CAMBRIDGE PHYSICAL SERIES.

CONDUCTION OF ELECTRICITY THROUGH GASES

CAMBRIDGE UNIVERSITY PRESS WAREHOUSE,
C. F. CLAY, MANAGER.
London: FETTER LANE, E.C.
Glasgow: 50, WELLINGTON STREET.

ALSO
London: H. K. LEWIS, 136, GOWER STREET, W.C.
Leipzig: F. A. BROCKHAUS.
New York: G. P. PUTNAM'S SONS.
Bombay and Calcutta: MACMILLAN AND CO., LTD.

CONDUCTION OF ELECTRICITY THROUGH GASES

BY

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SECOND EDITION

CAMBRIDGE:
AT THE UNIVERSITY PRESS
1906

PREFACE.

I HAVE endeavoured in this work to develope the view that the conduction of electricity through gases is due to the presence in the gas of small particles charged with electricity, called ions, which under the influence of electric forces move from one part of the gas to another. My object has been to show how the various phenomena exhibited when electricity passes through gases can be coordinated by this conception rather than to attempt to give a complete account of the very numerous investigations which have been made on the electrical properties of gases; I have therefore confined myself for the most part to those phenomena which furnish results sufficiently precise to serve as a test of the truth of this theory. The book contains the subject-matter of lectures given at the Cavendish Laboratory where a good deal of attention has been paid to the subject and where a considerable number of physicists are working at it.

The study of the electrical properties of gases seems to offer the most promising field for investigating the Nature of Electricity and the Constitution of Matter, for thanks to the Kinetic Theory of Gases our conceptions of the processes other than electrical which occur in gases are much more vivid and definite than they are for liquids or solids; in consequence of this the subject has advanced very rapidly and I think it may now fairly be claimed that our knowledge of and insight into the processes going on when electricity passes through a gas is greater than it is in the case either of solids or liquids. The possession of a charge by the ions increases so much the ease with which they can be traced and their properties studied that, as the reader will see, we know far more about the ion than we do about the uncharged molecule.

With the discovery and study of Cathode rays, Röntgen rays and Radio-activity a new era has begun in Physics, in which the electrical properties of gases have played and will play a most important part; the bearing of these discoveries on the problems of the Constitution of Matter and the Nature of Electricity is in most intimate connection with the view we take of the processes which go on when electricity passes through a gas. I have endeavoured to show that the view taken in this volume is supported by a large amount of direct evidence and that it affords a direct and simple explanation of the electrical properties of gases.

The pressure of my other duties has caused this book to be a considerable time in passing through the press, and some important investigations have been published since the sheets relating to the subjects investigated were struck off. I have given a short account of these in a few Supplementary Notes.

My thanks are due to Mr C. T. R. Wilson, F.R.S., for the assistance he has given me by reading the proofs and I am indebted to Mr Hayles of the Cavendish Laboratory for the preparation of the diagrams.

J. J. THOMSON.

CAVENDISH LABORATORY, CAMBRIDGE.
August, 1903.

PREFACE TO THE SECOND EDITION.

I HAVE made many additions to this edition and a considerable part of it has been rewritten, in the hope of introducing new material in a more logical and connected form than by merely adding new paragraphs to the old edition. This has increased the size of the book; on the other hand the publication, since the first edition of this book, of Rutherford's *Radio-activity* has enabled me to omit some matter fully treated by Rutherford. So many researches on Discharge through Gases have been made since the issue of the first edition that anything like a complete account of them is impossible within the space at my disposal. I have therefore limited myself to those which seemed most capable of testing the accuracy of the view of Electric Discharge advocated in this book.

The light which can be thrown by the study of the Electrical Phenomena occurring in Gases on many of the most interesting questions in Physics is now generally recognised, and the more the subject is studied the wider are seen to be its applications and the greater the opportunities for further research.

I take this opportunity of expressing the gratitude which all students of this subject must feel to the Société de Physique of Paris for the publication of the collection of original papers on Discharge through Gases in the volumes *Ions, Électrons, Corpuscles*, edited by MM. H. Abraham and P. Langevin.

J. J. THOMSON.

CAVENDISH LABORATORY, CAMBRIDGE.
September, 1906.

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CHAPTER IX.

IONISATION IN GASES FROM FLAMES.

121. It has been known for more than a century that gases from flames are conductors of electricity: a well-known application of this fact—the discharge of electricity from the surface of a non-conductor by passing a flame over it—was used by Volta in his experiments on Contact Electricity. We shall not attempt to give any historical account of the earlier experiments on this subject, because the conditions in these experiments were generally such that the interpretation of the results obtained is always exceedingly difficult and often ambiguous: the reason of this is very obvious—to investigate the electrical conditions of the flame wires are generally introduced, these become incandescent and so at once add to the electrical phenomena in the flame the very complicated effects we have been discussing in the last chapter.

The gases which come from the flame, even when they have got some distance away from it and have been cooled by the surrounding air, possess for some time considerable conductivity, and will discharge an insulated conductor placed within their reach. The conductivity can be entirely taken out of the gas by making it pass through a strong electric field, this field abstracts the ions from the gas, driving them against the electrodes so that when the gas emerges from the field, although its chemical composition is unaltered, its conducting power is gone. This result shows too that no uncharged radio-active substances, such as emanate from thorium and some other substances, are produced in the flame; these would not be taken out by the field, so that if they existed the conductivity of the gas would not be destroyed by the field. If not driven out of the gas by an electric field the ions are fairly long lived. Thus in some experiments Giese noticed that the gas retained appreciable conductivity 6 or 7 minutes after it had left the flame. The ions stick to any dust there may be in the air and then move very slowly so that their rate of recombination becomes exceedingly slow. M^cClelland[*] has shown that the velocity of the ions under a given electric force decreases very much as they recede from the flame; thus close to the flame the velocity under the force of a volt per centimetre was ·23 cm./sec., while some distance away from it the velocity was only ·04 cm./sec.

In order that a conductor should be discharged by a flame it is not necessary that it should be placed where the gases from the flame would naturally strike it—thus for example it will be discharged if placed underneath a Bunsen flame. The explanation of this is that the electric field due to the charged conductor drags out of the flame and up to the conductor ions of opposite sign to the charge.

This ionised gas is produced by flames of coal gas whether luminous or not, by the oxy-hydrogen flame, by the alcohol flame of a spirit lamp, by a flame of carbonic oxide; it is not however produced in very low temperature flames such as the pale lambent flame of ether. Thus to produce the ionised gas high temperature as well as chemical combination is required. That chemical combination alone is insufficient to produce ionisation is shown by the case of hydrogen and chlorine which do not conduct even when combining under ultra-violet light[†]. Braun[‡] has shown that in the explosive wave produced in the combination of certain gases there is ionisation, but in this case there is also very high temperature.

In the coal-gas flame the part where the gas comes in contact with the air and where there is most combustion is positively electrified, while the interior of the flame is negatively electrified; this accounts for the effect produced by holding a negatively electrified body near the flame, the luminous part turns to the negative body, and if this is near, stretches out until it comes into contact with it; if the flame be placed between two

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[*] M^cClelland, *Phil. Mag.* v. 46, p. 29, 1898.

[†] J. J. Thomson, *Proc. Camb. Phil. Soc.* xi. p. 90, 1901.

[‡] Braun, *Zeitschrift für Physikalische Chemie*, xiii. p. 155, 1894.

oppositely charged plates the bright outer portion of the flame is attracted towards the negative plate while the inner portion moves, but less markedly, towards the positive plate. This effect is illustrated by Fig. 49 taken from a paper by Neureneuf*. In some experiments made by Holtz†, one of which is figured in Fig. 50, the flame was divided by the electric field between the plates into two sheets; the reader will find many other interesting experiments on the effect of an electric field on the shape of flames in the papers by Neureneuf and Holtz. It appears from these results that in the bright portion of the flame where combustion is taking place there is an excess of positive electricity, while in the unburnt coal gas there is an excess of negative, a fact discovered a long time ago by Pouillet‡. If the hydrogen and oxygen were ionised by the heat, then since negative ions of oxygen combine with positive ions of hydrogen to form water, the

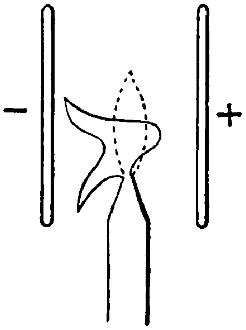

Fig. 49.

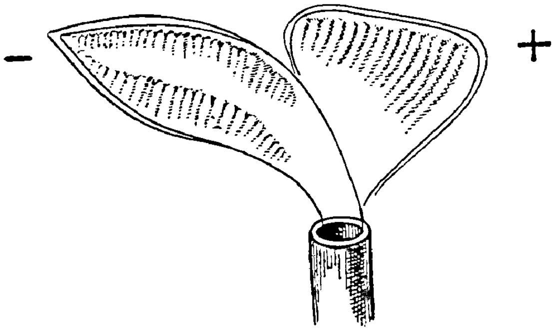

Fig 50.

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* Neureneuf, *Annales de Chim. et de Phys.* v. 2, p. 473, 1874.

† Holtz, *Carl Répert.* xvii. p. 269, 1881.

‡ Pouillet, *Ann. de Chim. et de Phys.* xxxv. p. 410, 1827.

negative oxygen ions and the positive hydrogen ones would get used up, and there would be an excess of positive electricity in the oxygen and of negative in the hydrogen. It is possible too that at a temperature corresponding to that of vivid incandescence in a solid the molecules of a gas may like those of a solid give out the negative corpuscles, on this account there would be a tendency for the hotter parts of the flame to be positively, the colder negatively, electrified. When as in luminous flames we have small particles of solid carbon raised to the temperature of vivid incandescence the electrical effects are complicated by those due to incandescent solids which as we have seen in the last chapter are very considerable.

When two wires connected together through a sensitive galvanometer are placed in different parts of the flame currents flow through the galvanometer; suppose one of the wires is placed in the cool inner portion of the flame where there is an excess of negative electricity, while the other wire is placed at the outside of the flame where there is an excess of positive electricity, there will, neglecting any ionisation due to the wire, be a current from the hot outer portion of the flame to the cool inner portion through the galvanometer: the wire in the outer portion will however certainly be raised to incandescence, if its temperature keeps so low that only positive ions are produced at its surface, then there will on this account be a current of electricity from the hot to the cool part of the flame through the flame and thus in the opposite direction to the previous current. If however the wire got so hot that it emitted more negative than positive ions the effect of the incandescence of the wires would be to increase instead of diminishing the current due to the flame itself. Thus we see that these currents will vary in a complex way with the temperature. For an account of the currents which can thus be tapped from a flame and for other electrical properties of flames we must refer the reader to the papers of Erman*, Hankel†, Hittorf‡, Braun§, Herwig‖, and

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* Erman, *Gilbert. Ann.* xi. p. 150, 1802; xxii. p. 14, 1806.

† Hankel, *Pogg. Ann.* lxxxi. p. 213, 1850; cviii. p. 146, 1859.

‡ Hittorf, *Pogg. Ann.* cxxxvi. p. 197, 1869; Jubelbd. p. 430, 1874.

§ Braun, *Pogg. Ann.* cliv. p. 481, 1875.

‖ Herwig, *Wied. Ann.* i. p. 516, 1877.

especially of Giese*, who was the first to suggest that the conduction of electricity through flames and hot gases was due to the motion of charged ions distributed through the gases: there is a very complete account of these researches in Wiedemann's *Elektricität,* Bd. IV. B, chap. 4.

Conduction of electricity through flames.

122. The passage of electricity through flames has been investigated by Arrhenius†, H. A. Wilson‡, Marx§, Starke||, Moreau¶, Stark**, Tufts††, and Tufts and Stark‡‡. The most important phenomena of flame conduction are as follows.

Distribution of electric intensity between the electrodes.

There is a very intense electric field close to the negative electrode and a weak uniform field between the electrodes, the field

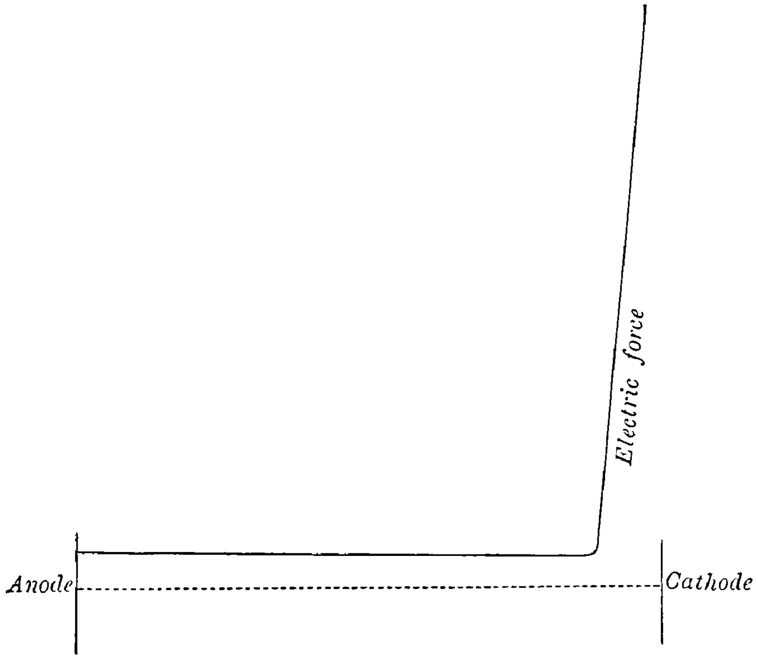

Fig. 51.

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* Giese, *Wied. Ann.* xvii. pp. 1, 236, 519, 1882; xxxviii. p. 403, 1889.

† Arrhenius, *Wied. Ann.* xliii. 18, 1891.

‡ H. A. Wilson, *Phil. Trans.* A, 192, 499, 1899; *Proceedings Physical Society.*

§ Marx, *Ann. d. Phys.* ii. 768, 798, 1900; *Verh. d. D. Phys. Ges.* v. 441, 1903.

|| Starke, *Verh. d. D. Phys. Ges.* v. 364, 1903; vi. 33, 1904.

¶ Moreau, *Ann. de Chimie et de Physique,* vii. 30, p. 1, 1903.

** Stark, *Physik. Zeitschr.* v. 83, 1904.

†† Tufts, *Physik. Zeitschr.* v. 76, 1904.

‡‡ Tufts and Stark, *Physik. Zeitschr.* v. 248, 1904.

near the positive electrode although not nearly so intense as that close to the negative is stronger than that at some distance from either electrode. The distribution of electric intensity is of the type shown in Fig. 51.

Fig. 52 represents the distribution of electric potential measured by H. A. Wilson between electrodes 18 cm. apart in a long flame from a quartz tube burner. The difference of potential between the electrodes was 550 volts and it will be noticed that a drop of 450 volts occurs quite close to the cathode.

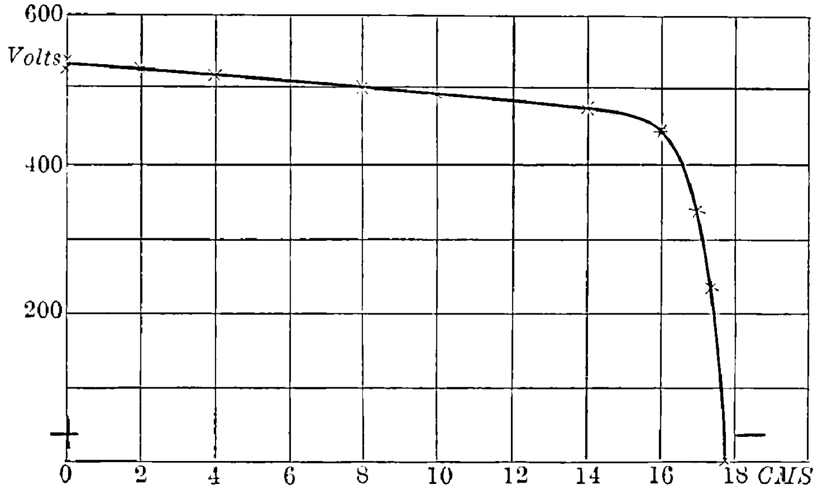

Fig. 52.

If X is the electric intensity at a point x, q the amount of ionisation per unit volume, k_1, k_2 the velocities of the positive and negative ions under unit force, m, n the number of positive and negative ions per unit volume, we have by equation (7), p. 86,

$$\frac{d^2X^2}{dx^2} = 8\pi e(q - \alpha nm)\left(\frac{1}{k_1} + \frac{1}{k_2}\right).$$

Since X is constant along the flame $\frac{d^2X^2}{dx^2}$ vanishes, hence

$$q = \alpha nm.$$

Thus the ionisation balances the recombination: as recombination of the ions is certainly taking place in the flame it follows that there must be ionisation throughout the flame. In the first edition of this book the view was taken that by far the greater part of the ionisation took place in the immediate neighbourhood of the glowing electrodes. Some of the results obtained by H. A. Wilson, especially the fact that even with large potential differences the current was almost independent of the distance between the electrodes, were readily explained on this view; while assuming that the large potential difference was able to saturate the current they were inconsistent with the existence of uniform ionisation throughout the flame, with such ionisation the saturation current would be proportional to the distance between the electrodes. It appears however from the preceding results that even when the potential difference is large the electric field is weak except close to the cathode, so that there is no approach to saturation throughout the flame. We investigated in Art. 48 the relation between the current and the potential difference when the velocity of the negative ion is very much greater than that of the positive; as this is the case in flames, we have by equation (7) of Art. 48

$$X^2 = \frac{\alpha i^2}{qe^2k_2^2} + \frac{\alpha i(i - i_0)}{qe^2k_1k_2}\epsilon^{-\frac{8\pi e^2qk_2}{i\alpha}x} \quad \text{..............(1)},$$

where i_0 is the number of corpuscles coming from unit area of the incandescent cathode per second, x is the distance from the cathode of the place where the electric intensity is X.

This equation represents a distribution of the electric intensity of the same kind as that found in flames, the first term on the right-hand side of the equation represents the uniform field, the second term the variable part near the cathode; since k_1, the velocity of the positive ion under unit force, is very small compared with k_2, the velocity of the negative ion, we see that unless i_0 is nearly equal to i the electric force at the cathode when $x = 0$ will be large compared with that in the uniform part of the field.

If we compare this formula with the results of H. A. Wilson's* experiments we are led to the conclusion that so far from there being an excess of ionisation close to the cathode the ionisation is less there than in the body of the flame. Let us take as an example the case represented by the curve in Fig. 52. Here the electric force in the uniform part of the field was about 8 volts per cm., or, as the quantities in equation (1) are supposed to be expressed in electrostatic units, 8/300. The current between the

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* H. A. Wilson, *Phil. Mag.* [6], 10, p. 476, 1905.

electrodes, which were discs 1 cm. in diameter, was $270 \times 8{\cdot}8 \times 10^{-9}$ amperes, so that the current per unit area in electrostatic units was $\frac{4}{\pi} \times 270 \times 8{\cdot}8 \times 3$. Thus we have

$$\frac{8}{300} = \left\{\frac{\alpha}{qe^2}\right\}^{\frac{1}{2}} \frac{1}{k_2} \frac{4}{\pi} 270 \times 8{\cdot}8 \times 3,$$

so that

$$\left(\frac{\alpha}{qe^2}\right)^{\frac{1}{2}} \frac{1}{k_2} = \frac{\pi}{4 \times 27 \times 10^4}$$

approximately.

The index of the exponential term is $\frac{8\pi e^2 q k_2}{i\alpha} x$; substituting the values of i and α/qe^2, we find that this is equal to $\frac{324 \times 10^6}{k_2} x$.

Now Wilson has shown that the velocity of the negative ion under a force of a volt per centimetre is about 1000 cm./sec.; k_2 is the velocity under unit electrostatic force, *i.e.* 300 volts per centimetre, *i.e.* k_2 is about 3×10^5. Substituting this value for k_2 we find that the exponential term is ϵ^{-1080x}, with this value of the exponential term the field would become practically uniform at a distance not exceeding a very small fraction of a millimetre from the cathode. An inspection of Fig. 52 shows that the variable part of the field extends to quite 1 cm. from the cathode, a result quite inconsistent with its representation by the term ϵ^{-1080x}. We have assumed that the q occurring in the exponential term is equal to that in the constant term, if however the ionisation is variable from point to point this will not be the case, the q occurring in the exponential term refers to the ionisation near the cathode, if this is less than the q in the body of the flame the index of the exponential term will be less than the value we have calculated. Now the electrode will conduct heat from the flame and will therefore cool it. The process of ionisation is however analogous to the dissociation of a diatomic gas into atoms, and the expression for the amount of this dissociation contains a factor $e^{-\frac{a}{\theta}}$ where θ is the absolute temperature, so that this factor varies very rapidly with the temperature. Thus a comparatively slight cooling of the gas near the cathode would produce a great diminution in q, this diminution in q would diminish the index in the exponential term in equation (1) and thus increase the thickness of the variable part of the electric field.

We have seen on page 97 that equation (1) leads to the following relation between V the potential difference between the plates, i the current through unit area and l the distance between the electrodes:

$$V = \frac{il}{k_2}\left\{\frac{\alpha}{qe^2}\right\}^{\frac{1}{2}} + \frac{i\sqrt{i(i-i_0)}}{k_1^{\frac{1}{2}}k_2^{\frac{3}{2}}}\frac{1}{8\pi}\left(\frac{\alpha}{qe^2}\right)^{\frac{3}{2}} \quad \ldots\ldots\ldots(2).$$

When i_0 is small compared with i, this equation becomes

$$V = \frac{il}{k_2}\left(\frac{\alpha}{qe^2}\right)^{\frac{1}{2}} + \frac{i^2}{8\pi k_1^{\frac{1}{2}}k_2^{\frac{3}{2}}}\left(\frac{\alpha}{qe^2}\right)^{\frac{3}{2}} \quad \ldots\ldots\ldots\ldots\ldots(3).$$

The first term represents the fall of potential in the body of the flame, this is proportional to the current; the second term represents the drop of potential at the cathode, this is proportional to the square of the current. H. A. Wilson has shown that the relation between the potential difference and the current can be expressed with great accuracy by an equation of the type

$$V = Ai + Bi^2.$$

Conductivity of Gases containing Salt Vapours.

123. When the vapours of salts are introduced into a flame the conductivity between metallic terminals is very greatly increased, and the electrical properties are simpler and more regular than in pure flames; the laws of the flow of electricity through these salt-laden flames have been investigated by Arrhenius* and H. A. Wilson†. The method—devised by Arrhenius and adopted by Wilson—of introducing the salt into the flame was as follows: a dilute solution of the salt was sprayed into exceedingly fine drops by a Gouy sprayer, the spray got well mixed with the coal gas on its way to the burner, and in the flame the water evaporated and the salt vaporised. The amount of salt supplied to the flame in unit time was estimated by determining

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* Arrhenius, *Wied. Ann.* xlii. p. 18, 1891.

† H. A. Wilson, *Phil. Trans.* A, 192, p. 499, 1899.