GAS-DISCHARGE TUBES

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FOREWORD

A fascinating field of modern science and technology is dealt with in this book. The author has spent almost a lifetime working on gas-filled discharge tubes for industrial and electrical engineering applications – doing research on them, developing them, testing them – and has thus covered the wide field of gas discharges from many angles. He therefore writes with the authority of experience, to the benefit of his readers – especially those who are new to this field.

The explosive expansion of this subject during the past half century has made it impossible for any one person to be an expert in the whole field. This makes it the more important that the author's ample store of practical knowledge and experience (much of which has never been published before) is laid down in this book. The younger generation of workers in this field will find much to interest, and maybe inspire, them, and even the expert will find facts which are new to him. Moreover, those who simply wish to use gas-discharge tubes without going too deeply into the theory of their operation will find this book invaluable.

We of the old brigade in this interesting field of applied science appreciate it highly that the author had the initiative, the energy and the patience to complete this valuable book. We commend it to the readers, and wish it many years of fruitful life.

November 1963 Dr. J. G. W. Mulder

Translated from the Dutch by R. H. Bathgate, Knegsel, The Netherlands

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PREFACE

The extensive periodical literature on electronics contains many articles dealing with gas-discharge tubes, but it will be difficult to find a good review article on this type of tube. This book has been written to fill this gap. It describes the construction and operation of these tubes and the physical principles on which they are based, and gives practical details of typical applications.

Gas-discharge tubes exist for all kinds of purposes, but this book deals only with the most important types as used at present in industry and research, and for traction purposes. Some of the tubes described here have been, or are likely to be, superseded by more modern electronic devices such as semiconductor diodes and transistors; but others, e.g. mercury vapour rectifiers, are still in active development for welding and other heavy-duty applications (e.g. traction, inverter stations and transmitter supply). Other tubes are finding growing application in nuclear research and allied fields (e.g. as radiation counters), where there is still plenty of room for expansion.

Gas-discharge light sources are not dealt with in this book.

The author's aim has been mainly to give the user of gas-discharge tubes sufficient information (including plenty of practical examples) to enable him to deal with any problems which may arise in connection with the application of these tubes. The scientific level of the treatment makes it suitable for a skilled technician (what is known as a "practical engineer" in the U.S.A., or the graduate of a "higher technical school" in Holland).

It is clear that the electronic circuits associated with gas-discharge tubes may take many different forms, depending on the precise problems to be dealt with. These circuits are only described in sufficient detail to explain the different applications of the tubes in question; for further details, the reader is referred to the literature. (References in brackets throughout this book refer to the bibliography at the end of the book.)

Note:

The reader will notice that the characteristics of several types of tubes are given with quite a wide tolerance. Similar characteristics are met with in the operating data supplied by the manufacturers of these tubes. For a given tube, the characteristic can in fact be specified much more closely:

the tolerance indicated is due to the spread in the characteristics of different tubes of the same type. This spread will probably be gradually reduced in the future, as the factors governing the manufacturing process come to be better known. However, the spread does not normally matter in practice, since the operating conditions are usually flexible enough to allow for it.

Acknowledgements

The author received much helpful information during the writing of this book.

In particular he is very indebted to Dr. Ir. J. G. W. Mulder who gave him valuable guidance during his first steps in the field of gas discharges and for so many years thereafter. He acknowledges his constructive criticism. He is also very thankful for the help and many important suggestions received from Dr. Th. P. J. Botden and from Prof. Dr. A. A. Kruithof.

Especially the part concerning radiation counter tubes has been thoroughly revised by Dr. K. van Duuren, for whose help the author is very much obliged.

Moreover he wishes to thank very much Dr. O. Reifenschweiler who gave much constructive assistance in the writing of the section dealing with neutron generators. Prof. Dr. K. S. Knol's kind advice re noise tubes is gratefully acknowledged.

Many thanks are also due to Mr. R. H. Bathgate who translated the Dutch manuscript into English.

Finally he is very grateful to his friends and colleagues who offered their assistance during the preparation of the book, and he wishes to express his gratitude to the firms and individuals who gave their permission to reproduce certain illustrations. The sources are indicated in the captions to the figures in question.

November, 1963. H. L. van der Horst

CHAPTER I

PHYSICAL PRINCIPLES

1-a Introduction

Under normal circumstances, a gas is a nearly perfect insulator: the molecules and atoms are electrically neutral, so that their motion is not affected by electric or magnetic fields. If we are to get an idea of what happens in a gas discharge, we must first realize how a gas can become conducting. In order for this to happen, *free* charged particles must be produced in the gas. These will then move under the influence of the electric field produced between the negative electrode (the cathode) and the positive electrode (the anode), causing an electric current to flow. In this chapter we will first discuss some properties of gases, then some ways in which free electrons can be produced in gases, how their motion is determined and what effects this has on the gas. Finally, those types of discharges which are most important from the point of view of this book will be treated.

1-b The gas

1-b-1 TYPES OF GASES AND VAPOURS

Both inert gases and non-inert gases are used in gas-discharge tubes. The inert gases, helium, neon, argon, krypton and xenon (chemical symbols He, Ne, A, Kr and Xe) have only one atom per molecule and are chemically inactive. Non-inert gases, such as hydrogen, nitrogen, oxygen or carbon dioxide (H_2, N_2, O_2 and CO_2) have more than one atom per molecule, and can take part in chemical reactions.

Vapours (e.g. mercury vapour or alcohol vapour) are sometimes used in gas-discharge tubes instead of gases. We speak of a *saturated* vapour when, at a given temperature, the substance in question exists in the liquid (or sometimes solid) state as well as in the vapour state. At each temperature an equilibrium is established, so that the rate of passage of molecules from the vapour phase to the liquid phase is equal to that in the reverse direction. If the temperature is increased, the pressure of the saturated vapour increases rapidly, causing more and more liquid to evaporate. If the temperature is still increased after all the liquid has evaporated, the vapour is said to be unsaturated; it now behaves more or less like a gas.

I-b-2 GAS PRESSURE AND GAS DENSITY

Not only the nature but also the amount of the gas in the discharge tube is of great importance. This is usually given in terms of pressure, since this can easily be measured. It is however better to use the *density* of the gas, as the density of the gas in an enclosed space is independent of the temperature, while the pressure is not.

The molecules of a gas are in continual rapid motion, and frequently collide with each other. If the temperature is not too high, these collisions are completely elastic, i.e. they only cause changes in the velocity of the molecules, but not in their physical or chemical properties. The molecules merely exchange energy. As long as no energy is lost through the walls of the vessel, the total energy of the gas remains constant and so therefore does its temperature.

If the temperature is increased, the gas molecules move faster. The force with which they collide with the wall of the vessel and the number of collisions will increase correspondingly, in other words the pressure will increase, even if the number of molecules remains constant. The relation between the gas pressure and its density (i.a. the number of molecules per unit volume) is

$$p = n\,k\,T \tag{1}$$

where p = pressure of the gas
n = number of molecules per unit volume = density
k = Boltzmann's constant
T = absolute temperature (in degrees Kelvin, i.e. degrees Centigrade + 273°)

The quantity

$$p_0 = \frac{p\,.\,273}{T} = 273\,n.k \tag{1a}$$

is often used, this is the pressure reduced to 0 °C (= 273 °K). If p_0 is given, it may be seen from (1a) that n is also defined, since 273 k is a constant. For gases and unsaturated vapours, the pressure is proportional to the absolute temperature if the density remains constant.

The pressure of saturated vapours increases much more rapidly than this, as may be seen for mercury vapour in Fig. 1. Since equation (1) still holds, it follows that the number of molecules per unit volume increases with the temperature.

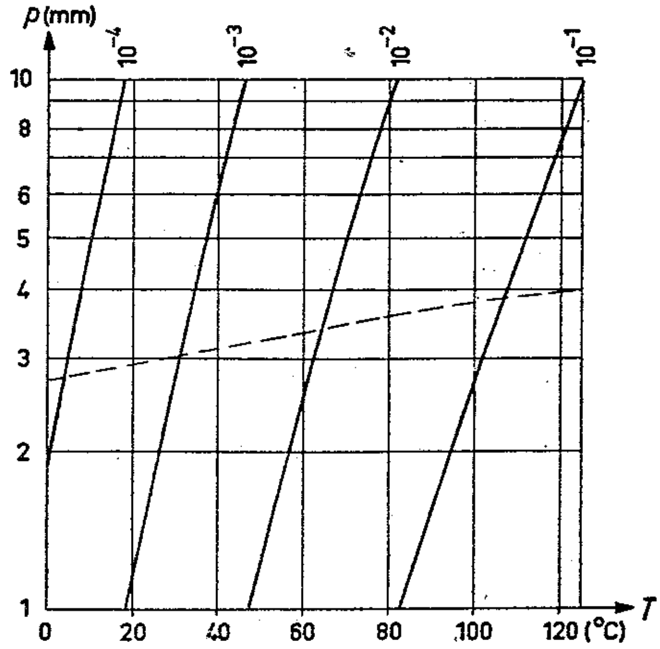

Fig. 1

Vapour pressure p of saturated mercury vapour as a function of the temperature T in degrees centigrade. The broken line represents an increase of the pressure of unsaturated mercury vapour which is proportional to the absolute temperature in degrees Kelvin.

I-b-3 MOLECULES AND ATOMS

The molecules of the gas in a gas-discharge tube occupy very little of the available space at the low pressures which are normal in such tubes. For example, at $p_0 = 1$ mm Hg, although there are about 5×10^{22} molecules per m^3, the average distance between molecules is about 100 times the diameter of a molecule, if we think of it as roughly spherical.

Although monatomic molecules do behave differently from polyatomic ones in a discharge, we will speak of atoms in what follows where these differences are of no vital importance. This is because most discharge tubes contain monatomic gases or mercury vapour, which is also monatomic.

I-c **Electronic emission**

Electrons are minute particles which all carry the same electric charge of about 1.6×10^{-19} coulombs. This charge is often denoted by the letter e.

Under normal conditions, a gas contains very few free electrons, although cosmic rays and other natural phenomena do produce a very small number. A larger number of electrons can enter the gas e.g. from the electrodes or from the walls of the tube. A solid, such as the metal from which an electrode is made, contains a large number of electrons, but it must be treated in some way to make it emit some of these. The three main ways of producing electrons from a substance are to heat it, to apply an electric field to it, and to shine light on to it. These three methods will be discussed in this chapter. Other, less usual, methods such as bombardment with electrons or positive ions will also be mentioned in this chapter in so far as they have an appreciable effect on the mechanism of the discharge. Further methods which have no appreciable effect on the discharge mechanism will not be treated.

I-c-1 THERMIONIC EMISSION [1]

Thermionic emission in vacuo

A metal can emit electrons if it is hot enough. This effect was discovered by Edison in an incandescent lamp in 1883, and is sometimes called the Edison effect. He noticed that a conducting disc in the lamp acquired a negative charge while the lamp was burning. If now an electric field is applied so that the disc is made positive with respect to the filament (i.e. the filament is the cathode and the disc is the anode; see Fig. 2), a stream of electrons will flow from the filament to the disc. It is normal to indicate the direction of flow of the electric current as being in the opposite direction from that of the electrons.

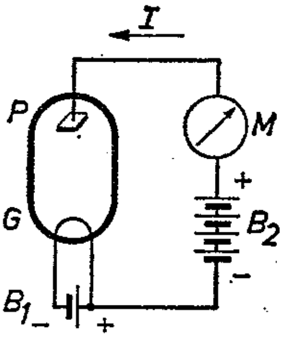

Fig. 2
The Edison effect.
If the voltage of the battery B_2 is applied between the filament G, which acts as the cathode and is heated to incandescence by the battery B_1, and the anode P (i.e. P is positive), electrons move in the tube from G to P. Since the electrons carry a negative charge, the meter M will indicate a current I in the direction shown in the figure.

Richardson's emission equation

The rate of emission of electrons from a thermionically emitting cathode depends on the temperature and the "work function" φ of the metal. This is equal to the potential difference in volts which the electron must overcome before it can leave the metal; in other words, an electron must possess an energy of $e\varphi$ joules before it can leave the metal.

The electron current which leaves the unit surface of a metal at a given temperature is known as the specific emission, and is given by Richardson's equation:

$$I_s = A\,T^2\varepsilon^{-\frac{e\varphi}{kT}} \qquad (2)$$

where I_s = electron current density in A/m^2 = specific emission,
$A \approx 10^6$ $A/m^2.\,(°K)^2$,
T = absolute temperature in degrees Kelvin,

ε = the base of the natural logarithms ($\sim$2.718),
and k = Boltzmann's constant (1.38×10^{-23} joule/°K).

As may be seen from Table I, each metal has its own value of the work function. However, changes in the state of the metal can have a large effect on the work function. For example, φ is much lower for a thin layer of barium atoms adsorbed on barium oxide (barium on barium oxide, Table I) than for barium metal in bulk. Similarly, thoriated tungsten (a specially prepared mixture of thorium and tungsten) has a lower work function than either thorium or tungsten by itself.

TABLE I

WORK FUNCTION φ IN VOLTS FOR A NUMBER OF METALS, CARBON, AND BARIUM ON BARIUM OXIDE, ARRANGED IN ORDER OF INCREASING MAGNITUDE

Material	φ	Material	φ	Material	φ
Barium on barium oxide	1.1	Thoriated tungsten	2.7	Iron	4.4
Caesium	1.9	Calcium	2.8	Carbon (graphite)	4.4
Potassium	2.1	Thorium (in bulk)	3.3	Mercury	4.5
Sodium	2.3	Magnesium	3.5	Tungsten (in bulk)	4.5
Barium (in bulk)	2.3	Tantalum	4.1	Nickel	4.9
Strontium	2.3	Zirconium	4.2	Platinum	5.3
		Molybdenum	4.3		

The specific emission of tungsten-oxide cathodes

The heater in a vacuum tube is often made of tungsten (symbol *W*), which has a high melting point (3655 °K).

In Table II are given the values of the specific emission I_s of tungsten at various temperatures. The total current emitted by a tungsten wire of diameter d metres and length l metres is thus $I = I_s \times \pi \times d \times l$ A.

TABLE II

SPECIFIC EMISSION I_S OF PURE TUNGSTEN AS A FUNCTION OF THE TEMPERATURE [112]

Temperature (°K)	2000	2200	2400	2600	2800	3000
I_s (A/m^2)	10	133	1160	7170	3.54×10^4	14.15×10^4

The rate of emission of electrons from a heated wire such as tungsten or nickel can be considerably increased by coating it with a suitable oxide, e.g. thorium oxide on tungsten or barium oxide on nickel. If a nickel wire is given such a coating, a very thin layer of barium atoms can be formed on top of the coating (this process is known as "activation"). It may be seen from Table I that these barium atoms have a work function of only 1.1 V. It follows from Equation (2) that the specific emission of such an oxide cathode is 1.5×10^4 A/m² at 1100 °K.

Saturation and space charge

If a voltage of e.g. a few tens of volts is applied between the cathode and anode of a vacuum tube, it will be found that the emission current is much less than that calculated from Equation (2).

Richardson's Equation gives the *saturation current,* i.e. the maximum current which the cathode can emit at the temperature in question. The fact that the actual current is much lower than this can be explained as follows: the electrons leaving the cathode build up as it were a negatively charged "cloud" of large density *(space charge)* in neighbourhood thus partly reducing the electric field just in front of the cathode and sometimes even reversing its sign (see Fig. 3, curves 1 and 2). The further emission of electrons from the cathode is thus hindered and many electrons even return to the cathode.

The negative space charge can be diminished by increasing the electric field strength between the cathode and the anode, e.g. by increasing the voltage between them. The emission current at a given cathode temperature will therefore increase as the voltage is raised (see Fig. 4). If the anode voltage is raised far enough, however, the electron emission no longer increases: the saturation current for that temperature has been reached. The field strength at the cathode will then no longer be negative (Fig. 3, curve 3). The voltage above which the current no longer increases is called the saturation voltage.

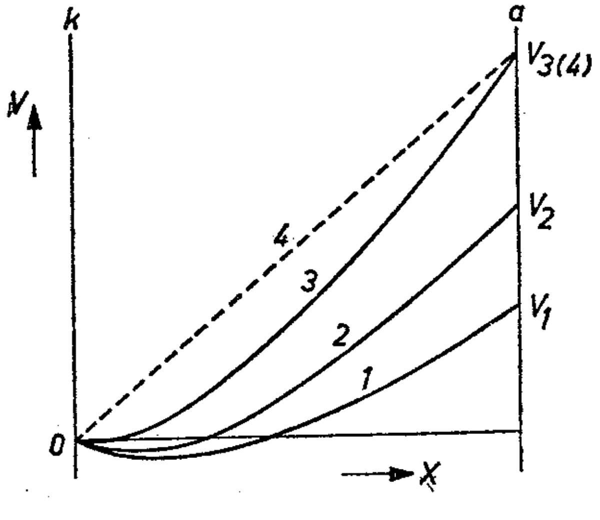

Fig. 3
The potential V as a function of the distance x between the electrodes k (cathode) and a (anode) for three values of the anode voltage: V_1, V_2 and $V_3 = V_4$. Curves *1, 2* and *3* relate to a cathode which is emitting electrons; curve *4* is without emission. The negative space charge near the cathode causes the potential curves to deviate from the straight line in a downward direction. Curve *3* starts off just horizontal by the cathode. The electrons which leave the cathode do not return, but all go to the anode; the saturation current is just reached for the anode voltage V_3.

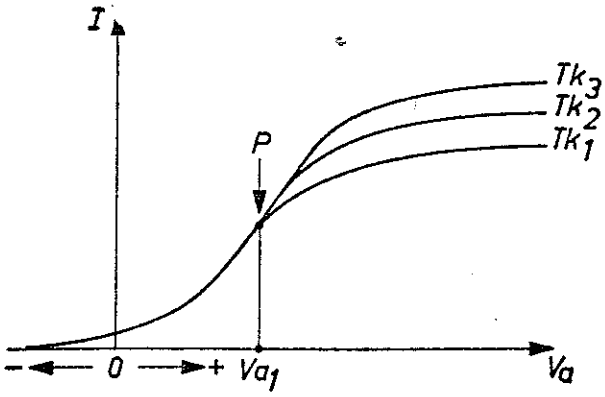

Fig. 4

The emission current I as a function of the anode voltage V_a for three values of the cathode temperture, T_{k1}, T_{k2} and T_{k3}. Up to the point P (anode voltage V_{a1}), the current is determined by the anode voltage alone. If the voltage is increased further, I tends to the saturation current, which is higher the higher the cathode temperature.

If on the other hand the anode voltage is kept constant at a value considerably below the saturation voltage and the cathode temperature is increased (Fig. 5), the emission current will also increase until a temperature is reached at which the negative space charge formed in front of the cathode is so great as to prevent the emission of further electrons. The maximum current then will be far less than the saturation current at that temperature.

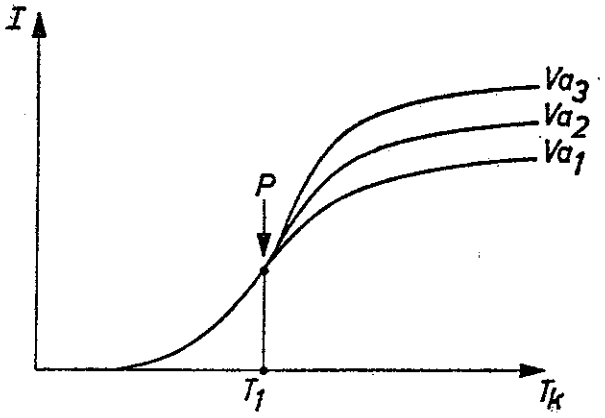

Fig. 5

The emission current I as a function of the cathode temperature T_k for three values of the anode voltage: V_{a1}, V_{a2} and V_{a3}. Up to the point P (cathode temperature T_1), the emission current is saturated and depends only on T_k. If T_k is increased beyond T_1, the anode voltage has an effect on I, and the emission is not saturated.

Thermionic emission in a gas

The saturation voltage of a vacuum tube is very high compared to that in a gas-filled tube. It is reasonable to expect that the number of electrons which a heated filament can emit at a given temperature will not depend on whether there is any gas present. It will be shown in Section 1-g-3. B that in a gas discharge the effect of the space charge in front of the cathode can be annulled under certain conditions, so that the saturation current is reached at a relatively low anode voltage.

I-c-2 FIELD EMISSION

Field emission, otherwise known as cold emission or auto-emission, is the emission of electrons by conductors at very high electric field strengths. A field strength of the order of 10^9 V/m is usually needed for this, although in certain cases 10^7 V/m is enough. The discharge currents measured in the latter case are, however, very small, of the order of thousandths of a μA [82, 83].

I-c-3 PHOTO-EMISSION

If light or some other form of electromagnetic radiation falls on an electrode, electrons will be emitted under certain circumstances. This will be discussed in further detail in Chapter II and VII.

I-d **Collisions between electrons and gas atoms**

I-d-1 MOTION OF THE ELECTRONS IN THE GAS

Let us imagine a closed vessel containing gas atoms and electrons. There are two reasons why the electrons should move. In the first place they will move from regions where they are concentrated to regions where they are not so concentrated, just like each atomic species in the gas. This type of motion is called *diffusion*. In a gas discharge, diffusion of the electrons will always be found when differences in the electron density occur. Secondly, the electrons will move under the influence of an electric field. If two metal electrodes are sealed into the above-mentioned vessel and a voltage is applied between them, an electric field will be produced in the vessel which will cause the negatively charged electrons to move away from the negative cathode and towards the positive anode. The distance an electron can move before it comes into collision with a gas atom depends on the density and nature of the gas. We speak of the *mean free path* λ_e of

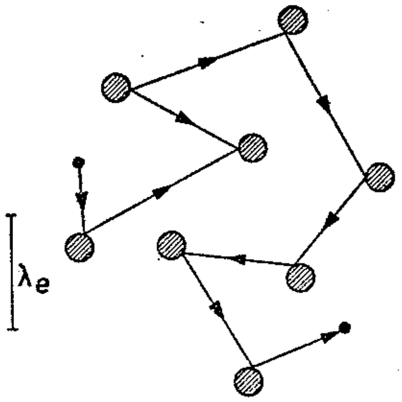

Fig. 6a

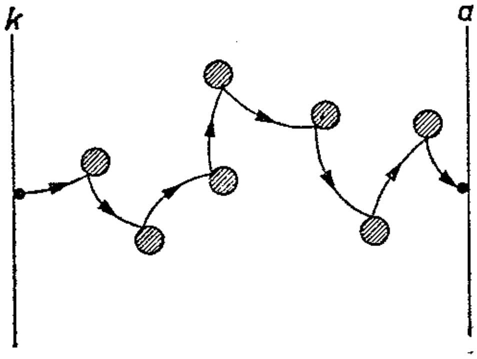

Fig. 6b

▨ = gas atom
● = electron
λ_e = mean free path of the electrons.

Fig. 6a
The path described by an electron in a gas in the absence of an electric field. The electron moves in straight lines between collisions. λ_e = mean free path.

Fig. 6b
The path described by an electron in a gas under the influence of an electric field. The electron moves along curved paths which are concave towards the anode.

the electrons, because the distance moved between two collisions varies because of the irregular distribution of the atoms in space. The value of λ_e is lower the more atoms there are per unit volume, and the larger these atoms are. The connection between these quantities is given by:

$$\lambda_e = \frac{4}{\pi d_a^2 n} \tag{3}$$

where d_a = diameter of atoms
and n = number of atoms per unit volume = density of atoms.

It follows from Equation (1) together with Equation (1a) of Section I-b-2 that λ_e is inversely proportional to the reduced pressure p_0.

The motion of diffusing electrons is sketched in Fig. 6a, and that of electrons in an electric field in Fig. 6b.

I-d-2 ELASTIC COLLISIONS

Let us suppose that an electron of mass m, after having obtained a velocity v, and thus an energy $\frac{1}{2}mv^2$, as the result of previous collisions, collides with a gas atom with the much greater mass M. In by far the most collisions, the electron will give up only a small part of its energy to the atom, and will move off in a new direction after collision. The energy transferred to the atom will manifest itself as an increase in the heat of the gas, and not as a change in the state of the atom. Since the atom behaves as a completely elastic body, such collisions are known as *elastic collisions.*

The fraction of the energy of the electron transferred to the atom can be calculated by the methods of classical mechanics, and is found to have an average value of $2\ m/M$ per collision if enough collisions are considered. Now the mass of the electron is about 1/1840 times that of the hydrogen atom, while that of e.g. neon is 20.2 times that of the hydrogen atom, so the electron loses on the average 1/20,000 of its energy at each collision with a neon atom. This means that the energy of the electron is practically unchanged by the collision. The kinetic energy of the electron is thus equal to the potential difference passed through times its charge, $(V_2 - V_1)e$ joules, even if it undergoes elastic collisions.

I-d-3 NON-ELASTIC COLLISIONS

As the kinetic energy of the electrons steadily increases under the influence of the electric field, a moment is reached where the energy lost by the electron in some collisions is considerably greater than in the above-mentioned elastic collisions. In order to understand the consequences of these non-elastic collisions, we must briefly consider the structure of the atom.

Structure and excitation of the atom

According to Bohr's theory of the atom (see e.g. [92]), the electrons in an atom move, each in its own orbit, around the positive nucleus. Each orbit corresponds to a certain energy. Depending on the position of their orbit in the atom, the electrons are more or less firmly bound to the nucleus.

In a gas discharge we are almost entirely concerned with the electron in an atom which is most weakly bound, i.e. in one of the outside orbits. Now this electron is free to occupy a number of different, unoccupied orbits, in each of which its energy is different. These different energies are called the energy levels of the atom. If the atom is left alone, the electron in question will end up in the available unoccupied orbit with the lowest energy. The atom is then said to be in the ground state, and this energy level is known as the ground level. All other energy levels are reckoned from the ground level (see Fig. 7).

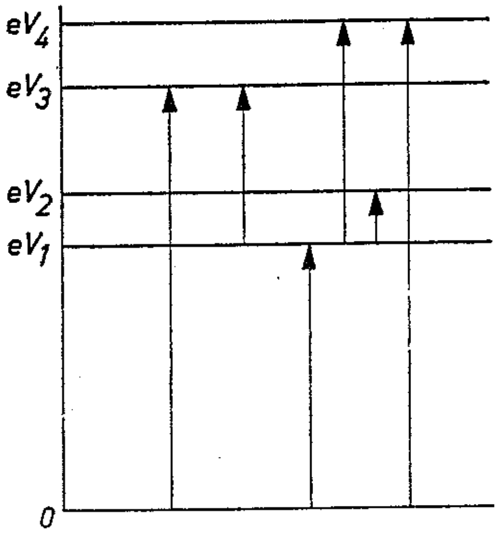

Fig. 7
Sketch of the energy levels of an atom. The ground level is represented by O. The energy differences between the first, second, third and fourth excited levels and the ground level are eV_1, eV_2, eV_3 and eV_4 respectively.

If the atom in its ground state is bombarded with electrons of steadily increasing energy, the outer electron will not be able to move to another orbit until the energy eV_1 of the bombarding electron is equal to the energy difference between the ground level and the next higher one. This process of bringing the electron into an orbit with higher energy is known as the excitation of the atom, which is then said to be in an excited state. The voltage V_1 is, therefore, known as the lowest excitation voltage of the atom.

For neon this excitation voltage is 16.55 V. Bombardment with electrons of energy less than 16.55 e joule cannot thus lead to excitation. If the electrons possess a greater energy than this, excitation is possible and will indeed occur in some of the collisions. The excited state can usually only last for a short time (about 10^{-8} second), after which the electron which has been displaced returns to the ground state, emitting radiation in the process.

The energy of the emitted radiation is again exactly eV_1 joule, the energy difference between the (first) excited state and the ground state. The frequency ν of the radiation is now given by Planck's quantum law:

$$eV = h\nu \tag{4}$$

where eV is the energy of the radiation
and h is Planck's constant, 6.625×10^{-34} watt-second^2.

The atom has many other excited energy levels above the first excited energy level, each with its own energy. If the atom is excited into one of these higher energy levels by a fast electron, it can return to the ground state either directly or via one or more other excited states, each successive one lying closer to the nucleus. Each time the atom passes from one state to a lower one, it emits energy in amounts characteristic of the atom. Since the quantum law always holds for this emission, the radiation emitted by the atom can have a series of sharply defined frequencies, each one corresponding to a line in the spectrum, which are also characteristic of the atom. In other words, if light is emitted by a gas in a gas discharge, the spectral lines in the emitted light indicate the nature of the gas. Often the colour alone is enough to show which gas is used in the tube.

On the other hand, a quantum of radiation coming from outside can be absorbed by the atom and excite it if it is of the right size (e.g. eV_1 for the first excited level).

Metastable states

In some excited states of the atom, the excited electron can remain in its orbit for much longer than 10^{-8} second — up to e.g. more than 0.1 second.

The atom is then said to be in a *metastable* excited state. According to the quantum theory, this is because the atom in such a state cannot return to the ground state simply by emitting radiation, but must lose some or all of its energy by collision with other atoms or with the wall of the tube. It can also happen that the atom collides with another fast electron, which excites it to a still higher state from which it can easily return to the ground state.

Ionization

If an electron which collides with an atom in the ground state has enough energy (at least eV_i joule), it can free the outermost electron completely from the atom. The minimum energy necessary is known as the ionization energy, and the corresponding voltage V_i, as the ionization voltage. After this collision, the atom has become a positively charged *ion*, since it has lost an electron, while we now have two free electrons instead of one. This process is called ionization by collision. For neon the bombarding electron must have a kinetic energy of at least 21,5e joule for this to be possible.

If metastable atoms with an excitation energy of eV_a' are produced in a discharge, the bombarding electrons only need to have the energy eV_i—eV_a' to ionize the atom. In this case, we speak of cumulative ionization.

As we have already seen, an ion is a charge carrier, in contrast with an excited atom or an atom in a metastable state, which is electrically neutral.

Now it can happen — but only with non-inert gases — that one or more free electrons tack on to an originally neutral gas atom, thus forming a negatively charged ion. In the tubes we are going to consider, however, only the positive ions are of importance.

An atom can be ionized in other ways than by collision with an electron: by collision with a positive ion, by quanta of radiation of energy $hv \geqslant eV_i$ joule or by collision with fastmoving neutral atoms at high temperatures. These other possibilities are also negligible compared to ionization due to electrons in all the gas discharge tubes discussed in this book, so we will not consider them any further.

Ionization probability and excitation probability

Let us consider an electron moving through a gas under the influence of an electric field. In the beginning, when its velocity, and thus its energy, is low, it will only undergo elastic collisions. The atoms are not changed by the collision, and the energy of the electrons increases steadily. When this energy exceeds eV_a joule, there is a chance at each collision that the atom will be excited, although most of the collisions will still be elastic. Finally, when the energy exceeds eV_i joule, there is a chance that the atom will be ionized, besides the chance that it will be excited. If it is ionized, we then have two free electrons instead of one.

Both of these electrons have a low energy, and the process just described repeats itself. A kind of chain reaction is thus produced, which may result in a "avalanche" of electrons.

Let us now consider a stream of electrons moving in an electric field through a gas. At every spot we will find some electrons with a low energy and some with a high energy. Those with a low energy will only undergo elastic collisions, while those with high energies may also excite or even ionize the atoms of the gas.

It has been found for a discharge in neon between two plane electrodes a large distance apart, where the ratio of the field strength F to the reduced pressure p_0 of the gas is $F/p_0 = 10^4$ V/m . mm Hg, that 32 % of the energy which the electrons gain from the field is used for ionizations, 44 % for excitation and 24 % heats the anode; the energy transferred to the gas by elastic collisions is less than 1 %. The corresponding percentages for other values of F/p_0 are shown in Fig. 8.

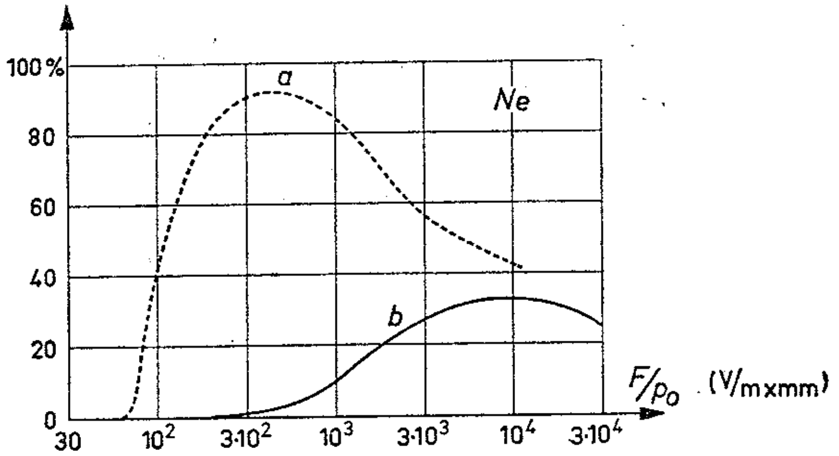

Fig. 8

The percentage of the energy which the electrons gain from the electric field (which is a function of F/p_0), used for:
a = excitation of the atoms,
b = ionization,
F = electric field strength,
p_0 = reduced pressure of the gas [67].

The ionization coefficient

If a stream of electrons passes through the gas in a homogeneous electric field, the number of newly formed electrons is proportional to the electron current, so that the percentage increase per volt potential difference passed through is constant. This percentage also depends on the increase in the velocity of the electrons per mean free path caused by the field. This increase is proportional to the electrical field strength F and to the mean free path $\lambda_e = 4/\pi d_a^2 n$ (see I-d-1 (3)), i.e. inversely proportional to n or to p_0 (see I-b-2 (1a)).

The increase in the velocity of the electrons is thus proportional to F/p_0; and the relative increase in the electron current per volt potential difference passed through, which is called the ionization coefficient (per volt) η, also depends on the ratio F/p_0.

Another ionization coefficient, $\alpha = \eta \times F$, is sometimes used. Since, in a homogeneous field, F is the potential difference per metre, α represents the relative increase of the electron current per metre passed through. The ionization coefficient was introduced by Townsend. We may now write $\alpha/p_0 = \eta\ (F/p_0) \times F/p_0$. It thus follows that α/p_0, like η, is a function of F/p_0.

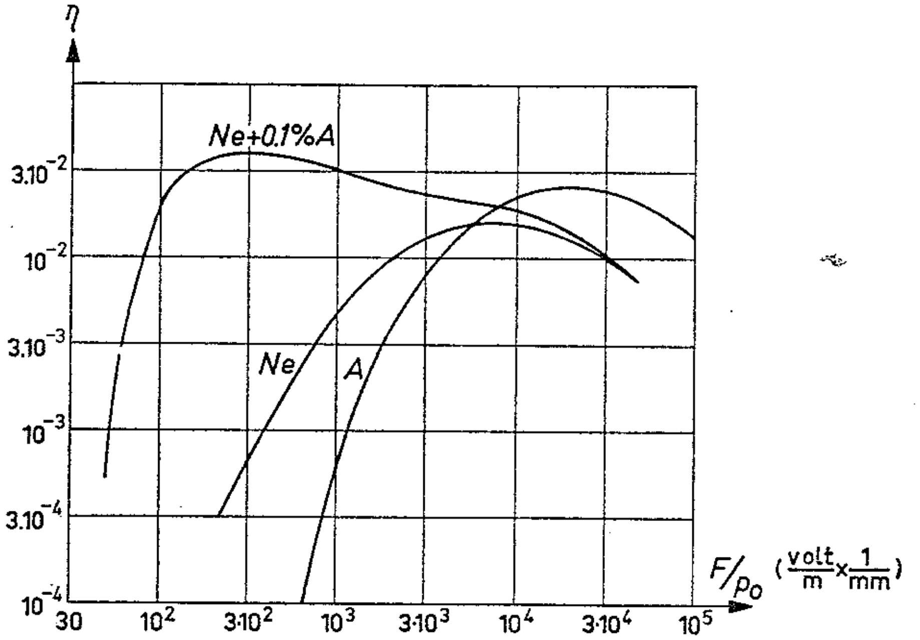

Fig. 9

The ionization coefficient η per volt potential difference passed through, as a function of the ratio of the field strength to the reduced pressure, F/p_0, for neon, argon and neon + 0.1 % argon.

Fig. 9 shows η as a function of F/p_0 for neon, argon, and the mixture neon + 0.1 % argon. The ionization coefficient η for pure gases shows a definite maximum at a certain value of F/p_0. As the value of F/p_0 decreases from this value, the excitation probability and the energy loss of the electrons with elastic collisions respectively will increase considerably at the expense of the ionizations; as F/p_0 increases the number of collisions decreases considerably, so that more energy is transferred to the anode and thus lost for ionization. It may also be seen from the figure that the ionization increases considerably if a little argon is mixed with the neon. Especially at low values of F/p_0, a large number of neon atoms are excited. Among these will be quite a large number of metastable neon atoms with $V_a' = 16.55$ V. These last for a relatively long time, and thus have quite a fair chance of losing their energy by collision with an argon atom. Since the ionization voltage of argon is only 15.7 V, the argon atom may be ionized by such a colission. This phenomenon is known as the *Penning effect*. It can also occur if other gases than argon are added to the neon, as long as they have an ionization voltage of less than 16.55 V. As metastable atoms have a relatively long life, they are capable of undergoing many collisions before they lose their energy, so only a very small percentage of e.g. argon need be added to increase η considerably.

I-e **Ignition and extinction of the discharge**

While the current in a resistor or a capacitor starts to flow as soon as a potential difference is applied, this it not so with a gas discharge. It takes some time for the current to reach its full value. Similarly, some time is necessary for the conducting state to disappear when the current is cut off. The times which characterize these phenomena are of importance in many circuits. We shall therefore consider them in some detail.

I-e-1 STATISTICAL DELAY TIME AND BUILD-UP TIME

We must make a distinction between the statistical delay time and the build-up time of a discharge. The former is only of importance with discharges which have no source of electrons such as a hot cathode or a photocathode. A number of electrons must then be formed by e.g. cosmic radiation before ionization can begin. Since it is a matter of chance whether a quantum of cosmic radiation enters the tube, the formation of these first electrons is governed by statistical laws. Each free electron thus formed can give rise to an avalanche of electrons, and each electron in the avalanche can give rise to a further avalanche. It is these avalanches which serve to ignite the discharge. The formation of the first avalanches is also governed by statistical laws, and together with the formation of the first electrons determines the *statistical delay time.*

Apart from this, all gas discharges need a certain time for the desired discharge current to be built up. This is the *build-up time.* Before the electron current can reach its final value, the ions formed must have time to spread throughout the tube, especially in order to neutralize the negative space charge near the cathode. The ions, which are much heavier than the electrons, move relatively slowly towards the cathode, so that it takes a certain time before the final state is reached. This time is shorter as the anode voltage is raised, as the ions then move faster. The build-up time of discharges in rare gases may be of the order of a microsecond under favourable circumstances.

I-e-2 THE DISAPPEARANCE OF THE CHARGE CARRIERS

When the anode voltage is removed from a discharge, the current naturally stops immediately; but the charge carriers do not disappear at once. In general the ions and electrons in a discharge can disappear in two ways: by recombination in the gas or by diffusion to the walls or the electrodes and recombination there.

Recombination in the gas

In pure inert gases or metal vapours at low pressures, such as are found in most of the gas-discharge tubes discussed in this book, the recombination of positive ions with electrons in the gas is a most unlikely process. According to the laws of mechanics, such recombination can only occur if another particle is involved in the collision, which is thus called a "three-body collision". The number of such collisions at the low pressures normally found in gas-discharge tubes is negligibly small.

Recombination in the gas is however possible in non-inert gases such as hydrogen, which can form molecular ions.

Recombination at the walls

In pure inert gases or metal vapours, the disappearance of electrons and ions only occurs by means of collisions of these with the walls of the tube or the electrodes, which thus as it were play the role of the "third body". For this to be possible, the charged particles must diffuse to the walls. Ions diffuse slowly, because each collision with neutral atoms causes them to lose much of their energy, while their velocities are naturally low as a result of their large masses. The electrons, which acquire much higher velocities because of their low mass, initially arrive at the walls in large numbers, giving them a negative charge. This causes the electrons remaining in the gas to be retarded and the ions to be attracted and the build-up of the wall charge proceeds more slowly, until finally in the steady state as many ions as electrons reach the walls per second. The energy released by the recombination is taken up by the walls as heat.

Recombination after the discharge is stopped

When the discharge is stopped, the recombination on the walls and electrodes continues, and the number of free electrons and ions in the tube gradually decreases.

The diffusion of the ions to the walls or electrodes can be considerably increased by giving them a negative electrical potential so that they attract the ions. Even if the optimum value of this voltage is chosen, the complete disappearance of ions and electrons from a mercury discharge takes a millisecond or more.

I-f **The discharge plasma** [3, 4, 67, 78 and 79]

The concentrations of positively and negatively charged particles in a space containing the atoms, electrons and ions of a gas discharge will not be the same at all points. In some places, there will be more electrons than ions, and at other places the reverse will be true.

Where there is an excess of negative charges, we speak of a negative space charge, and where positive charges are in the majority of a positive space charge. In the special case that the negative charges completely neutralize the positive charges of the ions, or very nearly do so, we speak of a *(discharge) plasma.* We will meet a number of discharge plasmas in the various types of discharges discussed below, e.g. the dark part *F* of the glow discharge between two plane electrodes, which occurs next to the glow itself (cf. Fig. 10) and the positive column in a long cylindrical tube.

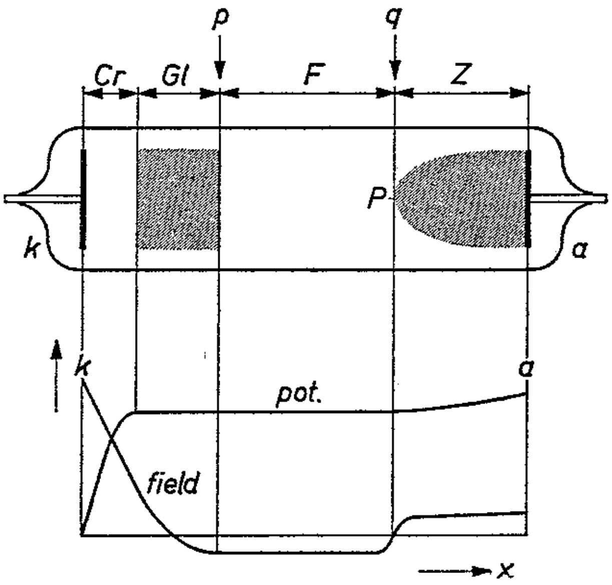

Fig. 10

Light effects in a tube with two flat electrodes.

Cr = Crookes dark space.
Gl = negative glow.
F = Faraday dark space.
Z = positive column.
p = boundary between negative glow and Faraday dark space.
q, *P* = start of the positive column.
x = distance from *k*.

The variation of the potential and the field between the electrodes are also shown.

There is practically no electric field in a plasma, because of the neutralization of the space charge. The particles are in continual motion, which is mainly random and only slight in any given direction. Each type of particles, the gas atoms, the electrons and the ions, has its own velocity distribution; if the current in the discharge is not too low, this is a "Max-

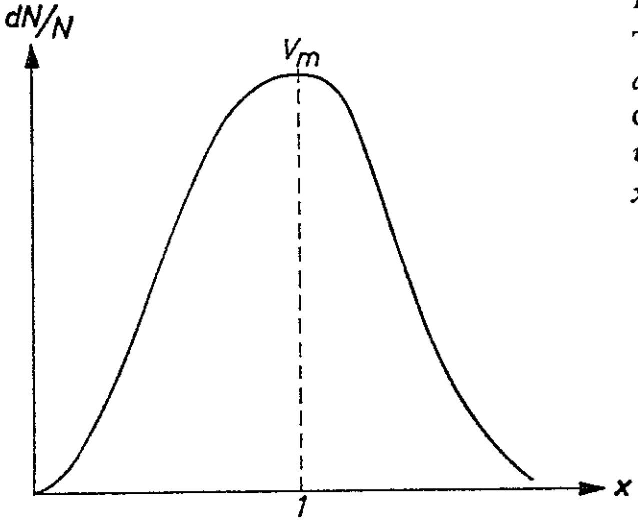

Fig. 11
The Maxwell distribution of velocities.
dN/N = fraction of the total number of particles,
v_m = most probable velocity,
$x = v/v_m$, where v = actual velocity.

well" distribution for each one. Such a distribution is sketched in Fig. 11. It may be described by the equation

$$\frac{dN}{N} = \frac{4}{\sqrt{\pi}} x^2 \varepsilon^{-x^2} dx \tag{5}$$

where dN/N is the fraction of the total number N of particles which have a velocity between v and $v + d\,v$, while $x = \frac{v}{v_m}$. We call v_m "the most probable velocity"; it is equal to 0.81 times the root mean square velocity $\sqrt{\overline{v^2}}$ (see Fig. 11). The only variable parameter which determines the precise form of the Maxwell distribution for a given case is v_m, which is closely related to the temperature of the "gas" (which may be a real gas, or an electron gas or ion gas) in question.

The mean kinetic energy W_m of the gas particles is equal to $\frac{1}{2}\, m\overline{v^2}$ and is proportional to the absolute temperature T:

$$W_m = \tfrac{1}{2}\, m\overline{v^2} = \tfrac{3}{2}\, k\, T \tag{6}$$

where k is Boltzmann's constant, 1.38×10^{-23} joule/°K.

The electron temperature [4]

If we apply the equation $W_m = \frac{3}{2}\, kT$ to the "electron gas" we obtain a certain temperature. We have already mentioned in I-d-2 that the free electrons in the plasma lose very little energy to the atoms when the collisions are elastic. The energy transfer in a discharge at low pressures does not become appreciable until the electrons have acquired so much energy from the field that they can excite the atoms. The mean energy of the electrons in the discharge will thus be much higher than that of the atoms. It is, for example, quite normal for the mean kinetic energy of the electrons to be about $2e$ joule. The corresponding temperature derived from the above equation is about 15000 °K, this means that if the electrons acquired all their energy from the heat of the whole system instead of from the electric field, the temperature would have to be about 15000 °K to give them the same energy. The electron temperature is then said to be 15000 °K. The atoms in the plasma of a low-pressure discharge have a temperature of only a few hundred degrees Kelvin (about 300 to 400 °K), and that of the ions is not much different.

Noise

An important property of the plasma is that the electron density at a given point continually varies about the mean. The space charge, therefore, also varies continually, and with it the voltage across the discharge. If these voltage variations, which are known as noise, are analyzed, it is found that they consist of a mixture of variations of all possible frequencies (up to a certain very high maximum frequency).

Another example of noise is the thermal noise in resistors and oscillating circuits. The density variations in the plasma are however much greater than in a resistor at the same temperature as the gas, since they are determined by the electron temperature and not by the much lower temperature of the gas itself. According to Nyquist, the maximum noise energy which the electrons can produce in any part of a circuit in a frequency band of width Δf is equal to $kT_e \, \Delta f$, where T_e is the electron temperature. The electrons in the plasma not only undergo density variations, but also velocity variations which are associated with the emission of electromagnetic radiation. If this radiation is taken up by a receiver, the maximum amount of energy thus transmitted in a frequency band Δf is also equal to $kT_e \, \Delta f$.

I-g **Types of discharges**

Gas-discharge tubes can be divided into three main groups according to the form of the electrodes, especially the cathode. In the first group we have those tubes with a plane cathode, the anode being e.g. another flat plate parallel to the cathode. In the second group the cathode is a heated filament which emits electrons, and in the third group the cathode is a mercury pool. We will begin by discussing the first group which contains a considerable number of different tubes.

We will then see how the discharges in tubes of the second group, are related to that in tubes of the first group, whereafter we will discuss the second group in some greater detail. The arc discharge which is produced at a mercury-pool cathode does not have a discharge of one of the first two types as precursor. The first stage in such a discharge, the production of an electron-emitting spot on the cathode surface, is discussed in Chapters II and VI. This type of discharge will not be mentioned further in this chapter.

I-g-1 DISCHARGES BETWEEN TWO FLAT PLATES, GLOW DISCHARGES

Non-self-sustaining discharges

We have seen in I-d-3 how an electron avalanche is produced under the influence of an electric field between two flat plates. We mentioned in this connection Townsend's ionization coefficient α, the relative increase of the electron current per metre passed through. If we start off with n electrons, a number $dn = n.\alpha.dx$ of new electrons will be formed in the distance dx. Solving this differential equation, we find that n_0 electrons which move through a distance x in a field F will increase to $n = n_0\ \varepsilon^{\alpha x}$, and $n_0\ (\varepsilon^{\alpha x} - 1)$ ions will be formed. Since the tube we are considering only contains two electrodes a distance d apart, all the $n = n_0\ \varepsilon^{\alpha d}$ electrons will end up on the anode, and will then not be able to cause any more ionizations, while the ions will move in the opposite direction, and end up on the cathode. The discharge will then be over.

It can only continue for an appreciable length of time if electrons are emitted from the cathode owing to some external cause such as irradiation with light. Such a discharge is said to be *non-self-sustaining*. Now various processes are known whereby apart from the above-mentioned "primary" electrons "secondary" electrons can be produced in the gas.

As an example we shall consider the formation of free electrons by the ions which move to the cathode. If each ion produces on the average γ electrons when it strikes the cathode, the above mentioned $n_0\ (\varepsilon^{\alpha d} - 1)$ ions will produce a total of $n_0\,\gamma\ (\varepsilon^{\alpha d} - 1)$ secondary electrons. The ionization coefficient γ depends on the cathode material, and on the ratio F/p_0 which we have already mentioned in connection with the ionization coefficients η and α This type of emission is known as the *gamma effect*, or secondary emission by positive ions.

The mean number of secondary electrons formed from one primary electron by all possible emission processes is denoted by q, and called the *multiplication factor*. We see that for the gamma effect

$$q = \gamma\,(\varepsilon^{\alpha d} - 1)\ .$$

If the voltage between the electrodes is increased, α and γ will in general increase, and q with them.

Self-sustaining discharges

When q is equal to 1, one secondary electron is formed from each primary one. The discharge is then self-sustaining. The value of the current under these conditions can vary from less than 10^{-10} to more than 10^{+4} A. If q becomes greater than 1, the current keeps on increasing until it is limited by the resistance in the circuit.

Breakdown, Paschen's Law

In what follows we will only consider the production of secondary electrons by ions. If other mechanisms also play a part, our conclusions will still be basically valid. If the voltage between the electrodes is increased until the multiplication factor is one, i.e.

$$q = \gamma\,(\varepsilon^{\alpha d} - 1) = \gamma\,(\varepsilon^{\eta V_d} - 1) = 1 \tag{7}$$

we say that *breakdown* has occured; the voltage V_d at which this occurs is called the *breakdown voltage.*

It follows from Eq. (7) that

$$\varepsilon^{\eta V_d} = 1 + \frac{1}{\gamma} \text{ or } \eta\, V_d = \ln\left(1 + \frac{1}{\gamma}\right) \text{ or } V_d = \frac{1}{\eta} \ln\left(1 + \frac{1}{\gamma}\right) \tag{8}$$

Since the logarithm of a number increases much more slowly than the number itself, we see from these equations that the value of the breakdown voltage depends mainly on η and not so much on γ. If we recall moreover that both η and γ are functions of F/p_0 (see I-d-3), it is clear that V_d will also be a function of this variable, and will to a first approximation be inversely proportional to η.

We can thus write

$$V_d = \mathrm{f}\,(F/p_0) \tag{9}$$

while the field strength between the two flat plates at the moment of breakdown is given by:

$$F = V_d/d \tag{10}$$

where d = distance between the plates.

It follows that

$$V_d = \mathrm{f}\left(\frac{V_d}{p_0 \times d}\right) \tag{11}$$

This can be regarded as an equation in V_d and $(p_0 \times d)$, which can be solved to give

$$V_d = \mathrm{g}\,(p_0 \times d) \tag{12}$$

In other words the breakdown voltage between two flat plates depends on the product of the pressure of the gas reduced to 0 °C (see I-b-2), and the distance between the electrodes. If p_0 and d both vary so that their product remains constant, V_d also remains constant. This is *Paschen's law* for the breakdown voltage, which is illustrated in Fig. 12 and 13. The physical significance of this law can be seen by substituting the Equations (1a) and (3) in (9).

This gives
$$V_d = \mathrm{f}\left(F \times \lambda_e \times \frac{\pi d_a^2}{4 \times 273\, k}\right) = \mathrm{f}\,(K \times \lambda_e \times F) \qquad (13)$$

Since the factor K contains nothing but constants for a given gas, we see that V_d is a function of $\lambda_e \times F$, the potential difference in the gas per mean free path. On the other hand, if we substitute the above expressions (1a) and (3) for p_0 and λ_e into the Equation (12), we find

$$V_d = \mathrm{g}\left(d/\lambda_e \times \frac{1}{K}\right),$$

i.e. V_d depends on the number of mean free paths between the two elektrodes.

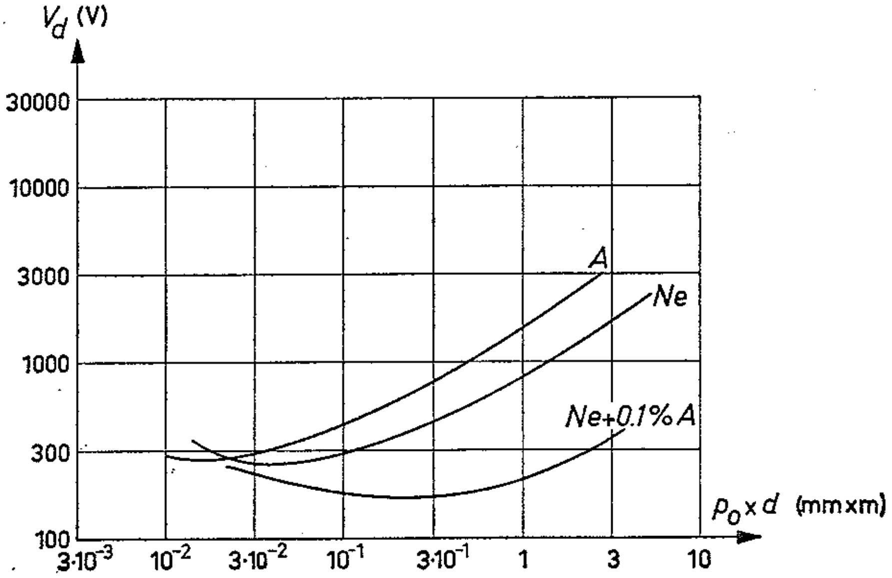

Fig. 12

Breakdown voltage V_d as a function of the product of the reduced pressure of the gas and the distance between the electrodes ($p_o \times d$) for neon (Ne), argon (A) and neon + 0.1 % argon.

We have already seen above that the breakdown voltage decreases as η increases. We are now in a position to understand that the breakdown of neon should be lowered by adding a small amount of argon. We have already seen in I-d-3 that this addition causes the value of η for neon to increase considerably. Fig. 12 shows the Paschen curves giving V_d as a function of $p_0 \times d$ for neon, argon, and a mixture of these two gases. The curves for the pure gases show a decided minimum, which is what we would expect since we have seen that V_d for a given gas is approximately inversely proportional to η, while η has a maximum at a certain value of F/p_0 (see I-d-3).

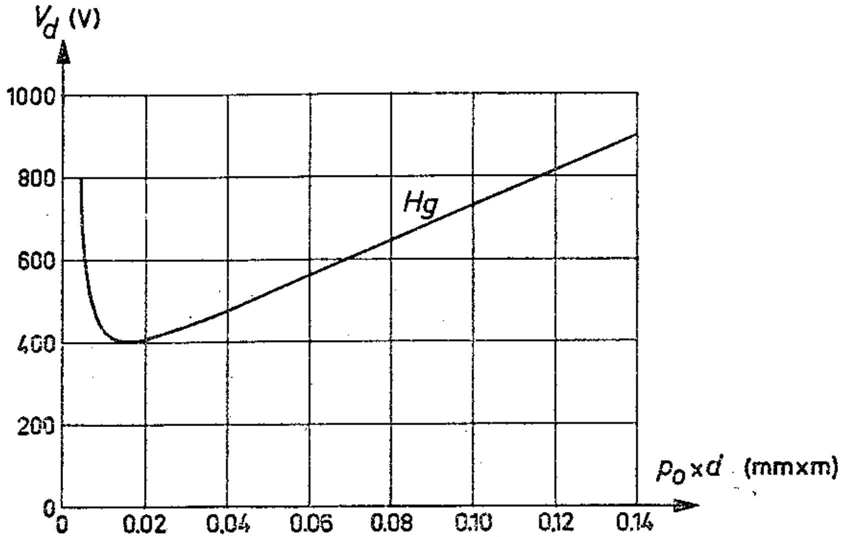

Fig. 13

Breakdown voltage V_d as a function of the product of the reduced pressure of the gas and the distance between the electrodes ($p_0 \times d$) for mercury vapour [46].

The current-voltage characteristic

Now that we have seen how the current through a tube is initiated, let us examine how the voltage across the discharge varies as we increase the current, i.e. let us have a look at the current-voltage characteristic of the discharge. This is sketched in Fig. 14. It may be seen that this curve can be divided into six portions, the most important of which will be discussed below. Directly after the breakdown follows the region of *Townsend* discharge, with currents up to about 10^{-6} A. The voltage across the tube in this region is practically constant and equal to the breakdown voltage V_d.

If the current becomes greater than about 10^{-6} A, the discharge becomes unstable and contracts to a small region near the cathode. The voltage thus drops while the current increases (the transition region *C-D* in Fig. 14).

This decrease of the voltage stops at 10^{-4} to 10^{-3} A. The discharge is then concentrated in a small spot on the cathode, called the *cathode spot.* As the current increases further this spot extends to cover the whole cathode, the burning voltage remaining constant. This is the region *D-E* of the characteristic, the *normal glow discharge.* At the point *E* the discharge covers the whole cathode.

If the current is increased even further, the burning voltage increases in the region *E-F,* called the region of *anomalous* glow discharge. The amount of heat dissipated at the cathode gradually increases, until at F thermionic emission begins to play a part.

This causes the burning voltage to decrease again until at G this voltage is low enough for an arc to be formed. After G we have thus an *arc discharge* and the burning voltage then is called an arc voltage.

The arc discharge is formed very easily when the cathode is hot and emits a large number of electrons. We will discuss this discharge in greater detail below.

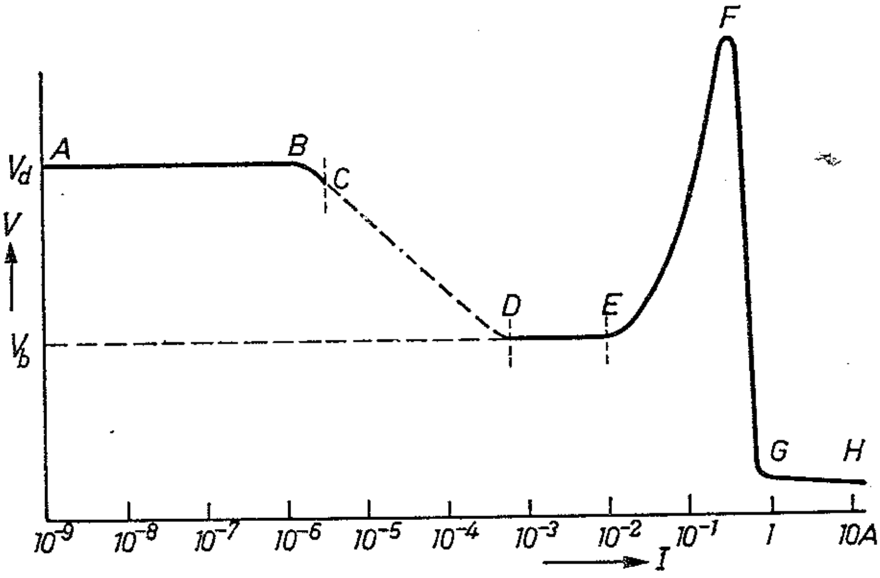

Fig. 14

The current-voltage characteristic for a discharge between two flat plates.
V = voltage, I = current.
V_d = breakdown voltage.
V_b = burning voltage of the glow discharge.
AB = characteristic of the Townsend discharge.
CD = unstable region.
DE = characteristic of the normal glow discharge.
EF = characteristic of the anomalous glow discharge.
FG = transition to the arc discharge.
GH = characteristic of the arc discharge.

The glow discharge

When the discharge is concentrated in a small spot on the cathode (see point D, Fig. 14), the current density is so great that a considerable positive space charge forms just in front of the cathode. The anode is thus, as it were, shifted to near the cathode, and the whole potential difference across the tube is concentrated near the cathode (see Fig. 15 curve 3). In the strong field thus produced, the electrons leaving the cathode rapidly gain enough energy to cause excitation and ionization. The *negative glow,* to which this discharge owes its name, is thus produced a slight distance in front of the cathode. The current density depends mainly on the nature and pressure of the gas in the tube, and is only a few tens of amps per m², so that the cathode remains cold. For further details see Chapter V, voltage stabilizing tubes.

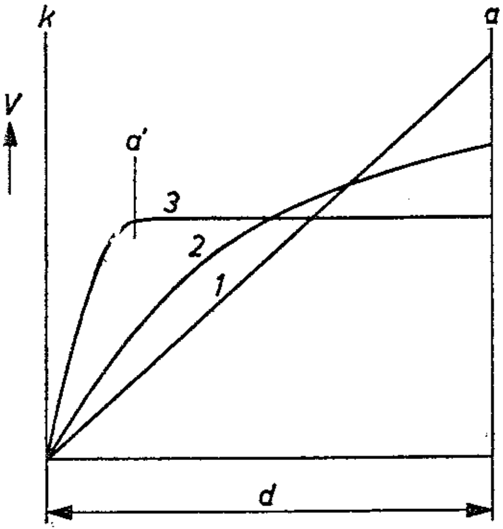

Fig. 15

Potential distribution in the glow discharge between two flat plates.

k = cathode, a = anode, d = distance between cathode and anode.

a' = apparent position of anode in the glow discharge.

1 = electrostatic potential distribution at zero current.

2 = unstable transition state.

3 = potential distribution in the glow discharge.

As we have seen, the burning voltage of the normal glow discharge is independent of the current. It depends on the nature of the cathode material, and of the gas in the tube, and is called the *cathode fall.*
On closer study, it is found that the variations of the intensity of the light in the tube are more complicated than described above.

Fig. 10 gives a more complete impression of these variations. The potential and electric field strength at the various points of the tube are also indicated in this figure. Right in front of the cathode is a relatively dark space (*Cr*), the *Crookes dark space.* The electric field is very large in this space, and the potential difference across it is nearly equal to the cathode fall. Although not much light is emitted here, ionization does take place. Next comes the glow (*Gl*) to which we have already referred, where the field is slight so that the electrons are no longer accelerated so much, but with the energy they gained in the Crookes dark space they are able to cause appreciable excitation, giving rise to the emission of light, and strong ionization. Next we see the second dark space, the *Faraday dark space (F).* There is no field here, i.e. the potential is constant. The electrons move so slowly that they can no longer cause excitation or ionization. This space contains a *discharge plasma* (see I-f). Each volume element contains just as many electrons as ions, on the average.

I-g-2 ANODE FALL AND POSITIVE COLUMN

It was assumed in the above that the flat plates acting as the cathode k and and anode a for the discharge were fairly close together. If we increase the distance between these two plates, we find a new glow of light near the anode, which is accompanied by changes in the potential distribution in this region. If the electrodes are separated even further, we finally obtain the *positive column* (Fig. 10 region Z).

We have already seen that the Faraday dark space contains a discharge plasma. The density of this plasma decreases with increasing distance from the cathode. If an anode, i.e. a metal plate with a positive potential, is placed in this plasma, the electrons will be attracted to it, and the ions repelled from it. At the beginning of the dark space (i.e. the end nearest the cathode), enough ions will be able to diffuse towards the anode, despite this repulsion, to compensate the space charge produced by the electrons, which must carry the whole discharge current in the neighbourhood of the anode. The potential of the anode is thus not much greater than that of the surrounding plasma.

If the anode is moved further away from the cathode, the concentration of the plasma near it decreases, and the number of ions which can reach the anode by diffusion is soon not enough to compensate the space charge of the electrons completely. There is thus a net negative space charge near the anode, which gives rise to an electric field. The potential of the anode will then be higher than that of the plasma. The potential difference between the anode and the plasma is called the *anode fall*. If the anode fall becomes equal to the ionization voltage of the gas, positive ions are produced at the surface of the anode. These hinder any further increase of the anode fall, since they compensate the negative space charge. This ionization is accompanied by excitation of the gas atoms, so that the anode is covered by a luminous film, the *anode light*. As a result of the anode fall, the losses at the anode increase so that this becomes warmer.

If the distance between the electrodes is increased even further, this luminous film changes into one or more balls of light, and finally the *positive column* is produced. The discharge then consists of three parts:

a. one part near the cathode, the cathode fall
b. a homogeneously illuminated region, the positive column
c. a part near the anode, the anode fall.

The start of the positive column (P in Fig. 10) is also the end of the Faraday dark space.

There are various kinds of positive column. We are, however, only interested in the homogeneous column, which is produced at low gas pressures. In such a column, the state of the discharge in different cross-sections is the same. If the distance between the electrodes is increased under these conditions, the voltage across the tube will increase linearly with the distance, the rate of increase being equal to the electric field strength or gradient in the column. This constant gradient depends on the nature of the gas, its pressure, and the diameter of the tube. Although the positive and negative space charges in the column do not cancel out completely, they very nearly do so, so we can regard the column as being a special sort of discharge plasma (see I-f).

The wall of the tube surrounding the column plays an important role. We have already mentioned (I-e-2) that electrons and ions recombine on the wall to form neutral atoms. The concentration of charge carriers at the wall is thus very small, so that they diffuse from the middle of the discharge to the walls.

The fast electrons initially cause a negative space charge near the wall, which gives rise to a radial field. The positive ions are accelerated in this field, so that finally ions and electrons arrive at the wall at equal rates. This combined diffusion of both sorts of charge carriers is called *ambipolar diffusion.*

This loss of charge carriers by ambipolar diffussion must be made up by ionizations in the column. The column can thus only remain in existence if enough fast electrons are produced in it to cause the necessary ionization. This condition is the reason for the electric field along the axis of the column, which gives the electrons just enough energy for the ionization which is needed.

In discharges in mercury vapour, the pressure is often very low. The mean free path of the electrons, λ_e, is then much greater than the radius of the tube. We will return to this in Chapter VI, in connection with the prevention of backfire. The above mentioned column discharges are used e.g. in gas-discharge lamps and in the so-called noise tubes (see Chapter VIII).

The presence of the above-mentioned glow discharge near the cathode is not essential to the existence of the column discharge. The glow discharge may under certain conditions be replaced by an arc discharge without destroying the column discharge in the rest of the tube. We will therefore now discuss the arc discharge in more detail.

I-g-3 THE ARC DISCHARGE

The arc discharge is produced when the anomalous glow discharge (I-g-1) changes into a thermionic discharge from the cathode via the unstable region *FG* (Fig. 14). Such a discharge is a typical self-sustaining discharge. Thermionic emission from the cathode can also be produced by heating the cathode by external means, e.g. by means of a heated filament. The arc discharge produced then is not self-sustaining. The burning voltage V_{arc} of an arc discharge without positive column is very nearly equal to the ionization voltage of the gas in which the discharge occurs, and decreases as the current increases. The arc discharge thus has a negative characteristic. The value of the current can be hundreds of amperes.

The name "arc" is derived from the shape of the discharge produced between two pointed carbon rods in gas (e.g. air) under about one atmosphere pressure. The upward flow of air due to convection gives rise to the typical arc form (the Davy arc lamp).

A. *The self-sustaining arc discharge*

An arc arises from the anomalous glow discharge as soon as the heat developed by the ion bombardment makes the cathode hot enough to emit the electrons needed to carry the discharge current. The surface of the cathode is usually inhomogeneous, so that the arc only takes up a part of this surface, finally occupying only a small point on the cathode. This type of discharge is much used in gas-discharge lamps, but not in gas-discharge tubes. We will, therefore, not discuss it any further.

B. *The non-self-sustaining arc or low-tension arc*

If the cathode of a gas-discharge tube is heated by external means until it emits electrons strongly, a discharge of high current density and even lower burning voltage than the ionization voltage of the gas can arise. Such a discharge, which can usually only exist if heat is continually supplied from outside, is called the *low-tension arc*. The cathode should be prepared in a special way if it is desired to obtain the low-tension arc easily (see I-c-1 and II-c-1). Let us examine this discharge rather more closely, in order to see what its typical characteristics are.

As we saw in I-c-1, a neon-filled gas-discharge tube with a hot cathode which gives strong thermionic emission of electrons and e.g. a flat anode will have a strong negative space charge due to electrons near the cathode. At an anode voltage of zero, the potential will show a minimum just in front of the cathode, so that very few electrons will be able to reach the anode. If the anode voltage is increased to 15 V (which is still below the ionization voltage, $V_i = 21.5$ V for neon), the depth of the minimum will decrease somewhat (see curve I, Fig. 16) and the electron current will increase, but will still not reach any very great value. As soon as the anode voltage exceeds V_i, the first ions will be formed near the anode, and will move under the influence of the electric field to the cathode where they will neutralize the negative space charge. The minimum in the potential curve thus disappears suddenly, and the anode current rises to the saturation current of the cathode, or to the greatest value permitted by the external circuit.

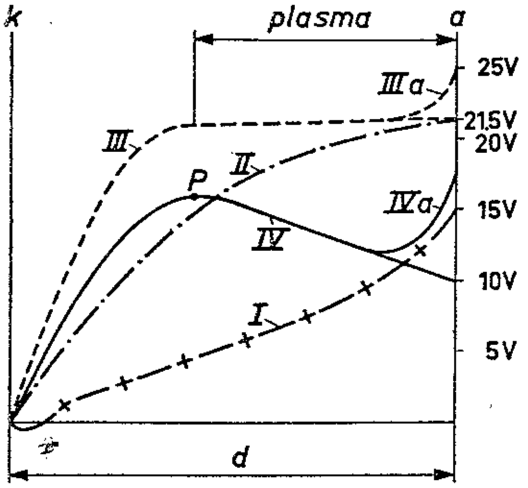

Fig. 16

Potential distributions occuring during the ignition of a low-tension discharge in neon. k = cathode, a = anode, d = distance between cathode and anode.

I. Potential distribution at anode voltage of 15 V tube not ignited.
II. Anode voltage 21.5 V, tube ignited, relatively small current.
III. Potential distribution at higher current.
IIIa. Anode fall.
IV. Potential distribution at even higher current than in III.
IVa. Anode fall.

This process is known as the *ignition* (or breakdown) of the discharge. If the external circuit only allows a relatively small current to pass, the potential varies as shown by curve II of Fig. 16. If the current is increased, the electric field shifts towards the cathode so that one would expect the potential distribution to be as shown by curve III of Fig. 16 (curve IIIa shows what happens if there is an anode fall). The concentration of metastable neon atoms in the discharge has, however, increased so much in the meantime that the large number of electrons present can ionize these metastable atoms. Only 16.6 eV is then in fact needed for the formation of ions. The burning voltage falls to about this value, and the potential distribution is as shown by curve IV of Fig. 16, with IVa representing the situation when anode fall is present.

We see from the above that the ignition voltage of the low-tension arc is always at least equal to the ionization voltage of the gas in the tube. The burning voltage is often considerably lower, in which case it is of the order of the first excitation voltage.

I-g-4 THE CORONA DISCHARGE [3, 67, 79]

The self-sustaining discharge in the inhomogeneous electric field between a thin wire and a coaxial cylinder is called a *corona discharge*. This name is descriptive of the light effects found if the voltage is several kilovolts and the gas pressure is high (e.g. in the atmosphere). The gas pressure need not be high for the discharge to occur, but at low pressure the corona is not visible.

The luminous part of the discharge is usually restricted to a region close to the wire, which may be positive or negative with respect to the cylinder.

Such discharges are found:

1. between the wires of a high-tension transmission system (above ground); here the atmosphere acts as the second electrode.
2. in certain forms of Geiger-Müller radiation tubes (see V-d-6).
3. as the primer discharge in certain trigger tubes (see V-f), and in certain other applications of cold-cathode tubes.

One distinguishes between positive and negative coronas, depending on the voltage of the central electrode. The positive corona consists of a *luminous film* on the wire, and the negative corona of a series of *luminous balls.*

The negative corona discharge

The ions which are formed in the strong field near the negative wire move towards the wire, and free so many electrons from it that the discharge is self-sustaining. Outside this ionization region, the electrons are practically the only charge carriers for the discharge current.

Fig. 17 shows the effect of the space charge on this corona discharge. The increase of the field caused by the ions near the wire can be clearly seen.

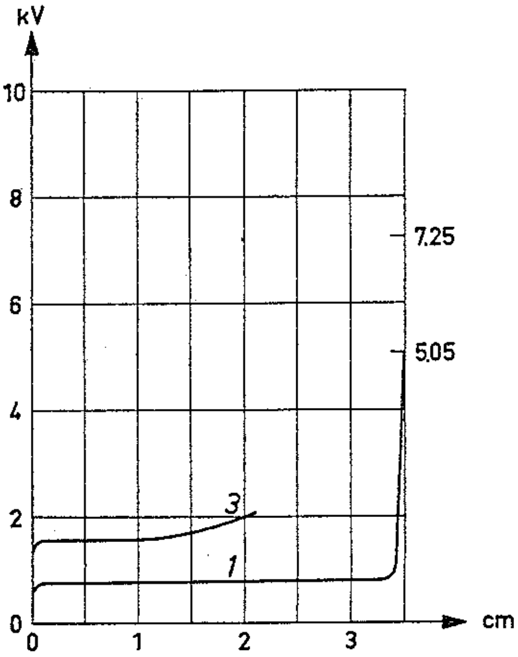

Fig. 17

Potential distribution in the negative corona discharge.
The anode is on the left of the figure, and the cathode on the right. The potential difference with respect to the anode is plotted upwards. The current corresponding to curve *3* is three times that for curve *1* [81].

The positive corona discharge

The positive corona discharge is more important than the negative one for the tubes discussed in this book. A number of electrons are first formed by radiation coming from outside the tube. These will then move

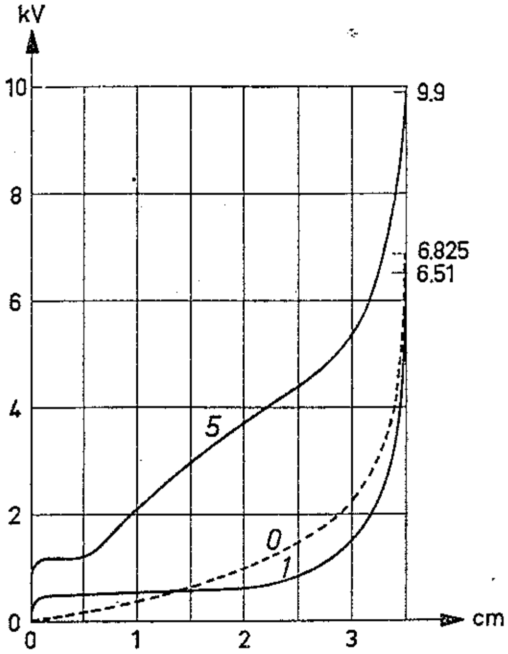

Fig. 18

Potential distribution in the positive corona discharge. The cathode is on the left of the figure, and the anode on the right.
Curve *0*, the electrostatic potential distribution at zero current.
Curves *1* and *5* correspond to two currents differing by a factor of five [81].

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towards the positive wire where the field strength is high, and avalanches will be formed from these primary electrons, giving rise to a short current pulse. The ions move away from the wire to the cylindrical cathode. Since the field strength near the cathode is weak, nearly all the current is carried by the ions in this stage. The discharge becomes self-sustaining when so many ions, light quanta or metastable atoms fall on the cylinder that sufficient secondary electrons are produced. The current-voltage characteristic, which is positive at low currents (about 10^{-8} A) and high pressures (about 1 atm), becomes negative at high currents (about 1 mA), and the corona degenerates into a glow discharge. At low pressures, e.g. 30 mm Hg, the ionization is not restricted to the neighbourhood of the wire. The current-voltage characteristic then becomes negative. We will show how use can be made of this discharge in the discussion of the Geiger-Müller counter tube in Chapter V. The change in the potential distribution as a result of the space charge is shown in Fig. 18. The broken line represents the electrostatic potential distribution at zero current.