**Physics.** — *On the liberation of electrons from a metal surface by positive ions.* By F. M. PENNING. (Communicated by Dr. G. HOLST.)

(Communicated at the meeting of October 29, 1927).

§ 1. The work to be described in the following pages was undertaken on the suggestion of Dr. HOLST, in order to get more information about the part played by the positive ions in a gas discharge. According to the theory of TOWNSEND [1]) new electrons are formed in the bulk of the gas as a consequence of the ionising action of the positive ions; according to another view it is the bombardment of the cathode by positive ions of rather high velocity which gives rise to the liberation of these electrons. Several years ago a new theory was developed by HOLST and OOSTERHUIS [2]). This theory supposes that positive ions, which strike without any appreciable velocity a suitable metal surface, are able to extract electrons from this surface (of course besides those which are required for neutralisation). The condition for this happening is $V_i > 2\varphi$ ($V_i$ = ionising potential of the gas, $\varphi$ = work function of RICHARDSON). This theory was suggested by the phenomenon of the "negative striations" which HOLST and OOSTERHUIS observed in Neon of about 10 mm pressure at low currents (about 1 $\mu A$) [3]). From the facts that these striations had a sharp boundary towards the cathode side and that the layer immediately before the cathode was absolutely dark, it was concluded that the electrons were liberated from the cathode surface and not from atoms in the bulk of the gas [4]). Moreover, the velocity of the positive ions in this case must be very small, as a consequence of the small value of the mean free path.

In this connection we shall mention an analogous phenomenon which was observed in this laboratory by G. HERTZ [5]). In a tube as shown in fig. 1. with a heating filament $K$ and an anode $A$ a Neon low voltage arc is burning (pressure about 1 cm). When the plate $P$ is held at a negative potential with respect to $A$, it attracts positive ions (which can diffuse through the gauze). Now between $P$ and $A$ striations are observed of the same kind as the above-said. Obviously these striations are caused by electrons which are liberated from $P$ by positive ions and which excite the neon atoms on their way to $A$. The first layer is observed at a potential

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1) J. S. TOWNSEND, Electricity in gases, 1915.

2) G. HOLST and E. OOSTERHUIS, Physica **1**, 78, 1921; Comptes Rendus **175**, 577, 1922; Phil. Mag. **46**, 1117, 1923.

3) l.c.

4) This may be concluded also from the fact that the material of the cathode has great influence on the sparking potential, see G. HOLST and E. OOSTERHUIS, Versl. Kon. Ak. v. Wet. Amsterdam **29**, 849, 1920.

5) Unpublished.

difference of about 20 V between $P$ and $A$. Under these circumstances the potential difference along the distance of a mean free path for a pos. ion is only 0.01 V ; clearly in this case there can be no question of a liberation of electrons by the bombardment of high velocity ions.

It seems possible, however, that in the experiment just described the electrons were liberated by radiation. In order to investigate this point, another discharge tube was used as designed in fig. 2. Instead of one plate there were two plates $P_1$ and $P_2$ mounted in the same way within two glass tubes $G_1$ and $G_2$. The radiation from the main discharge may

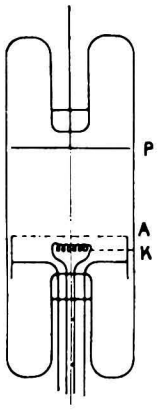

Fig. 1.

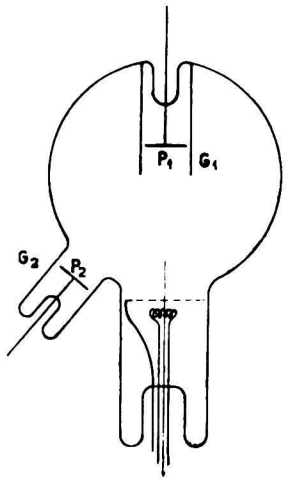

Fig. 2.

reach directly $P_1$ but it cannot reach $P_2$. However, the striations show themselves in about the same manner before $P_1$, as before $P_2$ ; therefore we may conclude that the radiation cannot have much influence.

§ 2. We have tried to determine experimentally how many positive ions (especially neon ions [1]) ) of zero velocity are required to liberate one electron from a metal surface. We should, however, mention immediately that up to the present only preliminary results have been obtained, as a consequence of the difficulties of these experiments.

For the first experiments a tube was used of the type shown in fig. 1, but with a gauze $G$ and a plate $M$ instead of the plate $P$ alone (fig. 3). In order to get a larger supply of ions, the anode $A$ was placed under the cathode $K$. When the gauze is brought at a negative potential with respect to $K$, it will be struck only by pos. ions; on the other hand, when $M$ is brought at a positive potential with respect to $A$, it will gather only electrons. In order that no electrons from the main discharge may reach $M$, the holes of the gauze should be small [2]); smallness of the holes on the

[1]) Unless otherwise mentioned the following experiments are made with neon.

[2]) The gauze used had 24 threads of 0.15 mm diameter at 1 cm in each direction.

other hand gives rise to the inconvenience that only a fraction of the electrons from $G$ reaches $M$.

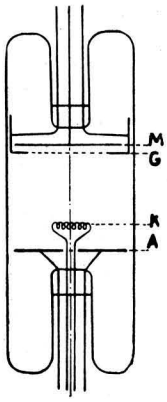

Fig. 3.

As our intention was to study the action of positive ions with low velocity, the values of the potentials in the tube should be chosen as small as possible. Therefore the gas-pressure should be high (several mm) and in that case the electrons, liberated from $G$, may ionise the gas atoms between $M$ and $G$, in case the potential of $M$ is raised. Therefore the current to $M$, plotted as a function of the potential of $M$, does not show saturation; distinct kinks are observed at the points where the potential has increased with $V_i$.

The electron current becomes more constant when the gas pressure is decreased, but then we must give up at the same time the advantage of the low potentials. When, moreover, the distance between $M$ and $G$ is taken as small as possible (about 1 mm), the current to $M$ becomes nearly constant with increasing potential. The number of electrons, reaching $M$, is then 3 to 5 % of the number of positive ions which go to $G$ (at pressures between 0.2 and 0.02 mm and pos. ion currents from 0.2 to 20 mA). Besides, the variation of the potential of $G$ (with respect to the cathode) between —20 and —80 V had little influence on this percentage; so it is obvious that the number of liberated electrons is affected only to a small extent by the velocity of the positive ions.

It is not right, however, to conclude from these measurements that from 20 to 30 ions are required to extract one electron from the metal; on the contrary a smaller number will be sufficient, because the electrons, liberated from $G$, will move partly also in the direction to $A$.

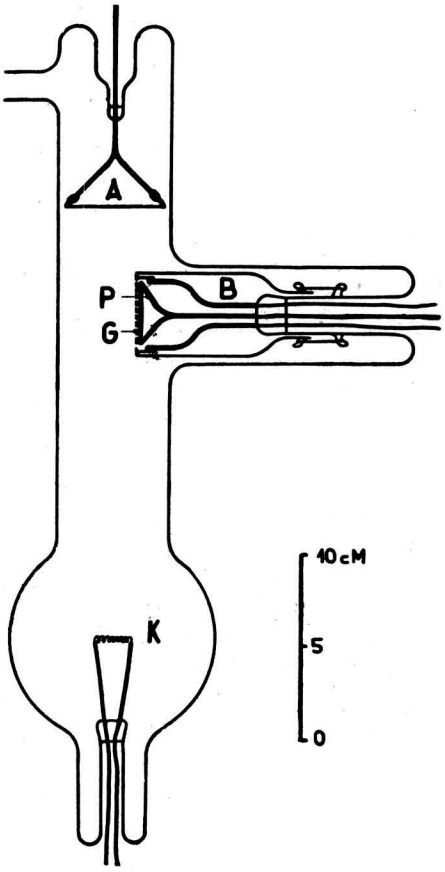

Fig. 4.

§ 3. For measurements of the same kind we used also a positive column in neon of low pressure (0.02 mm). The tube is shown in fig. 4. The discharge (some hundred mA) is maintained between the oxide cathode $K$ and the anode A. The

positive column contains a collector which, when brought at a negative potential, will gather pos. ions. In order to measure the number of electrons $\alpha$, which is liberated on the average by one positive ion, we use again the method described in § 2. A side tube contains a gauze $G$ (copper) and a plate $P$; the current to both these electrodes is measured. To protect the backside of the plate $P$ from electrons, this plate is enclosed in a glasstube $B$, which is fastened to the glasswall. The results for a few series of measurements are shown in fig. 5 [1]). The potentials are given with respect

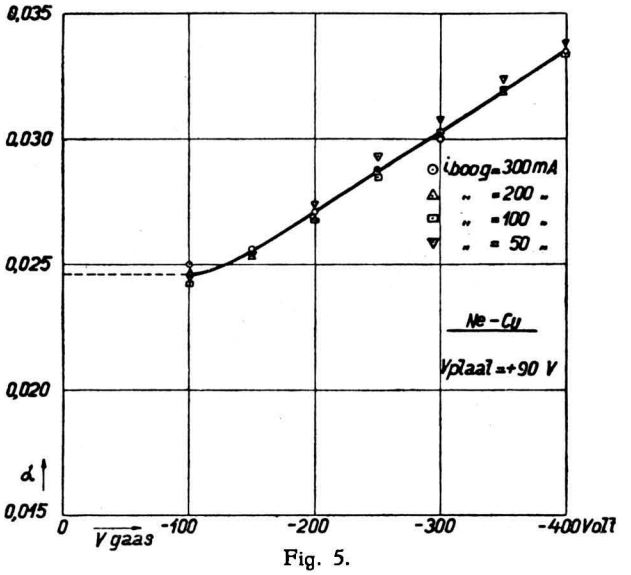


Fig. 5.

boog = arc, plaat = plate, gaas = gauze.

to the anode (this will always be done in the following). The gas in the neighbourhood of the gauze G will be on about the same potential as the anode, therefore, on the moment that the positive ions strike the gauze, their velocity (measured in Volts) will have about the same value as the potential of G. Because it is necessary that the electrons from the main discharge should be stopped, the gauze cannot be brought on a much higher potential as —100 V (the potential of the cathode is in this measurement about —60 V). The probable trend of the curve above —100 V is dotted in fig. 5. The value of $\alpha$ for a velocity zero ($\alpha_0$) is found to be about 2 % (even if the curve through the measured points should be extrapolated in a different way). As the gauze in this tube was of the same construction as that of § 2, these measurements are open to the same objection as mentioned there. From the measurements of this and the foregoing § we may conclude: 20 to 50 pos. ions (of zero velocity) at the utmost are required to liberate one electron from a *Cu*-surface.

The same tube was used also for measurements with argon filling and

[1]) The values of the electron currents are in this case from 0.1 to 0.01 mA.

with $Mg$ instead of $Cu$ as electrode material. As should be expected in connection with the values of $V_i$ and $\varphi$, the value of $\alpha$ was for $Ar <$ for $Ne$ and for $Mg >$ for $Cu$.

§ 4. To meet several drawbacks of the described measurements, afterwards another method was followed. It was desirable to study the action on the pos. ions in a space of very low pressure, where the collisions between positive ions (or secundary electrons) and atoms could be neglected. When the gas pressure in the main discharge is lowered under 0.02 mm the arc potential is rising rapidly. This should be prevented, as we shall study the action of pos. ions of low velocity. Therefore it is necessary to bring the pos. ions in a room where the gas is pumped away and which is communicating only through a narrow canal with the main discharge. After experiments with tubes of somewhat other constructions the tube of fig. 6 gave the best results (tube II) [1].

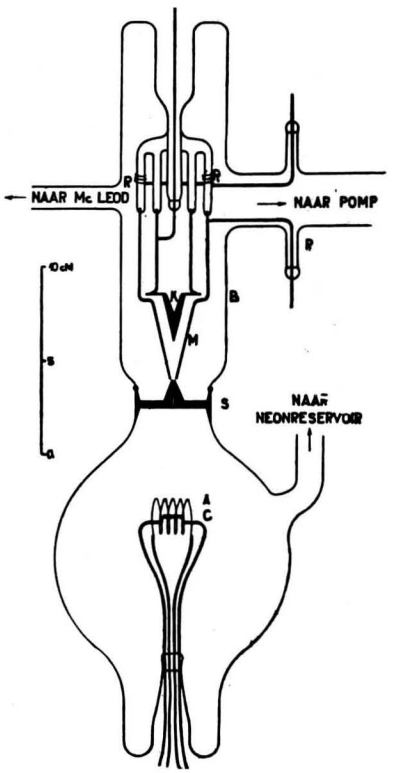

Fig. 6.

The cathode $C$ is an oxide filament, the anode a large tungsten spiral which could be degassed by glowing. In the sidewall of the bulb containing the main discharge, a chromic iron piece $S$ is molten and to this again the tube $B$ with the collector system. This system contains an iron cone $K$ which is used as a collector for the pos. ions; the cone is surrounded by a mantle $M$ which collects the secondary electrons. $S$ is perforated by a canal of 1 mm diameter and 15 mm length. $B$ is connected by a short, wide tube with a diffusion pump which keeps the gas-pressure on a value of about 0.0002 mm (with a pressure of 0.02 mm in the bulb). The pressure at both sides can be measured with a Mc-Leod gage. As in these experiments the gas is rapidly disappearing by metalsputtering, the bulb is connected with a large reservoir of 10 l capacity; in this way many measurements may be made before it is necessary to admit fresh gas. The discharge tube is

[1]) In the tube I, used before, the anode was mounted at a much larger distance from the cathode, so that a positive column occurred. The chromic iron piece $S$ was molten in the side wall of the tube, containing the positive column. The canal in $S$ was 20 mm. ong in this tube. The arrangement of tube II was chosen afterwards to lower the arc potential.

separated by tubes in liquid air from parts of the apparatus containing mercury or stopcocks.

As only a small number of pos. ions is reaching the cone $K$ the currents are very small (unto $< 10^{-9}$ A) ; therefore the electric insulation should be very careful. The leads-in of $M$ and $K$ are molten in the glass, at a large distance of each other. Moreover, the leads-in of $M$ and the glass-bars in the tube which support $M$ are surrounded by conducting guard rings $R$ which are helt on the same potential as $M$. In the same way the points of support of the connecting wires, of the galvanometer and so on are protected from leakage.

Before the measurements the tube was pumped at a temperature of about 400° C. Afterwards the metal parts were degassed ; the iron cone could be glown in vacuum by means of high frequency currents.

As it is impossible to measure directly with this arrangement the effect of positive ions with zero velocity, it was tried to measure the percentage of liberated electrons ($\alpha$) as a function of the velocity of the pos. ions, and to extrapolate to a velocity 0. The measurements were made in the following way : the canal in $S$ and the mantle $M$ were helt on the same potential, e.g. —100 V with respect to the anode (the arc potential is always $<$ 100 V). The pos. ions arrive in the part of low pressure with a velocity between 0 and 100 V. Between $S$ and $K$ a potential difference of 50—900 V is put, which accelerates the pos. ions ; as the pos. ions make nearly no collisions in this part of the tube (mean free path about 50 cm) they arrive at the cone with a velocity varying from 0—100 to 900—1000 V. The liberated electrons are moving towards $M$ ; indeed, although the end of the canal is at the same potential as $M$, the direction of the field is such that the percentage of the electrons which is going to $S$ may be neglected. Moreover as a consequence of the relative positions of $K$ and $M$ there is a strong electric field at the surface of $K$, so that we may expect a rapid saturation of the electron current. As a matter of fact with this collector system saturation was reached already at a potential difference of about 20 V between $K$ and $M$, whereas with a system used before, this was only the case at 200 V. To show this, in Fig. 7 are plotted the current to the mantle $M$ and the cone $K$ for tube I (collector system the same as in tube II [1]) ) with the following potentials :

Canal (= kanaal) : —150 V.
Cone (= kegel) : —500 V.
Mantle (= mantel) : varied.

(All these potentials are measured as before with respect to the anode.) An electron current in the direction from cone to mantle is taken as negative for both electrodes ; so in Fig. 7 for potentials above —500 V pos. ions are going to the cone and electrons to the mantle. In case

[1]) Compare the footnote on p. 18.

$V_{mantle} = V_{canal}$ the positive ions which energe from the canal will not be retarded ; when the mantle is made more negative, the ion current to the

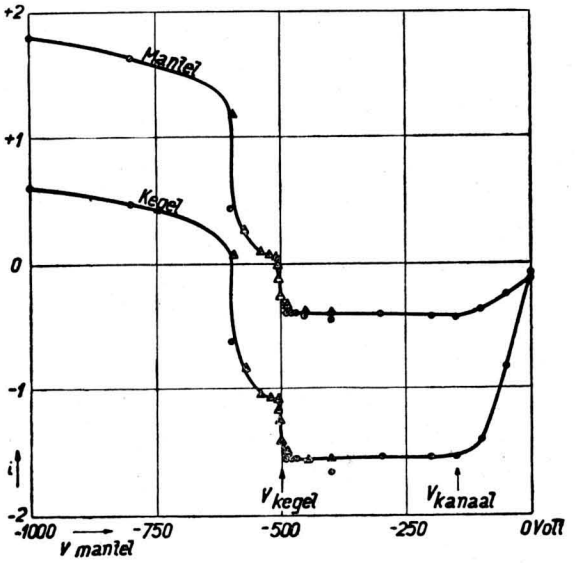


Fig. 7.

cone remains constant ; on the contrary, when the mantle becomes positive with respect to the canal the ions will be partly stopped and the current to the cone becomes smaller. For potentials of the mantle between —150 and —480 V the electron current and the pos. ion current remain nearly constant, showing a good saturation. When $V_{mantle} = V_{cone}$ the current of the mantle becomes positive instead of negative, as should be expected. The small pos. ion current to the mantle at first increases slowly but then again very rapidly and when $V_{mantle} =$ —1000 V the mantle and the cone have interchanged their functions. The value of $a$ which is deduced from the measurements at —1000 V is larger as that found in case the positive ions are collected by the cone, but in the first case the velocity of the ions is twice as large.

Concerning the final measurements the following may be remarked. The currents were measured with a galvanometer (sensibility $0.3 \times 10^{-10}$ A); in order to use the same instrument for both currents, a throw-over switch was applied, consisting of mercury cups in paraffine ; to avoid leaking currents each mercury cup was surrounded by a conducting ring helt at the same potential, in the way mentioned at the description of the tube II. With the aid of such precautions we succeeded in reducing the leaking currents to a negligeable amount. The electrodes were connected to the switch in such a way that the galvanometer deflections had the same direction for both currents, and further by suitable shunts, the order of magnitude of the deflections was made the same, in order to diminish the influence of the zero point of the galvanometer.

§ 5. The results of a few series of measurements with the tubes I and II are shown in Fig. 8. Every series was measured in the direction of increasing and of decreasing voltages (the corresponding points are designed as circles and triangles). As ordinate is plotted $a$ : the number of

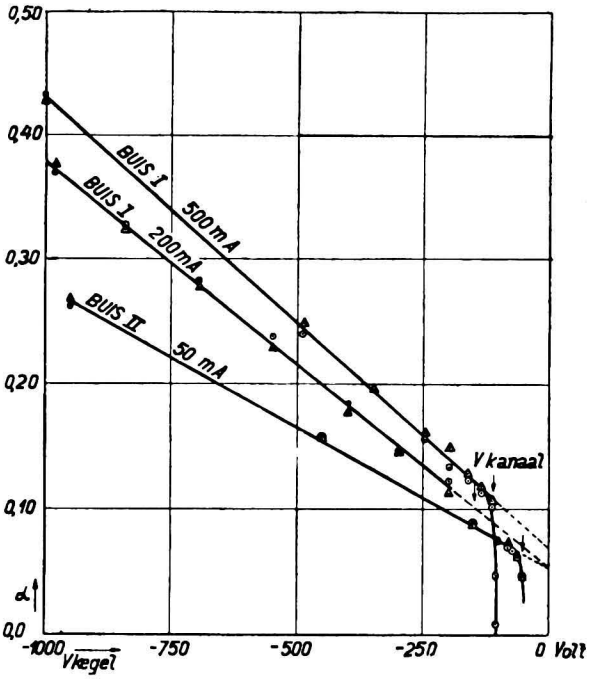


Fig. 8.
Buis = tube, Kegel = cone, Kanaal = canal.

electrons liberated on the average by one pos. ion. As the current to the cone consists of the sum of the pos. ions which reach it and the electrons which leave it :

$$a = \frac{| i_{\text{mantle}} |}{| i_{\text{cone}} | - | i_{\text{mantle}} |}.$$

As abscissa is plotted the potential of the cone ; this gives at the same time, within the limits already mentioned higher up, the velocity of the pos. ions (measured in Volts). The potential of the canal should of course be lower than the lowest point of the cathode ; the mantle is on the same potential as the canal. As soon as the potential difference between the cone and the mantle becomes lower than about 20 V, the mantle will no longer collect all the liberated electrons (see Fig. 7) ; the values, found for $a$, are then too low. Consequently, the curves in Fig. 8 are then deviating from the original direction ; when $V_{\text{mantle}} = V_{\text{cone}}$ they go down steeply. There is, however, no reason to suppose that the real value of $a$ also should vary suddenly ; on the contrary always when in consequence of a lower

potential difference between the cathode and the anode, a lower value could be chosen for $V_{canal}$, the curve bent off at a higher value of $V_{mantle}$. It is, therefore, very probable that we may extrapolate the curves of Fig. 8 in the manner as shown by the dotted lines and that for iron $a_0$ (the value of $a$ for pos. ions with zero velocity) is about 0.06 [1]).

The values of $a_0$ in Fig. 8 are diverging between 0.05 and 0.07. As a matter of fact in other series (measured partly with tubes of a somewhat other type) even more differing values were found, viz. unto 0.12 ; likewise the value of $a$ for larger ion velocities was not constant ; the value for 1000 V ($a_{1000}$) varied, e.g. with tube I in the course of the measurements (which extended over 19 days) between 0.44 and 0.27. Probably the condition of the metal surface has a great influence, as is apparent also in photoelectric researches [2]). We intend to make further researches with regard to this point. Anyhow it could be stated that immediately after the glowing of the metal $a_{1000}$ was smaller viz. 0.23—0.30 ; afterwards the value was increasing again gradually.

Though the value of $a$ is not yet known with sufficient accuracy, we may conclude from the above-mentioned experiments (also in connection with the results of § 2 and § 3) : Neon ions which reach without velocity a copper or iron surface are able to liberate electrons from this surface, and the value of $a_0$ is about 5 to 10 %.

§ 6. Finally, we shall try to answer the question how far the obtained results are in agreement with those of other authors. Many experiments of this type have been done with positive ions which are emitted in vacuum by heated aluminium phosphate and similar substances. We also tried at first in this way to get some information about the liberating of electrons by positive ions. The result was, that ions of this type with zero velocity did not cause any measurable electron emission from a Ni-surface [3]). At a velocity of 100 V, in our experiments $a$ was still $< 0.01$. However, we have in this case ions of $Na$ [4]) or other alkali metals with small $V_i$, and one should expect that an extra electron can be liberated

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[1]) Recently, by means of another apparatus, the measurements could be extended unto ion velocities of less than 7 Volts. In this case also the value of $\alpha$ was still a few percents, see Physica **8**, 13, 1928. (*Note added in the translation*).

[2]) See e.g. LEE A. DU BRIDGE, Phys. Rev. **29**, 451, 1927. This writer measured the total photoelectric current from a Pt surface. This was glown several times at 1250° C.; the constant limit value was reached only after 50, sometimes only after 150 hours glowing; after 20 hours glowing e.g. the measured value was still $2^1/_2\times$ the limit value.

[3]) The same result was obtained by N. CAMPBELL, Phil. Mag. **29**, 783, 1915; W. L. CHENEY, Phys. Rev. (2) **10**, 325, 1917; A. L. KLEIN, Phys. Rev. (2) **26**, 800, 1925; W. F. JACKSON, Phys. Rev. (2) **28**, 524, 1927. Compare also: E. BADAREU, Phys. Zts. **25**, 137, 1924. The numerical values for $\alpha$ at higher velocities show very large differences.

[4]) See e.g. O. W. RICHARDSON, The emission of electricity from hot bodies, 1921. By measuring the current in a diode (with a hot anode, covered with aluminium phosphate) as a function of the potential, we could show that the ions in the above-said experiments were Na-ions.

only by an ion when $V_i > \varphi$. Now this condition is not fulfilled for the ions used and for metals as *Fe*.

With gas ions ($H_2$) experiments have been done by BAERWALD. This physicist also used a tube which was devided into two parts by a canal. This canal was used as a cathode of a glow discharge; therefore the canalrays which entered the low pressure part of the tube always had a rather large velocity. As collector metal brass was used. In order to compare our method with that of BAERWALD [1]), we performed also some measurements on hydrogen. A tube of type I was used, but with a somewhat different collector-system. However, we found with ions of 1000 V velocity a value of $\alpha$ which was only 10 % of that found by BAERWALD. This must perhaps partly be ascribed to the different manner in which the pos. ions are formed (molecule- and atom ions?); also we should make allowance for the circumstance that BAERWALD's apparatus could not be pumped at higher temperature and that it could not be degassed; finally perhaps brass gives in this respect quite other results as *Cu* or *Fe*.

It is a pleasure for the writer to thank Mr. J. C. DOUZE for his assistance in the measurements and in the constructing of the tubes.

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*Eindhoven,* October 28th, 1928.

[1]) H. BAERWALD, Ann. d. Phys, **65**, 167, 1921.