**Physics.** — G. HERTZ: "*On the Mean Free Path of Slow Electrons in Neon and Argon.*" (Communicated by Prof. P. EHRENFEST).

(Communicated at the meeting of March 25, 1922).

The reason for undertaking these measurements was given by researches concerning the efficiency of non-elastic impacts of electrons in neon and argon at potentials just above the excitation-potential. It is known, that those collisions between electrons and the atoms of rare gases, which take place below the excitation-potential characteristic for each gas follow the laws of elastic collisions. As soon as the kinetic energy of an electron surpasses the value corresponding to the excitation potential, it can, on collision with an atom, transfer energy to the latter and thereby raise it from its normal state to a higher quantum-state. This, however, does not take place at every collision between a sufficiently fast electron and an atom; only a certain part, in the case of rare gases most probably only a small fraction, of these collisions is non-elastic and causes excitation of the colliding atom. This fraction we call the efficiency of the particular non-elastic impact. It is equal to the probability that an impact of an electron possessing the required energy really leads to a transfer of energy. It is naturally a function of the velocity of the electron. The form of this function however is not yet known.

In a glow-discharge the two rare gases neon and argon show a characteristically different behaviour, which among other things manifests itself under similar circumstances by producing in neon a much more intensive emission of light than in argon. The reason for this different behaviour according to G. HOLST and E. OOSTERHUIS [1]) probably lies in the fact, that in argon electrons having a velocity above the excitation-potential readily transfer their kinetic energy to the argon-atoms thereby exciting the emission of ultraviolet rays (resonance), while in neon only a small fraction of the impacts leads

[1]) G. HOLST and G. OOSTERHUIS, Physica. 1, 78, 1921.

to radiation the majority of the electrons only imparting their energy to the neon-atoms after falling through a potential-difference equal to the ionization-potential, thus causing ionization.

In consequence one would expect a great difference in the efficiency of the first non-elastic impact in neon and argon. Preliminary experiments concerning the relative value of the efficiency in these gases however have shown, that this difference is not large enough to explain the different behaviour. So there must be another reason. Beside the excitation-potential and the efficiency there is only one quantity which determines the number of the non-elastic impacts, and that is the mean free path of the electrons. Up to now it was assumed, that the value derived from the kinetic theory of gases for particles of infinitesimal small dimensions and large velocity, viz. $4\sqrt{2}$ times the mean free path of a gas-molecule, should hold for the electrons. Recently however, H. F. MAYER [1]) and C. RAMSAUER [2]) have found, from the measurement of the mean free path of electrons, that also for slow moving electrons this quantity depends on the velocity of the electrons, this dependence being different for different gases. Especially between neon and argon RAMSAUER found a very marked difference. While in neon the mean free path depends only to a slight degree on the velocity of the electrons and is nearly equal to the value of the kinetic theory, argon shows for very slow moving electrons, below 1 volt anomalously large values of the mean free path. The mean free path then decreases and becomes a minimum at approx. 12 volts, the minimum being about one third of the value of the kinetic theory. This fact must be of importance for the phenomena produced by electrons passing through a gas, especially in the case of argon, where the mean free path has its minimum value at a potential nearly equal to the excitation potential.

Considering the great importance of the dependence of the mean free path on the velocity, not only for the understanding of the action of electrons in gases, but also for the theory of the atom, it appeared desirable to me, to verify this dependence by direct experiments, in order to obtain accurate values for the ratio of the mean free paths in neon and argon, this ratio being of importance for the evaluation of comparative measurements in the two gases. The applied method is based on the following idea: If in an apparatus of given geometrical dimensions electrons of a certain velocity are allowed to move in a rare gas in a space, in which there is

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[1]) H. F. MAYER, Ann. d. Phys. **64**, 451, 1921.
[2]) C. RAMSAUER, Physik. Zeitschr. **22**, 613, 1921.

no electric field, the mean free path alone will determine their movement and distribution, so long as the velocity of the electrons is not larger than that corresponding to the excitation potential, that is: so long as the impacts are entirely elastic. If the apparatus is then filled successively with different rare gases, the movement of the electrons in the one gas must be the same as that in the other, provided the pressures are chosen in such a way that the mean free path is the same. If, on the contrary, the pressures of both gases has been adjusted so as to make the movement of the electrons the same, the inverse ratio of the corresponding pressures will give the required ratio of the mean free paths under equal pressure. This ratio must be found to be independent of the pressure used in the experiments.

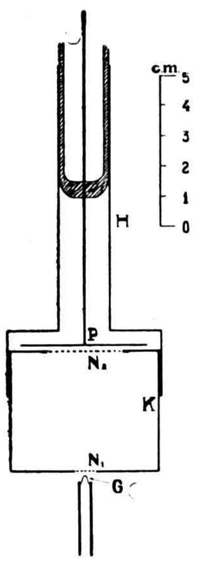



Fig. 1.

The apparatus used is shown in fig. 1. $G$ is a tungsten filament, $N_1$ and $N_2$ are grids $P$ is a receiving plate, and $H$ is a metal shield which prevents electrons from coming from $G$ to $P$ by any other way, than through the space between the two grids. All metal parts were made of copper. Before mounting the apparatus they were treated with nitric acid and showed a clean metallic surface after the tube had been exhausted during 5 hours at 400°. The gases used were so pure that no non-elastic impacts, below the excitation potential could be detected even by a very sensitive device.

Before the final measurements, preliminary measurements were made with a simpler device, which differed from that of fig. 1 by omission of the grid $N_2$. Though the experiments made in this way do not allow an accurate quantitative evaluation, the results are given here briefly, as they show very simply and clearly the different behaviour of neon and argon. During these preliminary measurements the entire apparatus was at earth-potential, except the filament which was brought at a variable negative potential, so as to produce an accelerating electric field between filament and grid. The electron-current passing on to the receiving plate $P$ was measured by a galvanometer. The measurement consisted simply in noting the current as a function of the accelerating potential between $G$ and $N_1$, in neon and argon under various pressures. In order to be independent of slow variations of the current in the filament, a second galvanometer registered the total electron current, and the quotient of the plate-current and the total

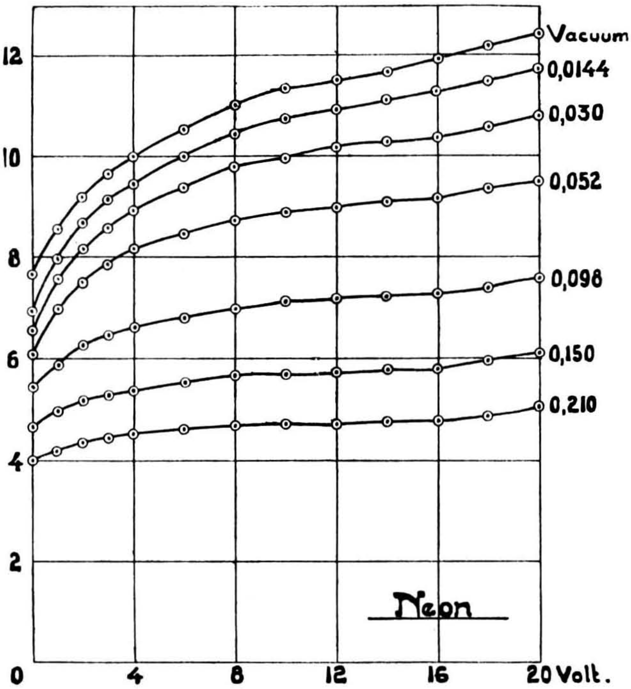
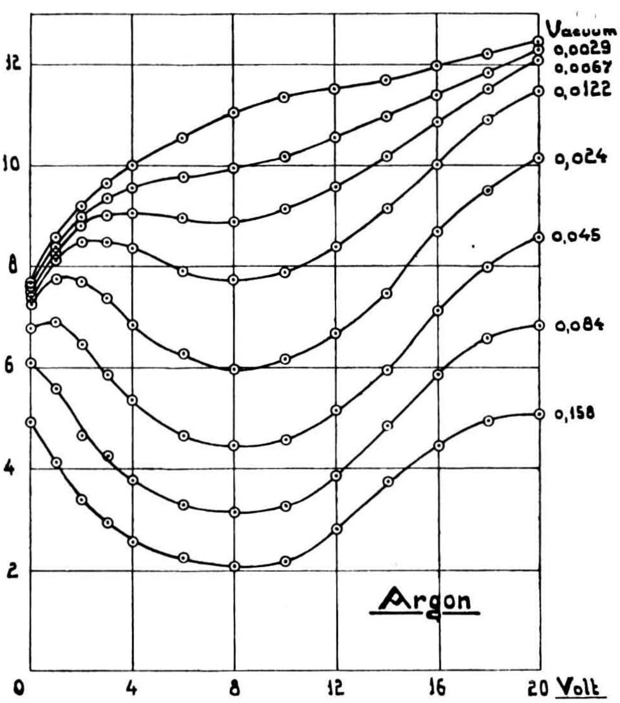

Vacuum
0,0144
0,030
0,052
0,098
0,150
0,210
12
10
8
6
4
2
0
4
8
12
16
20 Volt.
Neon

Fig. 2.


Vacuum
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0,0067
0,0122
0,024
0,045
0,084
0,158
12
10
8
6
4
2
0
4
8
12
16
20 Volt
Argon

Fig. 3.

electron current from the filament was calculated. As the temperature of the filament was always low, this quotient was independent of the intensity of the electron emission of the filament.

This quotient, multiplied by a constant is plotted in the curves of the figs 2 and 3 for a series of pressures in neon and argon as a function of the potential difference between $G$ and $N_1$. The numbers near the curves show the gas pressure in m.m. mercury. We see immediately the extra-ordinary difference in the behaviour of both gases. While in neon an increase of pressure for all velocities reduces the plate-current in about the same degree, argon shows at 10 volts a remarkable decrease of current at pressures, where at 1 volt practically no influence is observed. As the observed decrease of current can result only from the collisions between the electrons and the atoms of the gas, we can deduce from these measurements qualitatively, that the mean free path of electrons in argon varies strongly with the velocity of the electrons, while in neon this is not the case, or at any rate only to a small degree. A quantitative calculation in the sense of the above consideration can only be taken from these measurings for slow electrons up to about 10 volts; at higher velocities the electrons produce secondary electron emission from the metalwalls. To retain these secondary electrons, the second grid $N_2$ was introduced a retarding potential equal to $^3/_4$ of the accelerating potential between $G$ and $N_1$ being applied between $N_2$ and $P$. The result of such series of measurements is shown in figs. 4 and 5 wherein the numbers near the curves again show

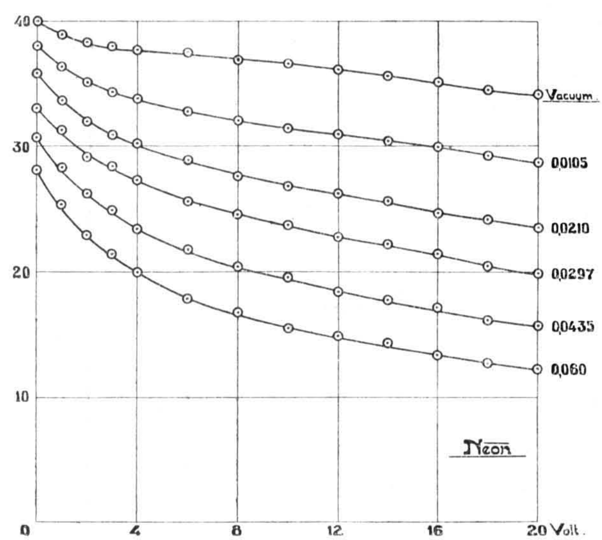


Fig. 4.

the gaspressure in millimetres mercury. For the evaluation of these measurements the distribution of the electron velocities was first measured in vacuo by means of a variable retarding field with the result, that, in consequence of the initial velocity of the electrons, the potential gradient at the filament and the Volta-potential difference

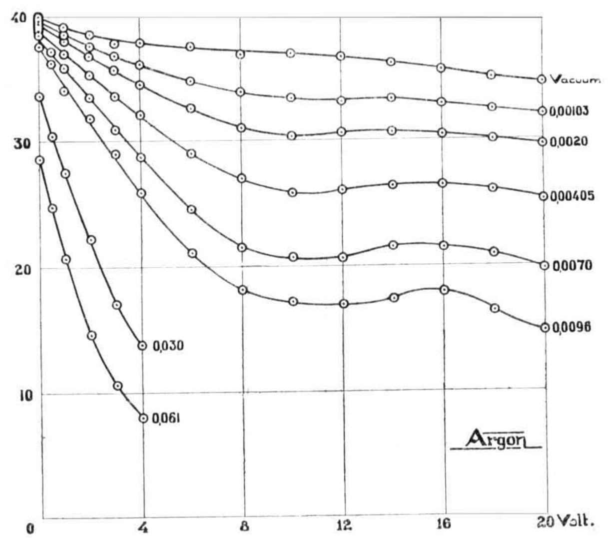


Fig. 5.

between filament and grid, 0.7 volt had to be added to the applied accelerating potential, in order to obtain the true velocity of the electrons. For a series of electron velocities the logarithm of the plate-current was registered as a function of the pressure in neon and argon. A similar character of the curves in neon and argon is to be expected, assuming that the method is correct, in such a way that for each velocity the proportion of corresponding pressures in neon and argon (i.e. pressures giving equal plate-currents) is constant. This is in fact the case for all electron-velocities up to 16 volts. To show this, the curves so obtained for a number of velocities are reproduced in fig. 6. The evaluation is simplified by the fact that the first part of the curves is straight. From the slope of these straight portions we can obtain directly the ratio of the corresponding pressures and so also the ratio of the mean free paths of the electrons.

A condition for the correctness of the method here applied is, that all collisions between electrons and atoms are absolutely elastic. By reason of the very low efficiency of the non-elastic impacts below the ionization potential in the rare gases this is no doubt the case for potentials between the excitation- and the ionization-potential and for the low pressures used here. Things are different above approx. 16 volts, the ionization potential of argon. This already can be observed at the curves for argon at higher pressures in fig. 5, by a bend in the curves at 16 volts; consequently the ratio of corresponding pressures is no more accurately constant there, as is to be seen in fig. 6 at the curves for 18 volt. At the same time this curve shows,

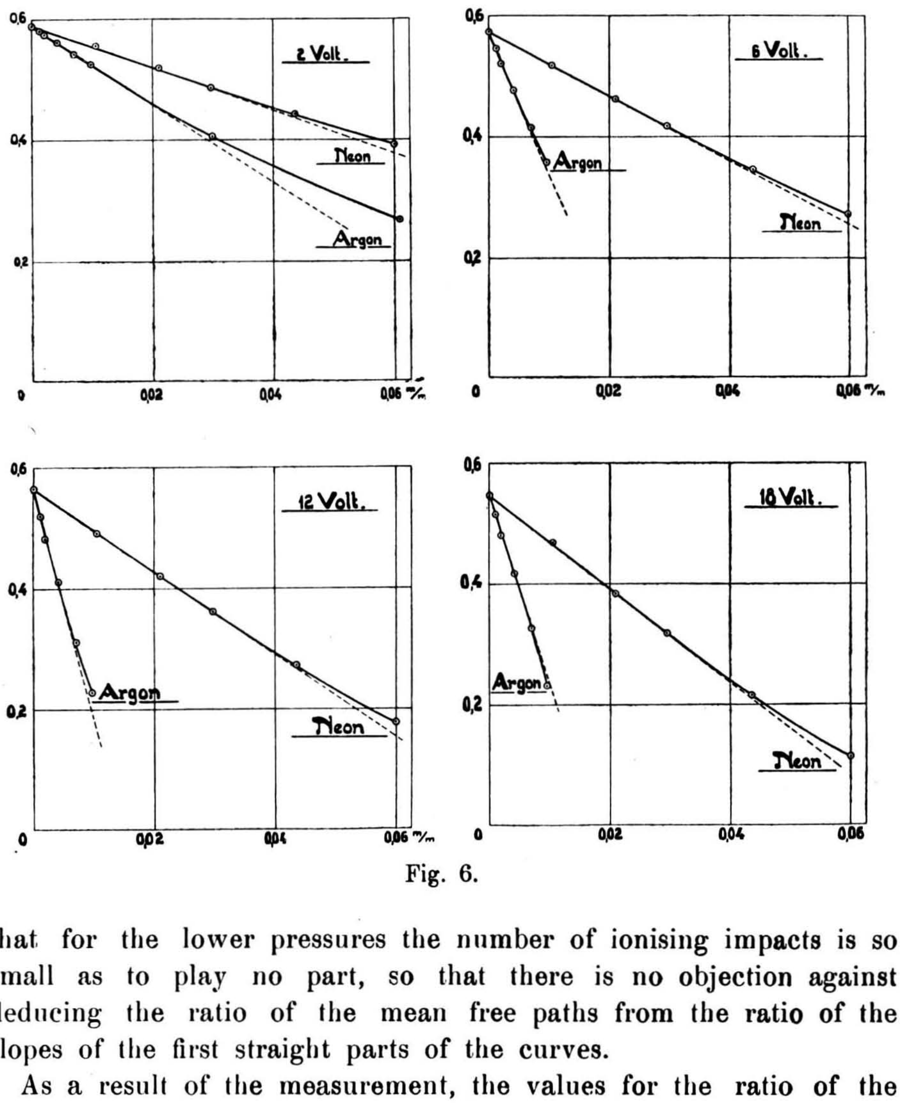


Fig. 6.

that for the lower pressures the number of ionising impacts is so small as to play no part, so that there is no objection against deducing the ratio of the mean free paths from the ratio of the slopes of the first straight parts of the curves.

As a result of the measurement, the values for the ratio of the mean free paths of electrons in neon and argon obtained in this way are shown in fig. 7 as a function of the potential corresponding to the velocity of the electrons; in fig. 8 they are plotted as a function of the root of this potential, being proportional with the velocity of the electrons. The dotted line in fig. 8 shows for comparison the values of this ratio as deduced from RAMSAUER's measurements. It will be seen that our measurements verify not only the fact of the variation of the mean free path of the electrons with their velocity, as found by RAMSAUER, but also the general character of this variation. The maximum of the curves was found in the present measurements at a potential about 2 volts less than in RAMSAUERS.

The action of the slowest electrons is theoretically of special interest. As however the accuracy of such measurings decreases for extremely slow electrons an extrapolation in the direction of the

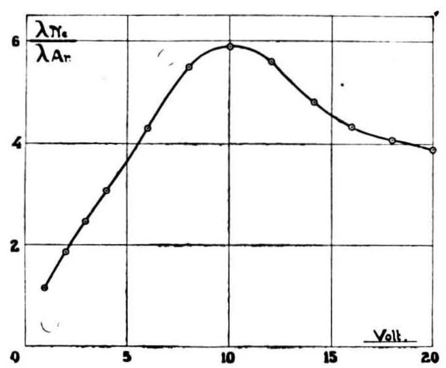


Fig. 7.

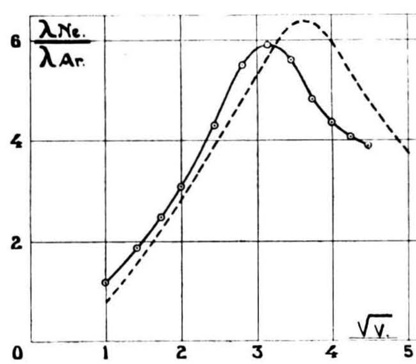


Fig. 8.

velocity zero is always doubtful. If we stipulate, according to the results of RAMSAUER that the electrons in neon show nearly normal values of the mean free path, it appears that, according to the here obtained results, the mean free path of electrons in argon on approaching zero-velocity, do not reach an infinite value, but one about 3 times that calculated from the kinetic theory for very rapidly moving particles of infinitesimal small dimensions. This figure can however, by no means lay claim to accuracy.

The number of collisions of an electron passing through a unit length under the influence of an electric field $E$, in a gas, in which its mean free path is $\lambda$, is $\frac{1}{E\frac{e}{m}}\,\frac{v^2}{\lambda^2}$, that is, inversely proportional of the square of the mean free path. In argon the mean free path, just below 12 volts, the excitation potential, reaches its minimum of about $^1/_8$ of the value derived from the kinetic theory. We can therefore conclude that an electron of this velocity in argon in passing through a length unit makes about 9 times as many collisions as would be expected from the kinetic theory, while in neon the number of collisions is nearly normal. This shows clearly, why tn argon non-elastic impacts above the excitation potential have a marked effect, while under similar conditions in neon they are hardly noticeable.

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