held by W. ROGOWSKI,[(1)] G. E. HOROWITZ[(2)] etc., but it does not agree with the experimental results and so the latter may be considered as the right one at present. This idea is supported by BRAUNBECK,[(3)] A. JOFFÉ,[(4)] L. INGE-A. WALTER,[(5)] A. v. HIPPEL[(6)] and R. WIDERÖE[(7)] etc.

In 1930, L. INGE-A. WALTHER[(8)] obtained the partial breakdown of glass and rocksalt, and thereafter the study on the breakdown of the solid insulator has made progress. A. v. HIPPEL[(9)] considered the partial breakdown or the streamer in rocksalt to have relation with the crystal axis, i.e. it extends out towards the face of the dodecahedron. From this fact, he deduced the mechanism of the breakdown of the solid; and he mainly described on his paper about the electron conduction in the solid. Moreover, the fundamental basis of his theory, that the streamer in rocksalt extends out towards the

(1) W. ROGOWSKI: Arch. f. Elektrot. 18. 1927. p. 525.
(2) G. E. HOROWITZ: Arch. f. Elektrot. 18. 1927. p. 535.
(3) BRAUNBECK: Zeits. f. Techn. Phys. 7. 1926. p. 391.
(4) A. JOFFÉ: Phys. Zeits. 1927. p. 148, or The Physics of Crystal, p. 162.
(5) L. INGE-A. WALTHER: Arch. f. Elektrot. 24. 1930. p. 259. Zeits. f. Phys. 64. 1930. p. 830. Phys. Zeits. der Sowjetunion. 3. 1933. p. 284.
(6) A. v. HIPPEL: Zeits. f. Phys. 67. 1931. p. 707; 68. 1931. p. 309; 75. 1932. p. 145.
(7) R. WIDERÖE: Arch. f. Elektrot. 26. 1932. p. 626.
(8) L. INGE-A. WALTHER: Arch. f. Elektrot. 24. 1930. p. 259.
(9) A. v. HIPPEL: Zeits. f. Phys. 67. 1931. p. 707; 68. 1931, p. 309. 75. 1932. p. 145.

face of the dodecahedron, is contradicted by L. INGE-A. WALTHER.(1) According to the experimental results by INGE-WALTHER, the direction of the streamer in rocksalt is not only limited to that towards the face of the dodecahedron, and it is changed with the polarity of the applied voltage and the temperature. That is, the direction of the streamer is not constant. From the experimental results by A. v. HIPPEL himself, the direction of the streamer in NaBr, KI etc. is also undeterminate. Hence, the fundamental basis of HIPPEL's theory may be doubted.

In this paper, the author has studied on the streamer in crystal and obtained from the experiments the following results. That is, it is entirely due to the method of the voltage application whether the direction of the streamer has relation with the crystal axis or not, and the results of HIPPEL or INGE-WALTHER show only a part of the facts. Besides, the writer has studied on the properties of the streamer in solid and liquid insulators, and has experimentally elucidated the fact that the characteristics of the streamer in solid are the same as of the streamer in liquid insulators and that those streamers are produced by the ionization due to electron impact. Moreover, the mechanism of the pure electric breakdown of the solid or of the liquid insulators has been deduced and the relation between the breakdown of the solid or of the liquid and that of the air has been cleared up.

II.) On The Pure Electric Breakdown of Liquid Insulators.

In the former studies on liquid or solid insulators, the breakdown voltages under the several conditions are usually measured. But the mechanism of the electric breakdown cannot be thoroughly known from those results if the partial breakdown of those materials are not studied. That is, consideration of the partial breakdown of the liquid and the solid insulator, or the streamer in those materials,

(1) L. INGE-A. WALTHER: Phys. Zeits. der sowjetunion 3. 1933. p. 284.

is most important and most suitable in the study of the mechanism of the electric breakdown of those materials just as a study of the corona is important in that of the gaseous insulator. Hence, the partial breakdown, or the streamers in liquids, such as transformer oil, glycerine, paraffinum liquidum, petroleum, xylol, toluol, hexan, gasoline and distilled water have been studied. In many cases arising in practice, the moisture, gases and impurities contained in the liquid insulators effect their breakdown voltage; therefore purified liquids only are used in the following experiments. Fig. 1 is the impulse

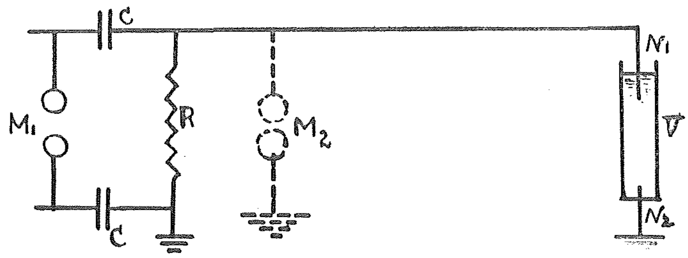


Fig. 1.

generator used throughout the experiments. M_1 is the sphere gap of 5 cm. diameter, C is the Meirowsky high tension condensor of 0.0177 m.f., R is the water rheostat, V is the glass vessel and N is the needle electrode. The needle electrode in this case is covered with a glass tube which prevents the streamer along the liquid surface. Moreover, the tip of the needle electrode is made as sharp as possible to produce the streamer in liquid when the lower voltages are used.

1) On the Pure Electric Breakdown of Distilled Water.

First, the experimental results on distilled water, which may be considered to have a comparatively simple construction, will be described. When the applied voltage on the needle electrode N is increased gradually, the streamer will come in sight at the tip of the electrode in the water. That is, a red streamer such as Fig 2, first, appears and then is stretches in all directions like a thread as Fig. 3, and finally it becomes as Fig. 4. The streamer in water has a twig-like form and the colour of it is red. If it is photographed with the lens, Fig. 5. is obtained. In this case, very small bubbles

Fig. 2.

Fig. 3.

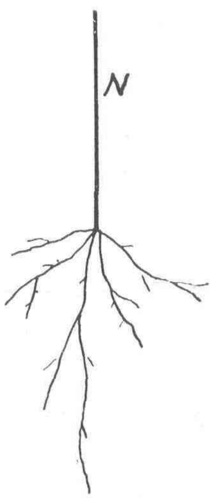


Fig. 4.

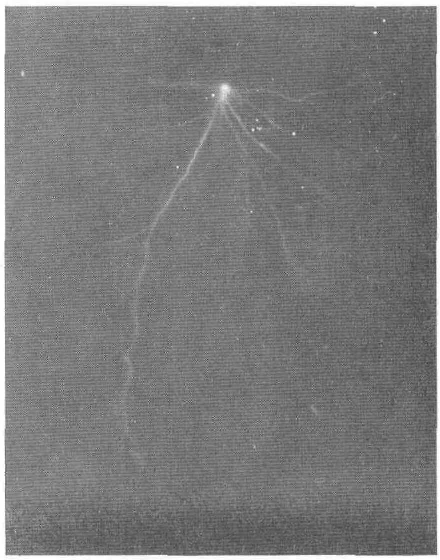


Fig. 5. Red streamer in water due to the unchopped wave.

are formed with the streamer. The streamer is more easily produced when an electrode of smaller radius of curvature is used.

Generally, the characteristics of the streamer in liquid do not differ with the polarity of the applied voltage, except in length.

The form of the negative streamer in liquid also takes a twig-like form and not a circular one as that of the air, but the length of the negative streamer is smaller than that of the positive as shown in Fig. 6. From this relation, it is known that the length of the streamer is generally proportional to the applied voltage.

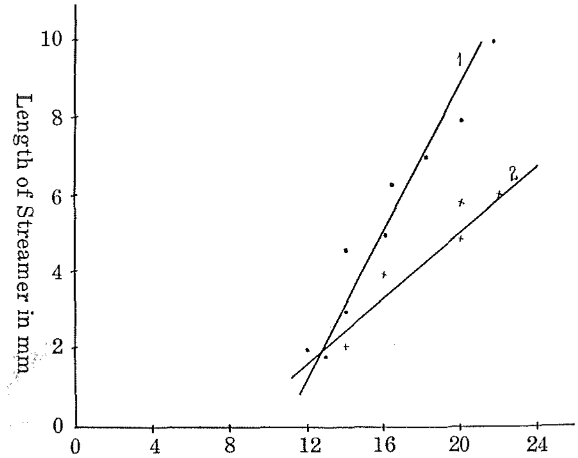


Fig. 6. Streamer in water to be produced with the unchopped wave.

The above results have been obtained with the unchopped impulse voltage, but different results are obtained if the chopped wave is applied. When the impulse voltage from the impulse generator of Fig. 1, is chopped with gap M_2, a white streamer as shown in Fig. 7, is obtained. That is, the colour of the streamer in water is changed from red to white. Now, if the gap length of gap M_1 is kept constant and the length of gap M_2 is increased gradually, the white streamer due to the chopped wave also extends out as shown in Fig. 8, i.e. the relation between the elongation of the streamer and the applied voltage is a linear one just as is the previous one.

With increase of the width of gap M_2, the chopped position moves toward the wave tail. When the impulse wave is chopped at

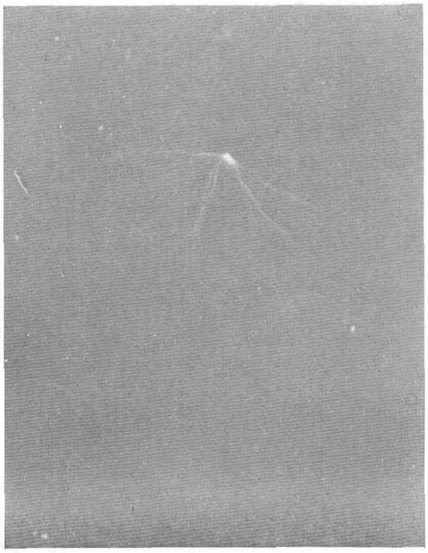


Fig. 7. White Streamer in water due to the chopped wave.

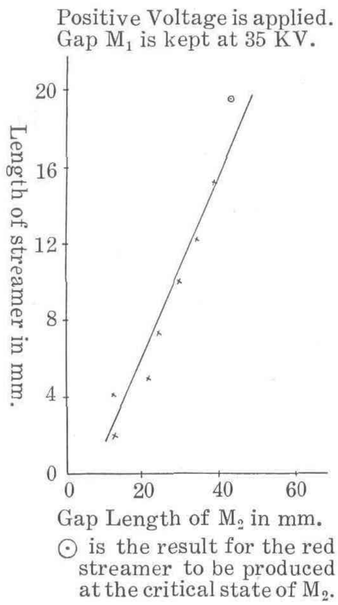


Fig. 8. Streamer in water to be produced with the chopped wave.

the wave top, the white streamer is torn to pieces and changes to a red one, i.e. the red streamer under this condition contains a pieces of the white streamer. But it finally becomes a pure red streamer as the previous one if the applied voltage is not chopped. In a word, the red streamer is obtained at the wave tail of the impressed voltage, or it is known that a considerably long time interval must intervene before the red streamer appears.

When the applied voltage, either chopped or unchopped, is increased gradually, the streamer in water extends out to a further distance, and no changes can be observed on the streamer until the breakdown is brought about. That is, either the red streamer or the white one extends out as it is until the spark-over. Hence, when the sparks due to the chopped wave and unchopped one are examined with the spectorograph, there is a difference between them exactly like that between the streamers. (An enormous shock may be exerted upon the wall of the vessel if the breakdown takes place. Hence the glass vessel ($10\times10\times12\times cm^3$) is shattered only with a spark).

2) On the Pure Electric Breakdown of Glycerine.

The breakdown of glycerine has been also studied and the characteristics of the streamer in glycerine found to be the same as those in water, but the effect of the duration of the applied voltage does not so easily appear on the glycerine as on the water. When the chopped wave is applied, a streamer of white twig-like form appears, a crowd of small bubbles is formed in company with it and a crowd of small bubbles of funnel-shape remains in the glycerine for a while as shown in Fig. 9, because the glycerine is very viscous.

However, the same results as above stated can be obtained even when the applied impulse wave is not chopped. But, when a very long impulse wave produced from the other impulse generators than that of fig. 1, is applied, the effect of the duration of the applied voltage appears; the colour of the streamer becomes bluish white and the spectrum of hydro-carbon will appear in addition to the continuous spectrum.

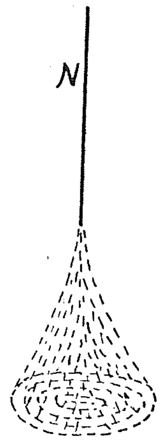


Fig. 9.
Bubbles in the glycerine.

3) On the Pure Electric Breakdown of Transformer Oil, Petroleum etc.

The breakdown of transformer oil, petroleum, gasoline, xylol, paraffinum liquidum etc., was also studied, and similar results were obtained for every liquid. For instance, the effect of the duration of the applied voltage also appeared even on the transformer oil. The two kinds of streamers, i.e. the streamer of a bluish fine thread and the streamer of a white twig-like form, are observed to exist in the transformer oil. It is no wonder that the two kinds of streamers may exist in the liquid, because the liquid has a complicated structure and the dissociation may be performed in several ways.

III.) On the Pure Electric Breakdown of Solid Insulators.

1) Method of Investigation.

As stated above, the partial breakdown or the streamer in solid insulator must be investigated if it is desired to know the mechanism of its breakdown. In fact, it is very difficult to obtain the partial breakdown of a solid insulator. L. INGE-A. WALTHER and A. v. HIPPEL[1] only barely obtained that of glass and rocksalt after their utmost efforts in a recent year. The present author has also studied on the partial breakdown of the solid insulator and devised the following method to get it. When this method is used, the partial breakdown or the streamer in solid insulator can be very easily obtained, and thorough studies made on the properties of the streamers.

When a very fine needle electrode is sealed in the bottom of a thick walled glass tube G and inserted in the liquid L, such as water or glycerine, as shown in fig. 10, the higher potential gradient appears at the tip of the electrode and the partial breakdown or the streamer in solid insulator can be easily obtained. (It is better to fill the gap between the needle electrode and the inner wall of the glass tube with mercury or some liquid insulator.) Moreover, the other electrode N_2 lies remote from the glass tube and then a complete breakdown between N_1 and N_2 does not occur even when a higher voltage is applied on the needle electrode N_1. Hence, the injury to be caused by the arc which follows after the breakdown of a solid insulator, is checked, and the procedure of the breakdown can be clearly observed.

In the case of the test of longer sample such as the glass tube, it is most suitable to use the method of fig. 10. But, if only a small sample is used, the method of fig. 11 may be profitable. A small hole in which the needle electrode is to be inserted, is dug into the sample,

(1) loc. cit.

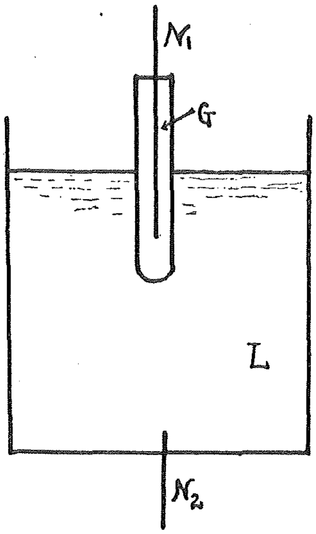


Fig. 10.
N: needle electrode
L: liquid
G: glass tube

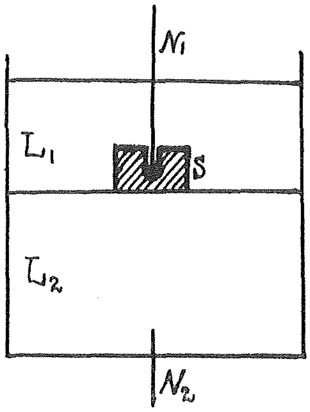


Fig. 11.
N: needle electrode
L: liquid
S: sample

which is placed on the surface of separation of two parallel liquids as shown in fig. 11. In this case, it is better to use water and a liquid of lower specific gravity and higher breakdown voltage; accordingly I have generally used water and parafinum liquidum. In this case, if small bubbles or small drops of the water are mixed in the parafinum liquidum, its breakdown voltage diminishes to a lower point, and then it is necessary to renew those liquids at every repetition of the experiments.

2) On the Pure Electric Breakdown of An Amorphous Substance.

A glass tube 9 mm. in diameter and 100 mm. in length, sealed at one end and blown into a sphere, is placed in a water bath as shown in fig. 10, and the impulse voltage is applied to the needle electrode N_1 in the glass tube. When the applied voltage is raised gradually, a point of white light is seen at the tip of the electrode and then it becomes a white twig-like streamer. The streamer in solid is more luminous than that in the air and can be photographed with the lens as fig. 12. It is noted that the appearance of the streamer in glass is entirely the same as that in water due to the chopped

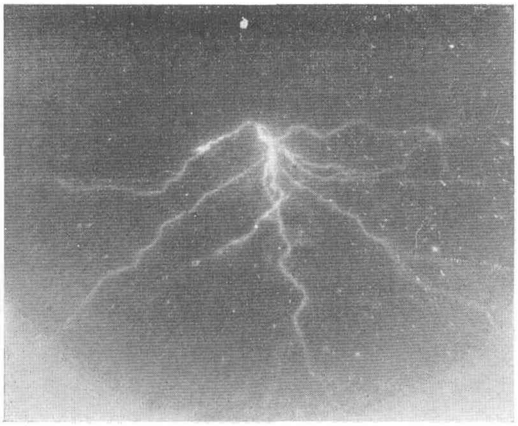


Fig. 12. Streamer in glass.
(magnification 30)

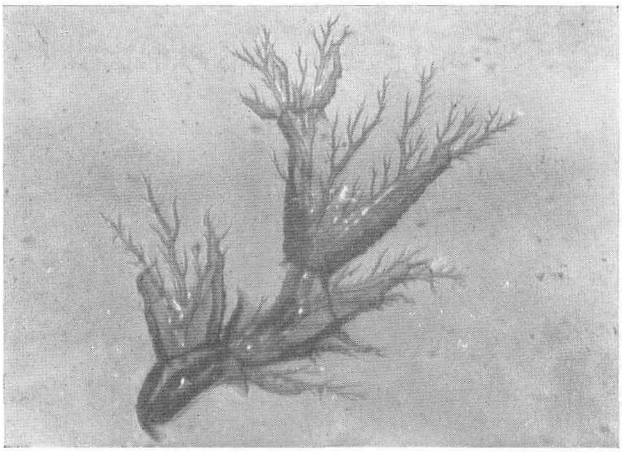


Fig. 13. Scabs due to the streamer left in the glass.
(magnification 50)

wave. When the streamer has been produced, scabs of a twig-like form are left behind in the glass as shown in fig. 13 and fig. 46. If a part of scab remainder is magnified, it becomes as shown in fig. 14. That is, cracks appear along the streamer. When the crack in the glass is larger, it appears even on the streamer itself as shown in fig. 15. In short, the crack may be produced in company with the streamer and plays an important rôle in the breakdown of the solid insulator.

When the applied voltage is raised still more, the streamer extends out a further distance and pierces through the glass tube. If the tip of the streamer just reaches to the outside of the glass tube, a fine channel is made through it and a very small hole is left on

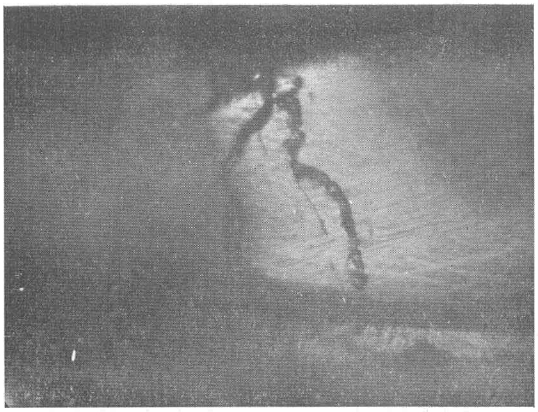


Fig. 14. Scabs due to the streamer left in the glass. (magnification 150)

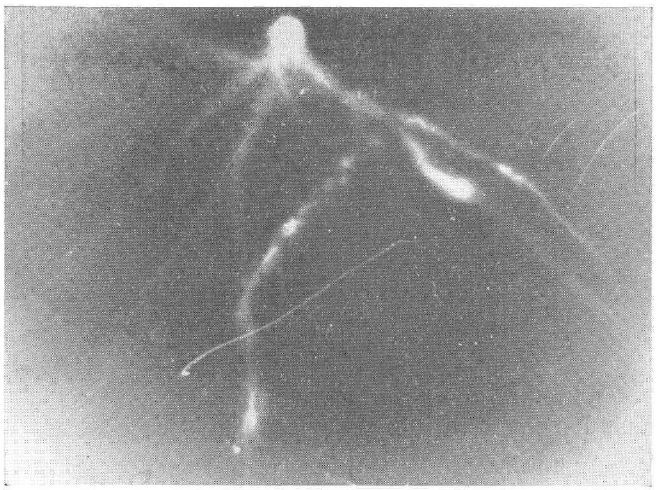


Fig. 15. Streamer in glass. (magnification 30)

outside of the glass tube without fail. If the other electrode N_2 should be contacted with the sample, the current would pass through the fine channel and an arc would be produced. But, in fact, when the other electrode N_2 lies remote from the sample as shown in fig. 10, the breakdown is checked at this point. In a word, the solid insulator is broken down just at the instant the streamer has pierced through it. The same relation as the above can be also obtained with the unchopped wave (10^{-5} sec.), i.e. the effect of the duration of the applied voltage scarcely appears in the breakdown of the solid. Moreover, the properties and the appearance of the streamer do not change with the polarity of the applied voltage, except the length of the streamer. Either the positive streamer or the negative has a white twig-like form and they extend out proportionally with the applied voltage as shown in fig. 16. The length of the negative streamer is generally less than that of the positive.

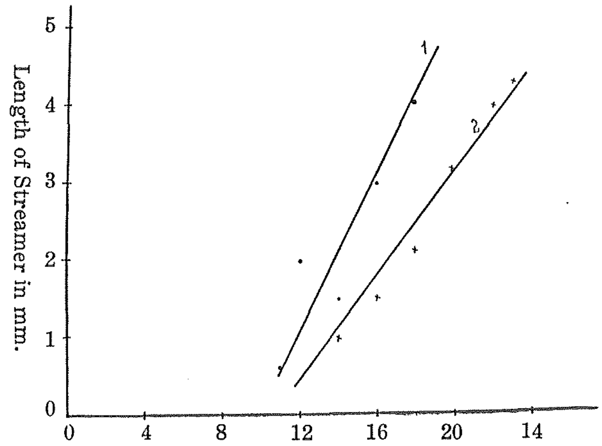


Fig. 16. Streamer in glass.

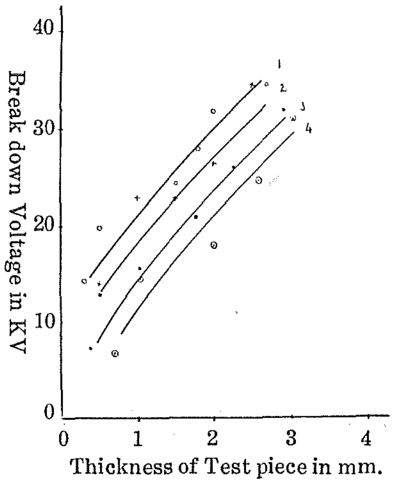
It must be noted that the streamer in this case is extended out from one of the electrodes N_1 and the other electrode N_2 is not concerned in it at all. That is, the streamer in this case corresponds to the positive streamer in the air. The solid insulator is broken down by the positive streamer itself. Hence, the properties of the streamer in solid differ entirely from those of the positive streamer in the air. Besides, the positive and the negative streamer in solid have entirely the same properties and the solid can be broken down by only the positive or the negative streamer itself. From these facts it may be seen that the positive and negative streamers in solid insulator are fairly good conductors.

3) Effect of the Crack Upon the Breakdown of the Solid Insulator.

From fig. 14, it is evident that the scabs left in the solid due to the streamer consist of small cracks. Hence, the crack may be produced in company with the streamer and plays an important rôle in the breakdown of the solid insulator. But it has been cleared up from the experimental results that the solid insulator can not be broken down only by the mechanical force due to the impressed voltage, but it is done by the ionization by collision of the electron. Hence, the crack may be produced after the ionization of the solid molecule, because the bonds between the atoms may be cut off if the solid molecule be ionized and dissociated. For example, let us consider the rocksalt. According to the experimental results of F. ZWICKY,[1] the tensile strength of rocksalt is about 6.3×10^7 dyn/cm^2. If one wants to obtain the mechanical force of this amount, the potential gradient of 5.3×10^6 volt/cm must be imposed. As rocksalt is broken down by the potential gradient of 2×10^6 volt/cm[2], the mechanical force of about one third the tensile strength may act on the molecule when the breakdown occurs. When the molecule has been ionised and dissociated, a considerable effect may be caused by the mechanical force due to the impressed voltage and a crack will be produced. When the cracks once appear in the solid, the over-potential gradient is produced at the tip of the crack and the molecule of the solid will be easily ionised, i.e. the solid will be easily broken

(1) F. ZWICKY: Phys. Zeits. 124. 1923. p. 131; or H. GEIGER & K. SCHEEL, Handbuch d. Phys. Bd. 24. p. 447.
(2) L. INGE and A. WALTHER: Zeits. f. Phys. 71. 1931. p. 627.

down. Therefore, it may be entirely due to the crack that the impulse ratio for the solid insulator is much lower than that for the liquid as shown already by L. INGE-A. WALTHER.(1) In addition, the author has compared the breakdown voltage of a brittle material and that of a viscous one of like nature to ascertain the effect of the cracks upon the breakdown voltage of the solid. The breakdown voltage of glass, liquid glass, sugar candy and caramel (at 40°C) have been measured and the results as shown in fig. 17 are obtained. The breakdown voltage of the brittle matter is lower rather than that of the viscous. In short, the crack plays an important rôle in the breakdown of the solid insulator.



1. Caramel at 40°C
2. Liquid glass
3. Glass plate
4. Sugar candy

Fig. 17.

4) On the Pure Electric Breakdown of Crystals.

With the method of fig. 11, studies have been made on the partial breakdown or the streamer in crystals, such as the single crystals of calcite, tartaric acid, alum, sugar candy, quartz, copper sulphate, magnesium sulphate, ammonium nickel sulphate and potassium iodide etc. Under this procedure, an exceedingly higher potential gradient can be imposed on the sample and the streamer in crystals can be easily studied. When the higher potential gradient due to the chopped wave (10^{-7} sec. or less) is imposed on the sample, the streamer of a twig-like form, such as fig. 18–23, only is obtained. That is the streamer in this case is independent of the direction of the crystal axis.(2)

(1) L. INGE & A. WALTHER: Arch. f. Elektrot. 27. 1933. p. 99.

(2) This result is not doubtful because cracks can be obtained which have no relation with the crystal axis, even by the mechanical shock itself. (c. p. S. IWASAKI; Text-Book on mineralogy. p. 174.)

Fig, 18. Streamer in tartaric acid.
(magnification 30)

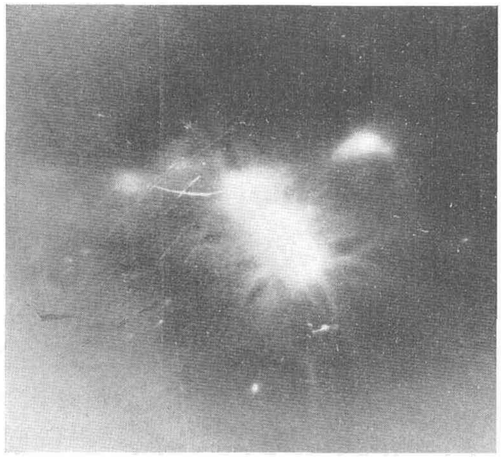


Fig. 19. Streamer in sugar candy.
(magnification 30)

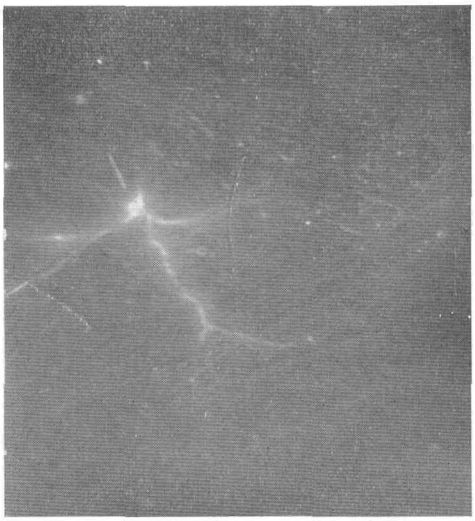


Fig. 20. Streamer in calcite.
(magnification 30)

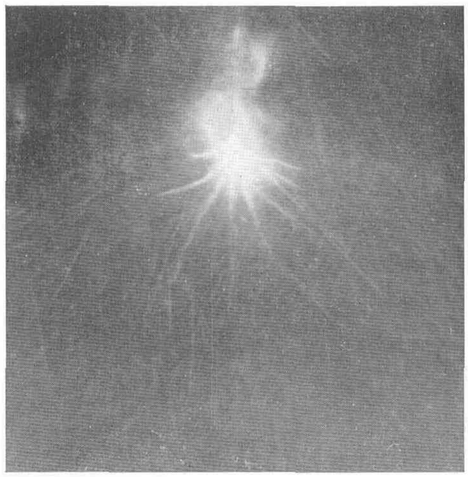


Fig. 21. Streamer in Alum.
(magnification 30)

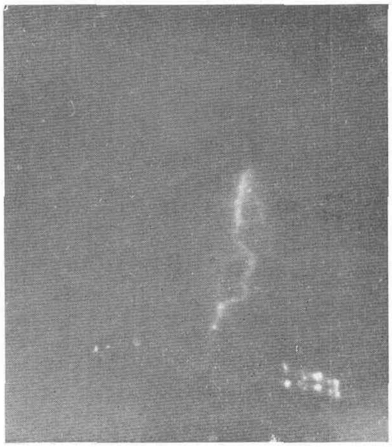


Fig. 22. Streamer in quartz.
(magnification 30)

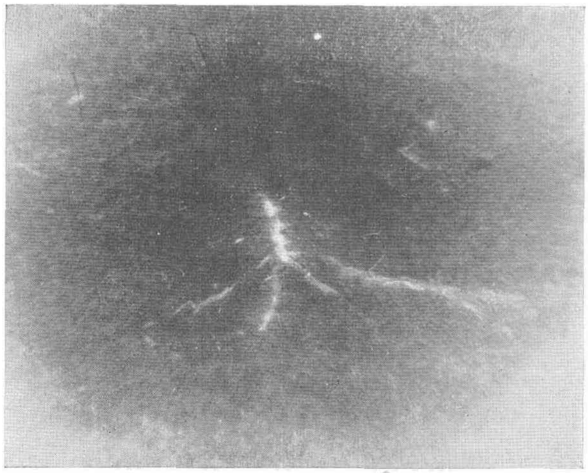


Fig. 23. Streamer in magnesium sulphate.
(magnification 30)

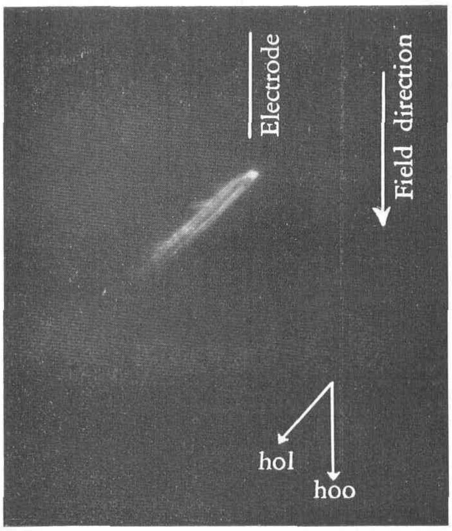


Fig. 24. Streamer in tartaric acid.
(magnification 10)

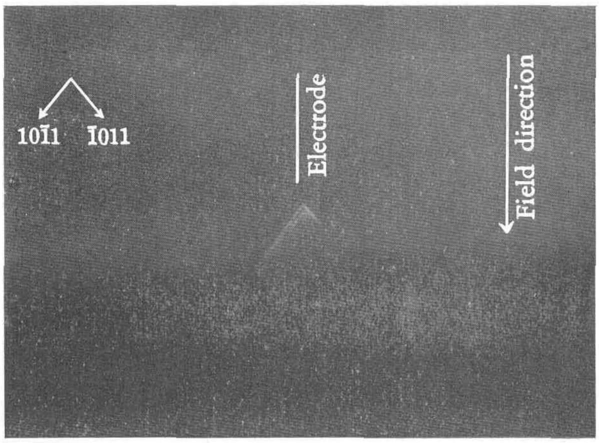


Fig. 25. Streamer in calcite.
(magnification 5)

However, when a lower voltage, accompanying which the glow may, or may not, be just found at the tip of the needle electrode, is repeatedly applied many times, the streamer extends out gradually and almost has relation with the cleavage of crystal as shown in fig. 24 and fig. 25. That is, the shape of the streamer may be changed with the method of the voltage application. Those relations can be obtained not only with single crystals, but also with mica. Figs. 26 and 27 are the results of the former case and figs. 28 and 29 are those of the latter. The above relations show almost no variation with the polarity of the applied voltage or with the application of the unchopped impulse wave (about 10^{-6} sec.). In short, when the exceedingly higher potential gradient is applied, every bond between the atoms can be easily cut off and then the final results become the same as those with the amorphous substance. But when the lower voltage, just sufficient to ionise the molecule, is applied, the weakest bond between the atoms only is cut off, and the streamer in this case has relation with the cleavage of crystal.

Up to the present, the partial breakdown or the streamer in crystal only has been described, but it is necessary to ascertain whether or not the path of the complete breakdown of the crystal is only the extension of the streamer. In the former case, when an exceedingly higher potential gradient is imposed, the streamer mainly extends out in the direction of the field and the path of the complete breakdown is no more than the extension of the streamer. But, in the latter case, when the lower voltage is repeatedly applied, the path of the complete breakdown is not the extension of the streamer; it may branch off on the way and the complete breakdown takes place in the direction of the field as shown in fig. 30 and fig. 31. At first, the weakest bond between atoms may be cut off successively, and then the streamer has relation with the cleavage of crystal. But, when the streamer has been extended out a further distance and approaches the other electrode, the potential gradient to be imposed on the solid molecule will become larger. Hence, the other bonds between atoms are also cut off as well as the weakest one, and the

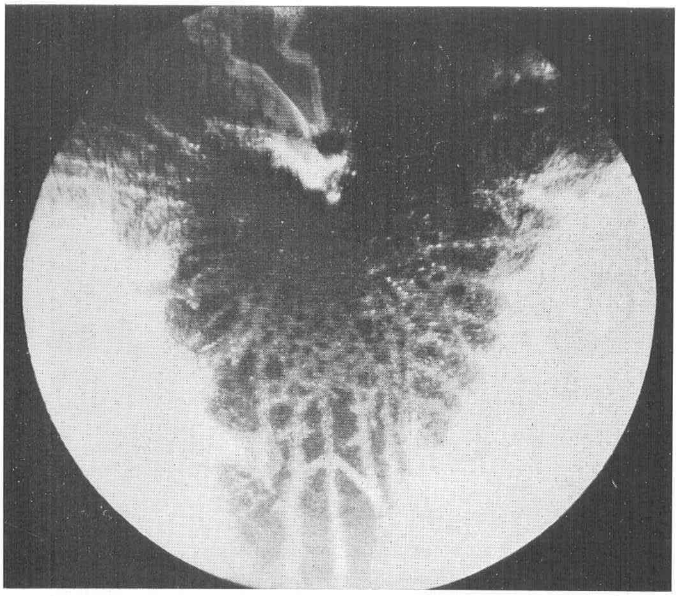


Fig. 26. Positive streamer in mica. (magnification 50)

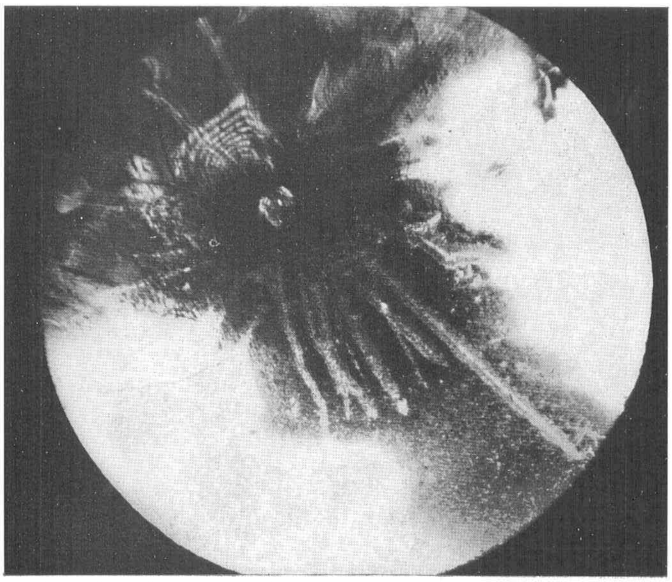


Fig. 27. Negative streamer in mica. (magnification 50)

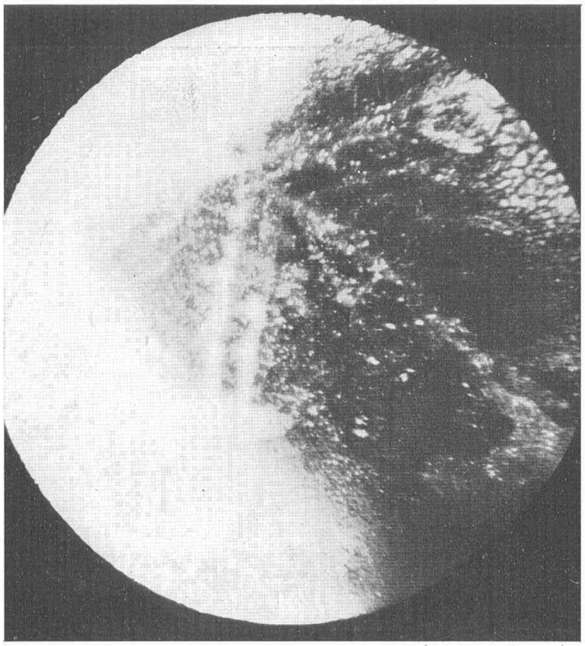


Fig. 28. Positive streamer in mica. (magnification 50)

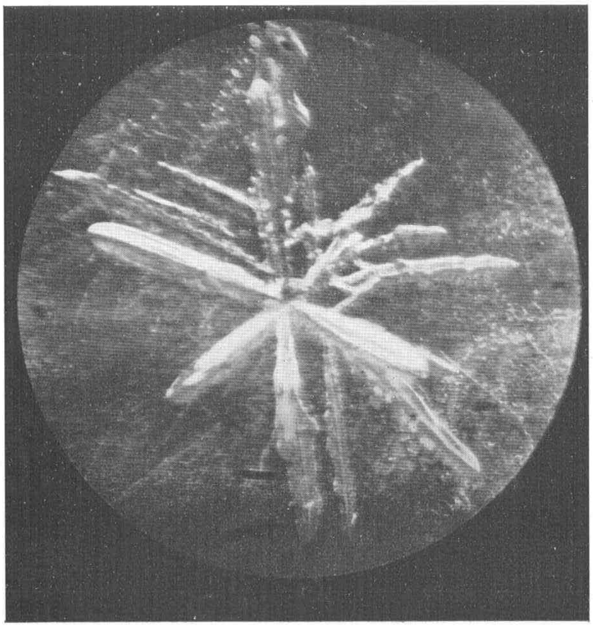


Fig. 29. Negative streamer in mica. (magnification 50)

streamer branches off on the way and extends out towards the other electrode. Therefore, the results of HIPPEL and INGE-WALTHER are only a part of the facts.

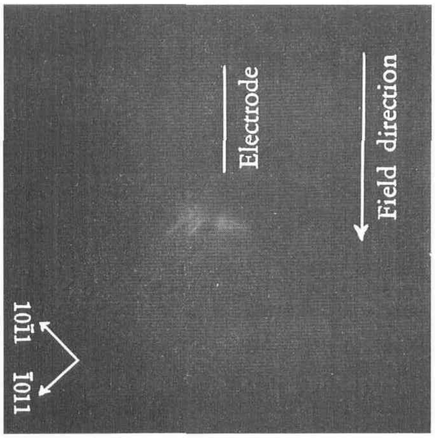


Fig. 30. Partial breakdown of calcite. (magnification 1)

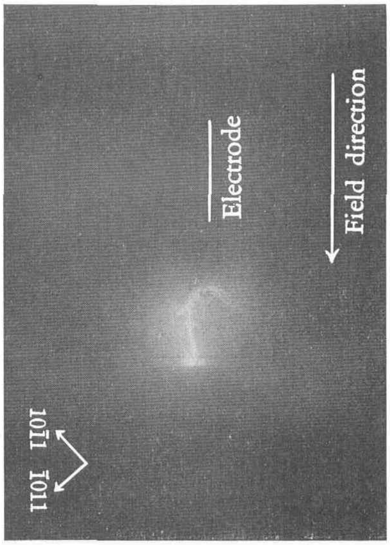


Fig. 31. Complete breakdown of calcite. (magnification 1)

IV.) On The Properties of the Streamer in Solid and Liquid Insulators.

1) Comparison by Spectroscopy between the Streamer in Liquid and that in Solid

The properties of the streamer in liquid or in solid were studied by means of the spectrograph. It is very difficult to obtain the spectrum of the streamer, because the light of the streamer is very feeble and the time to be exposed is very small. Hence, one reproduction of the streamer may be barely obtained when the photographic plate has been exposed during an entire week. In this experiment, it is difficult to find such a state that the spark does not take place at all and moreover that a considerable length of the streamer may be obtained. When a spark once takes place, the spectrum of the streamer is destroyed and the water bath is completely broken.

When the long impulse wave (10^{-6} sec. and more) is applied on the electrodes placed in the water, a red streamer is obtained at the tip of the electrode. If the light of the streamer is examined with the spectrograph, the result as shown in fig. 32 is obtained. That is, the spectrum of the Balmer series of H-line, OH-band and the continuous spectrum are found. However, when the chopped wave (about 10^{-7} sec.) is applied, a white streamer appears and its spectrum is only a continuous one (fig. 33). (When an absorption

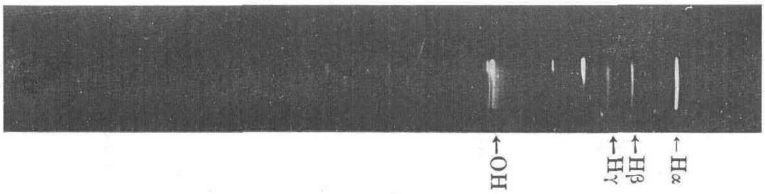


Fig. 32. Red streamer in water due to the unchopped wave.

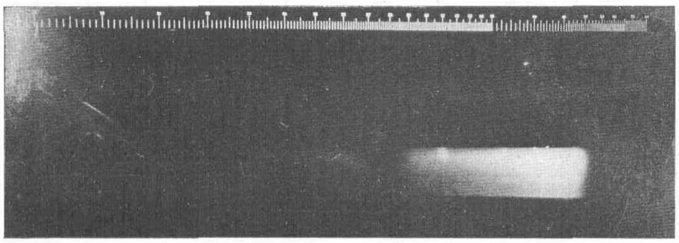


Fig. 33. White streamer in water due to the chopped wave.

spectrum due to the aluminum electrode is also produced, it is only due to the electrode material.) When the impulse voltage which lasts during a very short time, is applied, the continuous spectrum only is obtained; but the Balmer series of H-line and OH-band spectrum will result in addition to the continuous one if the time interval of the voltage application is increased. From the investigation of J. G. WINANS,(1) J. FRANCK(2) and Y. HUKUMOTO(3) etc., it is

(1) J. G. WINANS & E. C. G. STUEKELBERG: Proc. Nat. Acad. America. 14. 1928. p. 867.

(2) J. FRANCK & BLACKETT: Zeits. f. Phys. 34. 1925. p. 389.

(3) Y. HUKUMOTO: Sci. Report of Tohoku Imp. Univ. 1930. p. 178 etc.

known that the continuous spectrum is produced when the molecule is dissociated into atoms. Hence, the continuous spectrum from the white streamer is produced entirely by the dissociation of the water molecule into the atoms or other molecule. However, when the time interval of the voltage application becomes greater, the dissociated atoms and molecule are moreover ionised and give a peculiar spectrum of themselves. Hence, the Balmer series of H-line and OH-band spectrum appear in addition to the continuous one in case of the red streamer in water. (The electric discharge in the liquid vapour at a lower pressure was also studied. The characteristics such a discharge closely resembles that of the streamer in liquid, but the dissociation of the vapour is caused very easily and progressed at once to the ionization of the dissociated atoms and molecule. Hence, the water vapour gives at once the Balmer series of H-line and OH-band spectrum in addition to the continuous one, and further the intensity of the continuous spectrum of the vapour is more feeble than that of the liquid. Therefore, it is very difficult to check the ionization at the point where only the continuous spectrum is obtained. The effect of the duration of the applied voltage also appears not only on the liquid vapour but also on the gas. For instance, the spectrum of the electric discharge in air under lower pressure differs as shown in fig. 34 and fig. 35 with the duration of the applied voltage. It is known that a fair time must be needed to ionise the molecule.)

Hitherto, the partial breakdown or the streamer in water has been studied, but studies of the complete breakdown or the spark in water were also made as will be reported in the next paragraphs.

The spectrum of the spark in water is also varied with duration of the applied voltage. The continuous spectrum, as shown in fig. 36, in obtained for the spark in water due to the chopped wave, but the Balmer series of H-line and OH-band spectrum also appear on that of the spark due to the unchopped one. (fig. 37 and fig. 38).

If one considers the mechanism of the breakdown of the liquid which will be described later, it is natural that the effect of the duration of the applied voltage should appear on the spectrum of the spark in water.

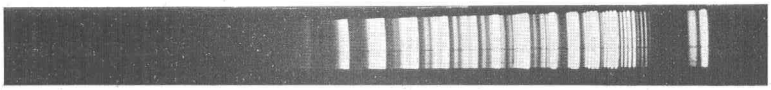


Fig. 34. Spectrum of the vacuum discharge in the air due to the unchopped wave.

Fig. 35. Spectrum of the vacuum discharge in the air due to the chopped wave.

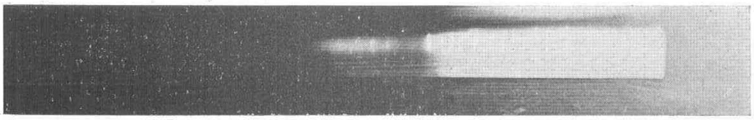


Fig. 36. Spectrum of the spark in water due to the chopped wave.

Fig 37. Spectrum of the spark in water due to the unchopped wave.

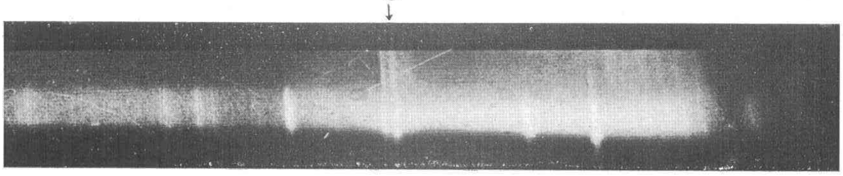


Fig. 38. Magnification of Fig. 37.

Fig. 39. Spectrum of the streamer in paraffinum liquidum due to the unchopped wave.

However, when the unchopped impulse wave (about 10^{-6} sec.) is applied on the viscous liquids, such as glycerine or paraffinum liquidum, the white streamer appears and the continuous spectrum only is obtained just as when the chopped wave is applied (fig. 39). The effect of the duration of the applied voltage does not so easily appear on those liquids as on water, or it disappears gradually with increasing of the viscocity of the liquids. Hence, if one wishes to obtain the spectrum of the peculiar lines of the atoms, the longer wave must be applied. For instance, the spectrum as shown in fig. 40 or fig. 41 are obtained when the longer wave (10^{-5} sec. or more) is applied on paraffinum liquidum or transformer oil.

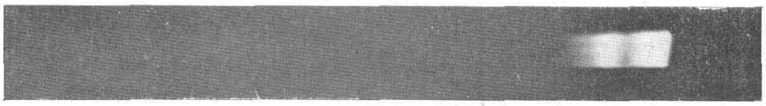


Fig. 40. Spectrum of the streamer in paraffinum liquidum due to the long wave.

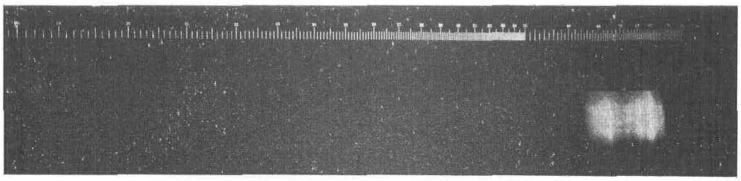


Fig. 41. Spectrum of the spark in transformer oil due to the long wave.

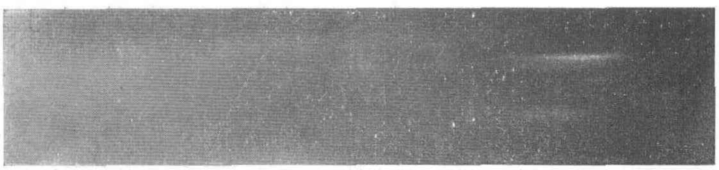


Fig. 42. Spectrum of the streamer in ice.

Next, the streamer in solids such as glass and quartz etc., are studied. In those materials, the streamers are the same as in water due to the chopped wave and give the continuous spectrum. Even with the streamer in ice which is a solidified body of water, the

Balmer series of H-line and OH-band spectrum can not be obtained but only the continuous one, as shown in fig. 42. (The form of the streamer in ice is exactly the same as that in water due to the chopped wave.) Hence, the solid is no more than an extremely viscous liquid and the properties of the streamer in solid and in liquid are exactly the same.

2) Comparison between the Streamer in Solid and in Liquid Insulators.

When the higher impulse voltage is applied to the needle electrode N_1 in fig. 10, the streamer in the glass extends out and pieces through the glass tube G and penetrate into the liquid as shown in fig. 43. (In this case, a microscopically small hole is left through the glass tube as stated previously). That is, the streamer in the glass penetrates into the liquid as it is and there is no change in crossing the surface of separation between the glass and the liquid. The streamer in the glass or in the liquid in this case is no other than that in glass or in liquid itself respectively. This result can be obtained with any solids or liquids, such as water, glycerine, paraffinum liquidum, petroleum, transformer oil, glass, quartz, calcite and tartaric acid, etc.

In this experiment, interesting results as shown in fig. 44 and fig. 45 are obtained. From the boundary surface between the liquid and the solid, the streamers extends out towards both directions, i.e. the streamer in the solid extends out towards the electrode N_1 and the streamer in the liquid towards the electrode N_2. If the scabs left in the glass due to the streamer are examined, the result as shown in fig. 46 is obtained; and then it is certain that the streamer has extended out from the boundary surface between the glass and the liquid. This streamer may be produced by the electron which has been produced by the ionization of the adsorbed gas on the glass surface. From this result it is clear that the streamer in solid or in liquid is not produced by thermal action, but by electric. That is,

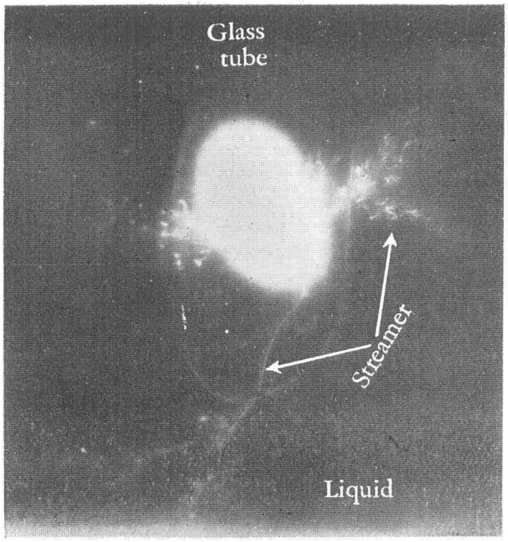


Fig. 43. Streamer in the glass tube and in the liquid (glycerine). (magnification 3)

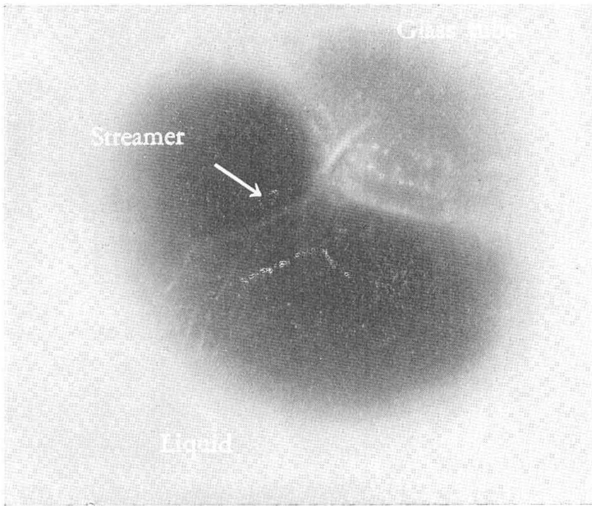


Fig. 44. Streamers in the glass tube and in the liquid (glycerine).

Boundary of the photo-graphic plate. →

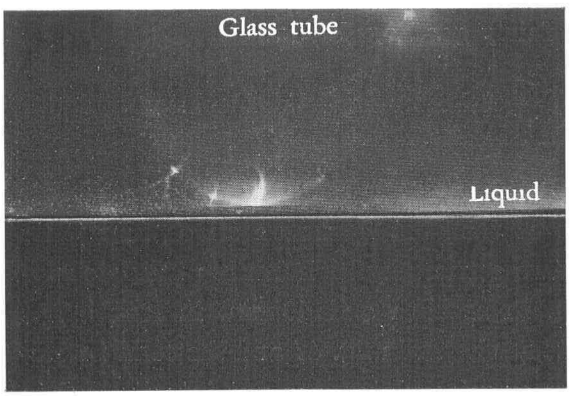


Fig. 45. Streamers in the glass tube and in the liquid (water). (magnification 3)

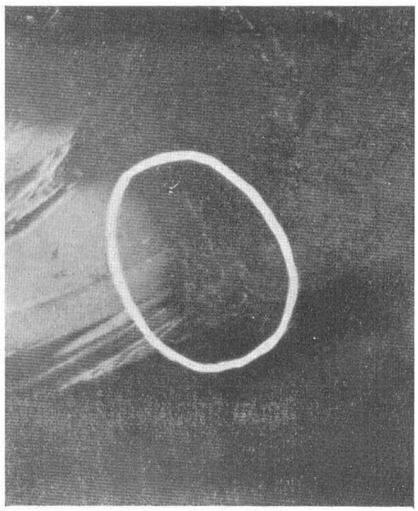


Fig. 46. Scabs due to the streamer in the glass tube. (magnification 10)

the electric breakdown of the solid or of the liquid is entirely due to the electric action and not to the thermal. Moreover, the streamers in solid or in liquid are produced by the ionization by collision of the electron and not by the mechanical force due to the impressed voltage. Because, if the solid should be broken down only by the mechanical force due to the impressed voltage, as stated by W. ROGOWSKI(1) etc., the streamer must be started from the electrode itself and extend out towards the outer surface of the glass tube, because the potential gradient at the tip of the needle electrode is much larger than that of any other parts in the glass. But it is contradictory to the facts and then the streamer in solid or in liquid may be entirely produced by the ionization by collision of the electron.

From the above experiments, the following facts are known.

i) The streamer may be produced without any action of the electrode itself or it is produced without any help of the electron from the cathode.

ii) The solid and the liquid insulators are broken down by the streamer itself.

Hence, it is known that the "second negative streamer"(2) which plays an important rôle in the breakdown of the air, does not exist in the breakdown of the solid or liquid insulators; and moreover the streamer in solid or in liquid is a fairly good conductor.

3) Relation between the streamer in Solid Insulator and that in the Air.

The relation between the streamer in solid and that in the air was investigated by means of the dust figure on an ebonite plate which is supported only at two corners by high tension insulators.

A narrow ditch 1 mm. in breadth and 40 mm. in length has been dug on the ebonite plate as shown in fig. 47 and the solid insulators, such as the cover glass or mica plates, are put into it. When the impulse voltage is applied on the needle electrodes N_1 and N_2

(1) W. ROGOWSKI: Arch. f. Elektrot. 18. 1927. p. 525.
(2) Y. TORIYAMA & U. SHINOHARA: Arch. f. Elektrot. 28. 1934. p. 105.

placed on the ebonite plate, a dust figure and scabs left in the cover glass are simultaneously obtained. Hence, the relation between the streamer in solid and that in the air can be compared with each other. It is known from the experimental results that the positive and negative streamers in the air can easily pierce through the cover glass as shown in fig. 48, but no scabs at all are left in the cover glass. That is, the positive and negative streamers in the air differ from that in solid and have no relation with it. However, when the "second negative streamer" in the air has penetrated through the

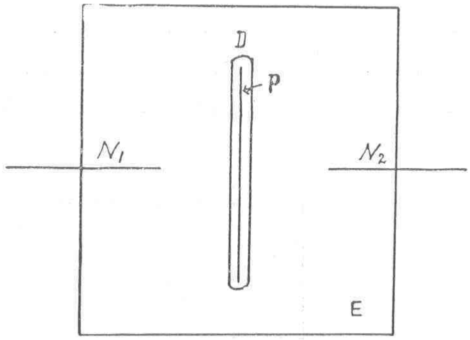


Fig. 47.

N : Needle electrode
D : Ditch
P : Cover glass plate
E : Ebonite plate.

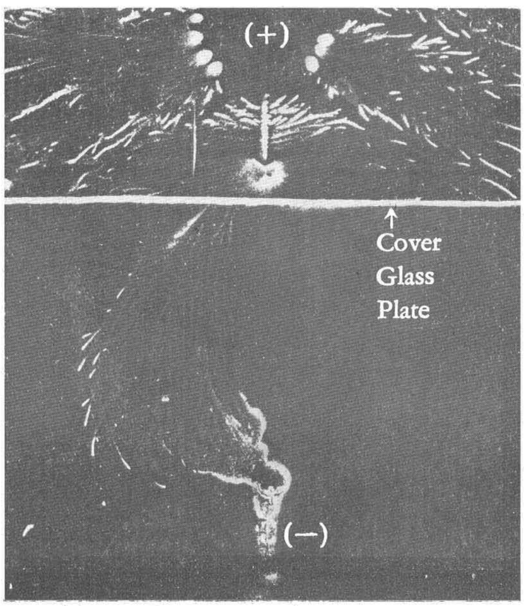


Fig. 48.

cover glass as shown in fig. 49, a microscopic small hole is left on the cover glass as shown in fig. 50. Hence, it is clearly known that the streamer has been produced in the solid in this case. The streamer in solid corresponds to the state when the "second negative streamer" extends out along the positive streamer in the air, i.e. to the state of

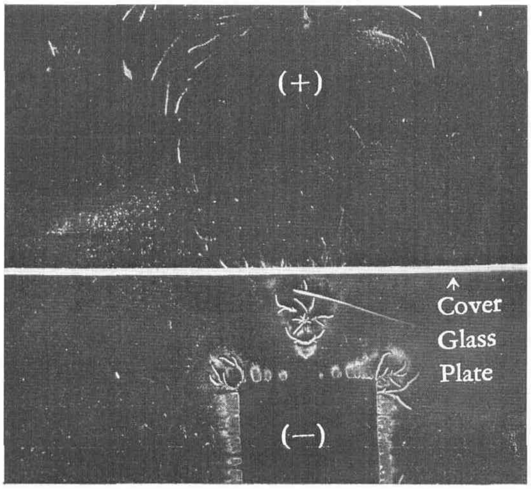


Fig. 49.

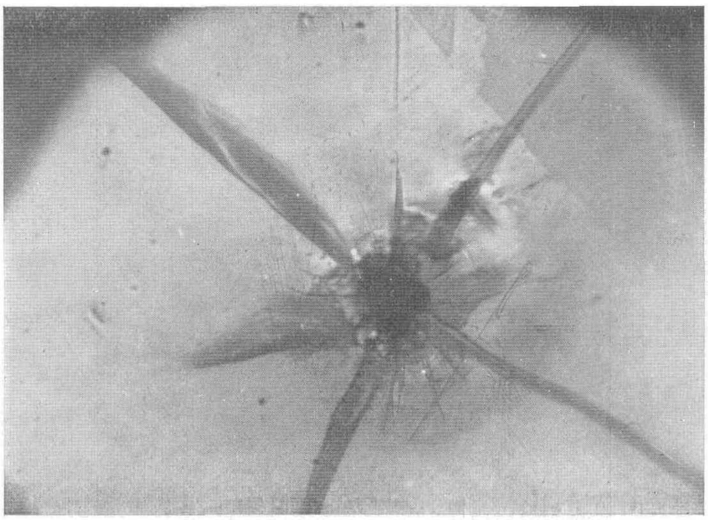


Fig. 50. Scabs due to the "second negative streamer" on the cover glass plate. (magnification 100)

the co-existence of the positive and "second negative streamer" in the air. The same conclusion can also be obtained, when the needle electrode is placed inside a capillary glass tube sealed at one end.

It is desirable to discover the distribution of the electric charge in the streamer in solid, but it cannot be done in practice. Hence, the following experiment has been done to make only an attempt toward the solution of this problem. Rather large amounts of resin powder and red lead powder are piled upon the ebonite plate to make a porous solid. If the impulse voltage is applied to the needle electrode buried in this porous solid, a dust figure such as fig. 51 is left

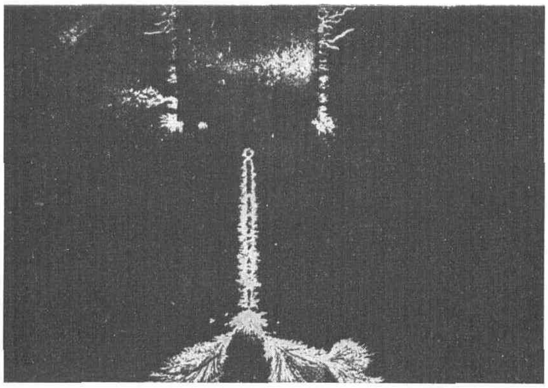


Fig. 51.

on the ebonite plate. The shape of the dust figure in this case is almost independent of the polarity of the applied voltage and moreover the positive and the negative charge are co-existent on it similarly to the dust figure in transformer oil which has been studied by Y. TORIYAMA.(1) In short, the positive and the negative ions may co-exist in the streamer in solid or in liquid.

From the experimental facts which have been already learned by physicists,(2) it is known that *positive and negative ions and electrons will be produced* when the molecule of solid or of liquid is

(1) Y. TORIYAMA, Phys. Rev. 37. 1931. p. 619.

(2) K. FUKUDA: Text-Book on Atom Structure. p. 202, or H. GEIGER u. K. SCHEEL: Handbuch d. Phys. Bd. 24. p. 438.

dissociated by the ionization due to electron impact. Hence, it is naturally considered that positive and negative ions are co-existent in the streamer in solid or in liquid.

4) On the Streamer Along the Liquid Surface.

To know the relation between the streamer in liquid and that in the air, the writer has studied on the streamer along the liquid surface. When the impulse voltage is applied on the needle electrode

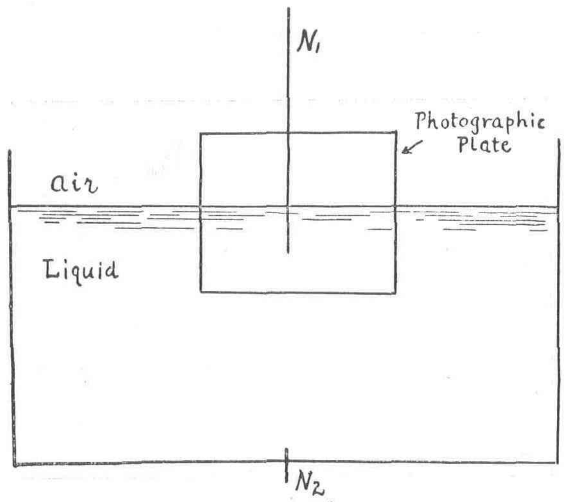


Fig. 52.

N_1 in fig. 52, a Lichtenberg figure as shown in fig. 53 is obtained on the photographic plate touched by the needle electrode. That is, a thicker streamer which entirely differs from that in the air, creeps along the liquid surface. The streamer is no other than the streamer of the liquid vapour as is ascertained if one observes the streamer in

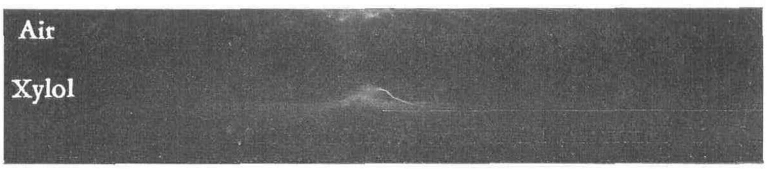


Fig. 53. Streamer along xylol surface.

a vacuum tube filled with liquid vapour and the spectrum of those streamers.

The streamer along the liquid surface is more luminous than that in the air and takes the form shown in fig. 54. This figure shows the positive streamer along the water surface, but the same result is obtained for the negative. The streamer along the liquid has almost the same properties as that in liquid, and it is also affected by the

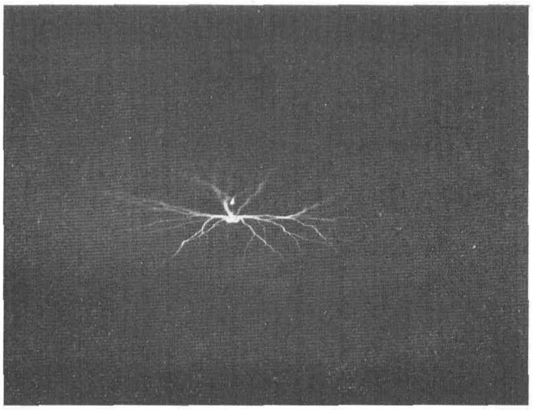


Fig. 54. Positive streamer along water surface.

duration of the applied voltage. That is, a red streamer is obtained with the unchopped wave and a white streamer with the chopped one. In short, the streamer along the liquid surface has almost the same properties as that in liquid, but it is entirely different from that in the air. If a comparison of those streamers be made, the following results are obtained.

a) The streamer in liquid is more luminous than that in the air.

b) When the current density of the streamer is measured by means of the length of the spark produced between the loose contacts of the needle and iron plate, the following result is obtained.[1] If an impulse voltage of 8 KV is applied to the needle electrode, the

(1) Compare the report by Y. TORIYAMA, Y. ICHIMURA & T. KAWAKAMI: Jour. of Elec. Eng of Japan. 1933. Aug.

length of the spark due to the loose contact between the needle and the iron plate becomes about 15 mm. for the positive streamer along the water surface, but it is nearly zero for the positive streamer in the air.

c) When the streamer along the water surface meets with a drop of petroleum, the petroleum may blaze up at once as shown in fig. 55, but this result cannot be obtained with the streamer in the air.

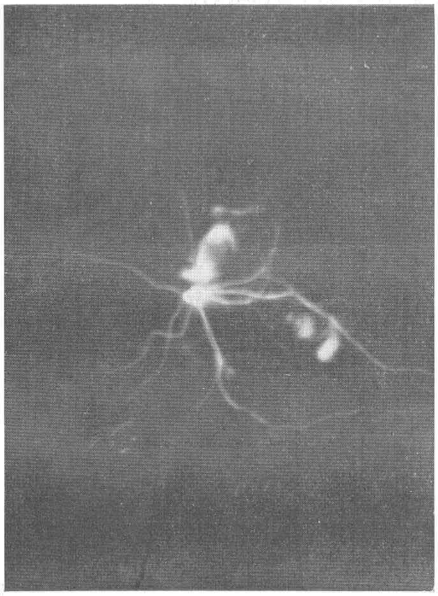


Fig. 55. A drop of petroleum is blazed up with the streamer along the water surface.

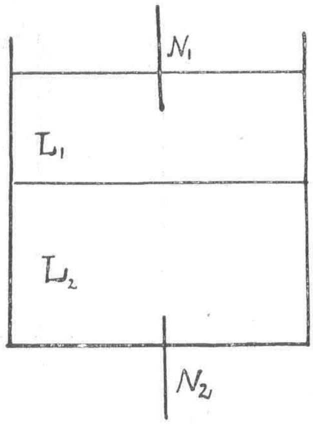


Fig. 56.
N: Needle Electrode.
L: Liquid.

Hence, it can be ascertained that the current density of the streamer in liquid is greater than that of the streamer in the air. Therefore, the streamer in liquid is a better conductor than that in the air.

5) On the Streamer in the Media of Two Liquids.

The properties of the streamer in liquid has been guessed from the aspect of the streamer in crossing the dividing line between two liquids. (fig. 56) The media are made with water and another lighter liquid, such as paraffinum liquidum or xylol etc. In this paper, the two parallel layers of water and paraffinum liquidum will be discussed in the following. Since the specific gravity of paraffinum liquidum is smaller than that of water, a distinct surface of separation will be produced between them.

When the higher impulse voltage is applied on the needle electrodes, the streamer pierces through the paraffinum liquidum and penetrated into the water. The streamer in the paraffinum liquidum has a bluish white colour, but the streamer in the water a red one. (When the chopped wave is applied, a white streamer can be obtained.) That is, the streamer in the paraffinum liquidum or in the water in this case is no other than that in paraffinum liquidum or in water itself respectively and there is no change in crossing the surface of separation. When the streamer has crossed over this surface between the paraffinum liquidum and the water, a fair quantity of small bubbles or small drops of water comes into the paraffinum liquidum and the paraffinum liquidum is muddied, and then the breakdown voltage of the paraffinum liquidum falls to a lower point. Hence, those liquids must be renewed every repetition of the experiments.

In the above experiments, the author has noted that the small bubbles produced by the streamer in the paraffinum liquidum are very easily ignited. When the small bubbles are intersected by the streamer along the liquid surface, they blazed at once with a yellowish flame like that of petroleum on the water surface (fig. 55). Since the paraffinum liquidum does not usually blazed easily, the phenomena of "cracking" seems to be caused by the streamer and the hydrocarbon of higher order may be changed into that of lower order.

With this experiment, the properties of the streamer in liquid and that in the air can be compared indirectly as following.

(1st Experiment)

When the impulse voltage applied on the needle electrode N_1 in fig. 56, is adjusted to a moderate value, one can produce the streamer in the paraffinum liquidum but not in the water. In this case, the small bubbles produced in company with the streamer, move as shown in fig. 57 and circulate in the paraffinum liquidum. Hence the paraffinum liquidum is muddied. But the surface of separation

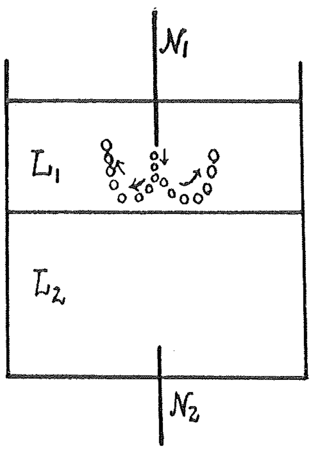


Fig. 57. Motion of the small bubbles in the paraffinum liquidum (L_1). (L_2 : water)

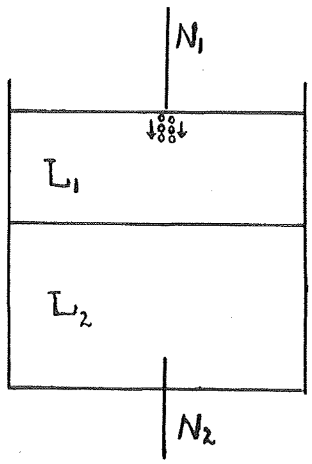


Fig. 58. Motion of the air bubbles in the paraffinum liquidum (L_1). (L_2 : water)

between the paraffinum liquidum and the water is scarcely disturbed, and it remains at the horizontal. When the electric charge in the paraffinum liquidum in this state is examined with the electrometer, no deflection of the electrometer can be obtained.

(2nd Experiment)

When the glass tube which covers the needle electrode N_1, is taken off and the tip of the needle is placed just on the liquid surface, small air bubbles are attracted into the paraffinum liquidum (fig 58) and circulate in it as shown in fig. 57. When the impulse voltage is repeatedly applied many times, the surface of separation bulges upward gradually and at last a part of it is raised up and ridges are made on the surface of the separation as in fig. 59 or fig. 60, and the small drops of water are attracted into the paraffinum liquidum from the top of the ridges. When those small drops of water are intersected with the needle electrode, a pale blue light appears at the tip of the electrode to continue during about one second. If the electric charge in the paraffinum liquidum in this state is examined with the electrometer, it deflects about 7 mm. (1 mm. corresponds to 300 volts.) That is, the paraffinum liquidum in this state possesses a fair amount of electric charge.

The cause of the phenomena may be considered as follows.

In the *2nd experiment,* the streamer in the air extends from the needle electrode into the air. As stated previously, the positive streamer in the air is the arrangement of the positive ions in succession and the negative streamer in the air is that of the negative ions. When the impulse voltage is applied, the small bubbles of air are attracted into the paraffinum liquidum and circulate in it as shown in fig. 57. With the movement of the charged particles, the water is attracted towards it. Since the paraffinum liquidum is more viscous than the water, the surface of separation bulges upwards and at last, a part of it bursts out, the ridges are made on the surface of separation and the small drops of water are attracted into the paraffinum liquidum from the top of the ridge. With the movement of the small drops of water into the paraffinum liquidum, they obtain a fairly large quantity of the electric charge and then the glow appears around the needle electrode if they intersect with the electrode. On the other hand, the needle electrode used in the *1st Experiment,* is sealed with a glass tube except for its tip, and then the streamer in the paraffinum liquidum is only produced at the tip of the needle electrode. Since, as stated previously, the streamer in liquid consists of positive and negative ions, there is scarcely any change on the surface of separation between the water and the paraffinum liquidum and no deflection can be obtained when the paraffinum liquidum in this state is examined by means of the electrometer. Hence, one can indirectly know that the streamer in paraffinum liquidum consists of positive and negative ions.

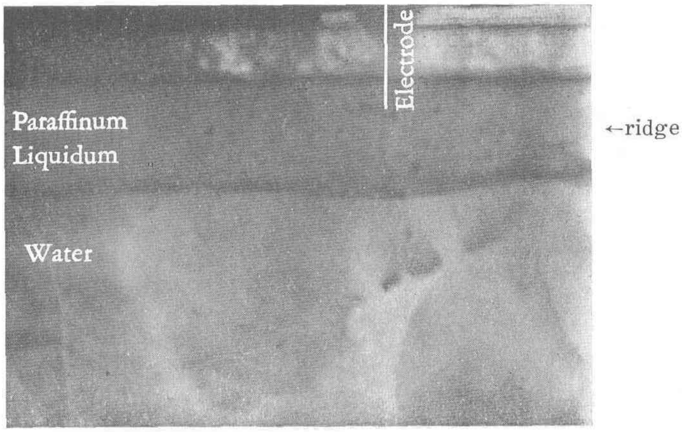


Fig. 59. Change on the surface of separation between the paraffinum liquidum and the water.

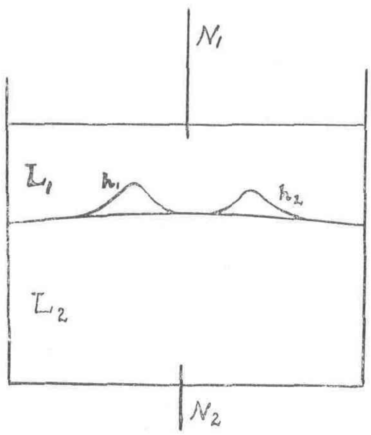


Fig. 60. Change on the surface of separation between the paraffinum liquidum and the water.

N : needle electrode,
L_1 : paraffinum liquidum,
L_2 : water,
h : small ridge of water.

6) The Relation Between the Streamer in Solid or in Liquid Insulators and the Wave Tail of the Impulse Wave, and its Relation with the Breakdown of those Insulators.

The following results can be similarly obtained with any materials, such as water, glycerine, paraffinum liquidum and glass etc. In this paper, the streamer in water will be described, for it is easily produced and extends out a farther distance than that of other materials.

When the gap length of M_1 in fig. 1 is kept constant, and the impulse voltage to be produced from it is chopped by means of gap M_2, the elongation of the streamer at any instant can be known. The streamer in liquid extends out a farther distance gradually with the increase of the gap length of M_2. At the same time, the streamer in liquid extends out farther even at the wave tail of the impulse wave. For instance, when a sphere gap coated with transformer oil is used as gap M_2, and the impulse wave is cut off at the wave tail, the streamer in this case also extends out a greater distance than that of the streamer due to the impulse voltage when it is chopped at the wave top. Moreover, the streamer extends out a much greater distance if the gap M_2 is entirely removed. For an example, the difference between the length of the streamer due to the impulse wave which is chopped at the wave top and that of the streamer due to the unchopped one, becomes as in Table I.

TABLE I.

(max. value of the applied voltage is kept at 25 KV.)

Resistance (R) in the impulse generator.	Length of the streamer in water due to the impulse wave which is chopped at the wave top.	Length of the streamer in water due to the unchopped impulse wave.
MΩ 0.2	2 mm	5 mm
0.5	2	8
1.0	2	12

In a word, the streamer in liquid gradually extends out even at the wave tail of the impulse voltage. Next, when the resistance R or the capacity C in the impulse generator is change, the total length of the impulse wave produced from the impulse generator is also changed. With this impulse wave, the streamer extends out as shown in fig. 61 and fig. 62. The streamer for the longer wave

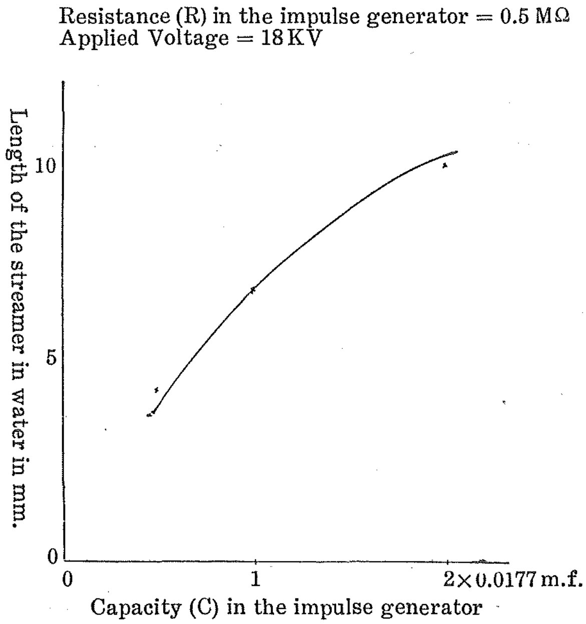


Fig. 61.

extends out a greater distance than that for the shorter one. This fact can be also obtained for any material, such as the glycerine, paraffinum liquidum, xylol, glass and quartz etc. That is, the streamer in liquid or in solid depend on the total wave length as well as on the maximum value (V) of the impulse wave (fig. 63). Hence the properties of the streamer in liquid or in solid differ from those of the streamer in the air which entirely depends on the maximum value of the impulse wave and not on the total wave length. The fact that the streamer in liquid or in solid extends out a further distance even at the wave tail, shows that it is a fairly good conductor and it becomes like an extension of the electrode itself. When the voltage V′ is imposed on the electrode, the voltage V″ which is analogous to V′, may be imposed on the tip of the streamer. (fig. 63). If the voltage V″ can ionize the liquid or the solid molecule, the streamer will extend out a greater distance. In short, the streamer in liquid or in solid is a fairly good conductor. Hence the breakdown of the liquid or the solid insulators must be defined as follows.

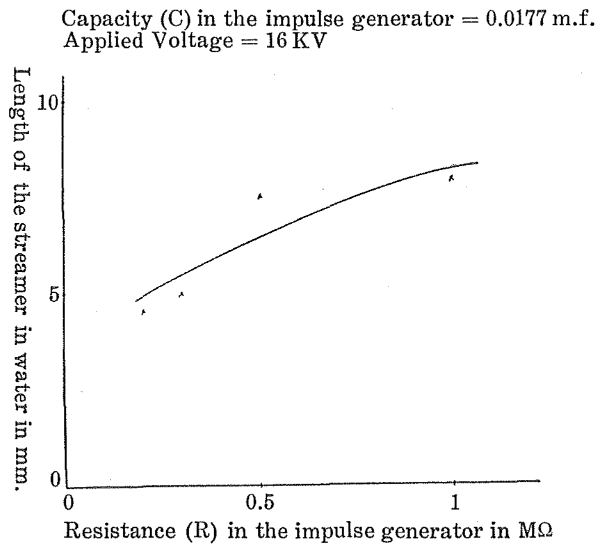


Fig. 62.

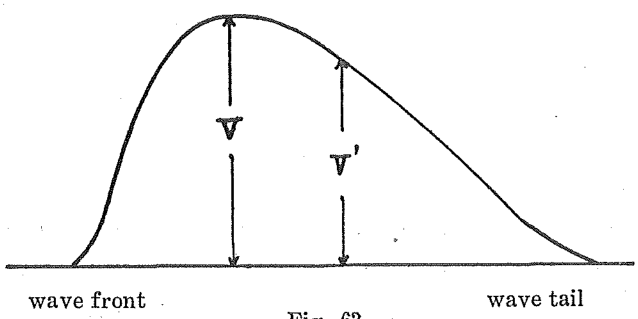


Fig. 63.

The solid or liquid insulator is broken down at the instant the positive and the negative electrodes are connected with the conductive streamer completely. After that, the current will merely flow on the conductive path between the positive and negative electrodes. The current in this case depends on the voltage which is just imposed on the electrodes at the instant, the positive and the negative electrodes being connected by the conductive streamer. Hence, even the aspect of the breakdown may differ, it only depends on the quantity of the current passed over the conductive path.

V) On the Mechanism of the Pure Electric Breakdown of the Solid and the Liquid Insulators and Its Relation with the Breakdown of the Air.

From the experimental facts it has been ascertained that the positive and the negative streamers in solid or in liquid insulators have the same form and the same properties with each other; that they are fairly good conductors, and moreover that they must be produced by the dissociation of the molecule due to the ionization. In general, when the molecules of solid or of liquid are dissociated by the ionization by collision of the electron, *positive and negative ions and electrons must be produced* as stated previously. At the same time *the mass of the molecules of the solid or the liquid are the heavier and moreover they can scarcely be moved because of the force of the cohesion,* especially in case the impulse voltage is applied. Hence it is reasonable that positive and negative ions co-exist on the streamer in solid or in liquid. First, let the mechanism of the streamer in the air be described for comparison.

1) On the Mechanism of the Streamer in the Air, Which has Already been Studied by Many Authorities.

When the impulse voltage is applied, the free electron is accelerated by the potential gradient, and collides with the air molecule, and ionises it. When the air molecule is ionised, the positive ion and the electron are produced. The electron is attracted towards and falls into the positive electrode, but the positive ions are repelled from the positive electrode, while the mass of the positive ion is heavier than that of the electron and the velocity of the former is about one-thousandth that of the latter. Hence the positive ion is left in the vicinity of the positive electrode and then the potential gradient at the tip of the positive ion becomes larger and the potential gradient between the positive ion and the positive electrode becomes much smaller. That is, the potential gradient is transferred from the electrode to the tip of the positive ion. Hence, the air molecules are ionised successively and the positive streamer spreads outwards from the electrode. That is, the positive streamer is an arrangement of the positive ions in succession. Similarly, the negative streamer is an arrangement of the negative ions in succession. (The mechanism of the negative streamer seems to differ somewhat from that of the positive, but it is certain that the negative streamer is an arrangement of the negative ions in succession.)

2) On the Mechanism of the Pure Electric Breakdown of the Solid and Liquid Insulators.

First, the mechanism of the positive streamer in solid or in liquid insulators will be described. When the molecules of the solid or of the liquid are ionised by the electron impact, positive and negative ions and electrons are produced. The electron is attracted towards the positive electrode and falls into it. Also the negative ion is attracted towards the positive electrode, but it can scarcely move as above stated. At the same time, the positive ion is repelled away from the positive electrode, but it also can scarcely move. Hence, the potential gradient at the tip of the positive ion becomes large and the potential gradient between the positive ion and the positive electrode becomes very small. That is, the over-potential gradient is transferred from the electrode to the tip of the positive ion and the molecules are ionised successively and the streamer spreads outward from the electrode. Therefore, the streamer takes a twig-like form and it is made up of positive and negative ions.

Next, the mechanism of the negative streamer in solid or in liquid will be treated. When the molecules of the solid or of the liquid are ionised by the electron impact, positive and negative ions and electrons are produced as in the previous case. The positive ion is attracted towards the negative electrode and the negative ion is repelled away from it, but those ions can scarcely move. The electron is also repelled away from the negative electrode and lies remote from it. Hence, the potential gradient is transferred from the negative electrode to the tip of the negative ion, but becomes smaller than that on the positive electrode. As the consequence, the length of the negative streamer become smaller than that of the positive streamer. The difference of the positive and the negative streamers in length is entirely due to the *electron*, or it depends on the degree of a through passage of the electron in the material. (From the experimental results of A. GÜNTHERSCHULZE,[1] it is also ascertained that the free electron may exist in a solid or a liquid and can be passed through it. Besides, Y. TORIYAMA[2] and K. PRZIBRUM[3] have studied on the relation between the length of the positive and negative streamers with the dust figure or the Lichtenberg figure. In some kinds of liquids, the length of the negative streamer is exactly the same as that of the positive.)

That is, the mechanism of the negative streamer is almost the same as that of the positive streamer. Hence, the positive and the negative streamers in solid or in liquid have the same twig-like form and the same characteristics, and those streamers are made up of positive and negative ions. Moreover, the situation of the atom and the electron in the streamers is almost the same as the situation of the atom and the electron which has been considered by

(1) A. GÜNTHERSCHULZE: Zeits. f. Phys. Bd. 86. 1933. H. 11/12.
(2) Y. TORIYAMA: 7th. Ann. Cov. of Inst. of Elec. Eng. of Japan. 1932. 7.
(3) K. PRZIBRUM: Phys. Zeits. 32. 1931. p. 481.

R. PEIERLS[1] or F. BLOCH[2] in their explanation of the conduction current in the metal. Hence, it is natural that those streamers may be fairly good conductors.

With the procedure above stated, streamers in solids or in liquids may be produced. As stated previously, the solid or liquid insulators are broken down at the instant the positive and the negative electrodes are completely connected by the conductive streamer. Hence, the mechanism of the streamer in solid and liquid becomes the mechanism of the pure electric breakdown of the solid and liquid insulators.

3) Effect of the Crack upon the Breakdown of the Solid Insulators.

In the practice, a crack may be produced in company with the formation of the streamer in solid insulator. The effect of the crack may be generally inserted on the way of the breakdown of the solid insulator and the breakdown voltage is decreased by it. That is, when the molecule of the solid has been ionised and dissociated, the bonds between the atoms are cut off. Under this condition, the mechanical force due to the impressed voltage, is exerted and the solid may be cracked. That is, the solid may be cracked in company with the formation of the streamer. When the cracks once appear in the solid, the over-potential gradient occurs at the tip of the crack and the molecule of the solid will be easily ionised. Hence, the solid will be more easily broken down. The crack may be said to promote the breakdown of the solid insulator, but it is no more than a secondary effect. That is, the mechanism of the pure electric breakdown of the solid insulator is not influenced at all.

4) Relation between the Pure Electric Breakdown of the Solid or Liquid Insulator and that of the Air.

As stated above, the properties of the streamer in solid or in liquid are altogether different from those of the positive and negative

(1) R. PEIERLS: Ann. d. Phys. 4. 1930. p. 121.
(2) F. BLOCH: Zeits. f. Phys; 52. 1928. p. 555.

streamers in the air, but such a streamer corresponds to the state of the co-existence of the positive and the "second negative streamer" in the air, or to such a state that the "second negative streamer" extends along the positive streamer towards the anode. In general, the spark-over in the air takes place in the following two stages.(1) In the first stage, the positive and the negative streamer develop independently. As the positive streamer extends out more rapidly than the negative, the former plays an important rôle in the first stage. In the second stage, the "second negative streamer" spreads towards the anode along the positive streamer and complete spark-over will take place if the "second negative streamer" extends to the positive electrode. While the positive streamer is no more than an arrangement of the positive ions in succession as stated before and the "second negative streamer" is also an arrangement of the negative ions in succession, the "second negative streamer" appears on the ebonite plate as a negative dust figure. Hence, the positive and the negative ions are co-existent on the portion of the "second negative streamer" which extends along the positive streamer (fig. 64) and this state corresponds to the streamer in solid or in liquid insulator. Therefore, the spark-over in the air takes place at once if the "second negative streamer" reaches to the positive electrode.

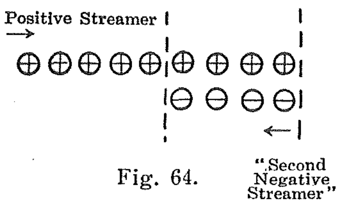


Fig. 64.

In many cases arising in practice, moisture, gases, and impurities contained in the insulators also affect the breakdown voltage of the insulators, but their consideration seems to be outside the author's present purpose, and so they may be left at one side.

VI.) Conclusion.

1) Either the positive or the negative streamer in liquid has a twig-like form and the same characteristics with each other, ex-

(1) Y. TORIYAMA & U. SHINOHARA: Arch. f. Elektrot. 28. 1934. p. 105. Jour. of Elec. Eng. of Japan. Dec. 1931: April, 1932; July, 1932: Feb. 1933.

cepting their length. In general, the negative streamer is shorter than the positive streamer.

2) The streamer in liquid insulator is generally affected by the duration of the applied voltage, but the effect decreases with increasing of the viscocity of the liquid.

3) The positive and the negative streamers in solid insulator have the same characteristics. The form of the streamer in amorphous substance is a twig-like one and entirely the same as that in water when the chopped wave is applied.

But the shape of the streamer in crystal is changed with the methods of the voltage application. When an exceedingly higher potential gradient is imposed, the streamer in crystal takes a twig-like form like the streamer in amorphous substance; but, when a lower voltage, with which the glow may, or may not, just appear at the tip of the needle electrode, is repeatedly applied many times, the streamer has relations with the cleavage of crystal.

4) The streamer in solid and in liquid insulators have entirely the same properties. And positive and negative ions co-exist in those streamers.

5) The streamer in solid and liquid insulators are produced, at first, by the ionization of the electron impact and not by thermal or mechanical action.

6) When the streamer or the partial breakdown is produced in solid or in liquid insulator, the molecule must be dissociated due to the ionization. That is, the dissociation of the molecule due to the ionization must be brought about in the pure electric breakdown of the insulators. Hence, the pure electric breakdown radically differs from pyro-electric or thermal breakdown.

7) The properties of the streamer in solid or in liquid insulator entirely differ from those of the positive and the negative streamers in the air. But the streamer in solid or in liquid rather corresponds to the state when the "second negative streamer" is extended out

along the positive streamer in the air, or to the state of the co-existence of the positive and the "second negative streamer" in the air.

8) The streamer in liquid or in solid insulator extends out a farther distance even at the wave tail, i.e. those streamers depend upon the total wave length as well as upon the maximum value of the applied voltage.

9) The streamer in solid or in liquid insulator is the path of low resistance. Hence, the solid or liquid insulators are broken down at the instant the positive and the negative electrodes become completely connected with the conductive streamer. Then, the mechanism of the pure electric breakdown of the solid or of the liquid insulators is exactly the same as the mechanism of the streamer in the solid or in the liquid.

10) The mechanism of the streamer in solid or in liquid insulator seems to be as follows. When the molecule of the solid or the liquid is ionised by the electron impact, positive and negative ions and electrons are produced. Since the positive and negative ions in this case can scarcely move, the over-potential gradient is transferred from the electrode to the tip of the ion of the same polarity as the electrode. Hence, the molecule is ionised successively and the streamer spreads outwards from the electrode. But the difference of the length of the positive and the negative streamer is entirely due to the electron. That is, in respect to the positive electrode, the electron is attracted and falls into it; but as to the negative electrode, the electron is repelled and lies remote from it. Hence the potential gradient to be transferred from the negative electrode to the tip of the negative ion, becomes smaller than that on the positive electrode.

11) In the solid insulator, the effect of the cracks produced by the mechanical force due to the impressed voltage, may be generally included as concomittant with the breakdown. The crack decreases the breakdown voltage to a lower point. But it is no more than a

secondary effect, and the mechanism of the pure electric breakdown of the solid insulator is not influenced at all.

The author wishes express his thanks to Prof. Dr. Y. TORIYAMA, for his advice during the work.