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Two Electrode High-Frequency Discharge at Pressures from 100 mm Hg to Atmospheric

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Two electrode discharges were investigated in air, nitrogen and argon, in pressures from 100 mm Hg up to atmospheric, and for frequencies of 35-36 mc. The intensity of the longitudinal electric field in the canal of a discharge was measured. Separate measurements were carried out at 1.5 mc. The experimental results are discussed.

THERE has been very little recent work aimed at clarifying the study of two electrode high-frequency discharges at low and atmospheric pressures. The structure of such discharges, the distribution of voltage among the different parts, and the electrical parameters have not been investigated. Isolated works[1-3] have paid principal attention to the measurement of the ignition potential, which characterizes the condition for onset of the discharge. Of these works, only the first was carried out in the shortwave region, the others being made with centimeter waves. However, the study of a steady, stationary discharge at short radio wavelengths presents some interest.

The purpose of the present research was the investigation of the structure of high-frequency two electrode discharge in air at atmospheric pressure, and also the measurement of the field intensity in the canal of the discharge in air, nitrogen, and argon at pressures from 100 mm Hg up to atmospheric.

1. HIGH-FREQUENCY DISCHARGE AT ATMOSPHERIC PRESSURE

A generator of high-frequency electromagnetic waves of conventional design was used to produce the discharge. The power supplied to the generator was 1.5-2 kilowatt, the frequency was 35-36 mc. The resonant circuit for the discharge was coupled inductively to the plate circuit of the generator and therefore did not have a high dc voltage.

The investigation of the discharge included measurement of the ignition potential for various distances between the electrodes. The discharge was simultaneously photographed. This permitted estimates of the sizes of the different portions of the discharge. Electrodes in the form of two iron spheres were placed one above the other in order to preserve the geometrically correct form of the discharge. The discharge was produced vertically, so that the convection currents of the heated gas did not distort its shape. The distance between the spheres was measured by means of a micrometer screw. The electrodes were made of sufficiently large diameter (33 mm) to avoid their being strongly heated.

One could follow the appearance of new portions of the discharge upon increase of the distance between the electrodes. A discharge with bright layers α in front of the electrodes was produced at $l = 0.2$ mm. Beginning at a separation of 0.6 mm, there appeared a new part β—narrower and not so bright—at the near-electrode layers (Fig. 1). Upon further increase of the separation to 1.4-1.7 mm, the canal of the discharge appeared. The diameter of the canal was 0.8-0.9 mm. The canal was surrounded by a corona, which is not visible on the photographs because of its low intensity.

The canal is the principal current carrying portion of the discharge. Observations of the transition from one electrode (jet) to two electrode discharge confirm this fact. Figure 2 shows a two electrode discharge which is produced from a one electrode discharge by the insertion of a metallic conductor. The canal discharge transferred to this conductor, which served as the second electrode. The less brightly illuminated region of the discharge, which surrounds the canal in the form of a corona, is left extended in the vertical direction by the convective flow of the heated gas, and takes an insignificant part in the transport of current in the two electrode discharge which is formed.

Beginning at a separation of 1.4-1.7 mm, i.e., at separations corresponding to the onset of the canal discharge, the potential increases almost linearly with increase in separation between the electrodes. Upon further increase in the separation,

[1] S. Githens, Phys. Rev. **57**, 822 (1940).
[2] McDonald and S. Brown, Phys. Rev. **76**, 1634 (1949).
[3] D. Q. Posin, Phys. Rev. **73**, 496 (1948).

the length of the discharge increases due to extension of the canal. This allows us to draw a conclusion as to the field intensity in the canal*.

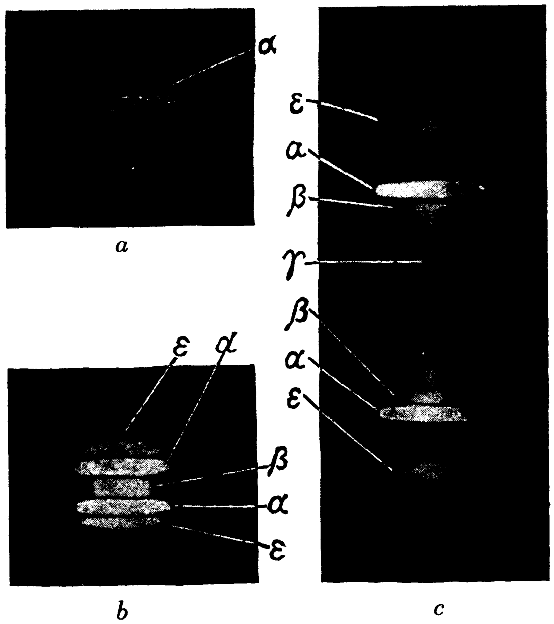


FIG. 1. Structure of a two electron discharge in air for different electrode separations. ∝, β, γ = different parts of the discharges, ϵ = flashing at the electrodes, occa- by the reflection of the discharge on them; *a:* l = 0.3 mm, *b:* l = 1.3 mm, *c:* l = 5.6 mm.

The magnitude of the field intensity in a discharge exposed to open air amounts to about 260 eff. volts/cm, which greatly exceeds the field intensity in the ordinary dc case. There is a total potential of 300 eff. volts in the near-electrode part of the discharge. The power in the electromagnetic vibrations in the discharge circuit changes with a change in the filament voltage of the generator tube. For different filament voltages, the magnitude of the field intensity changes in the range 250-300 eff. volts/cm. Figure 3 shows the dependence of the ignition potential on the electrode separation.

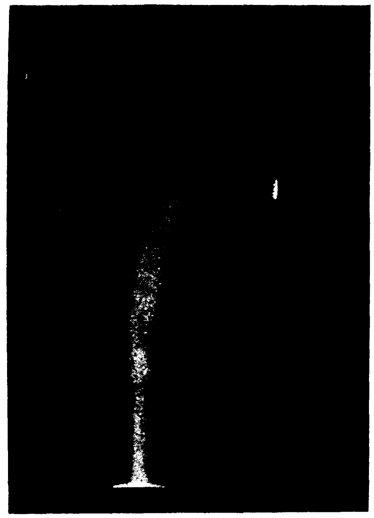


FIG. 2. Transition of a jet discharge into a two electrode discharge.

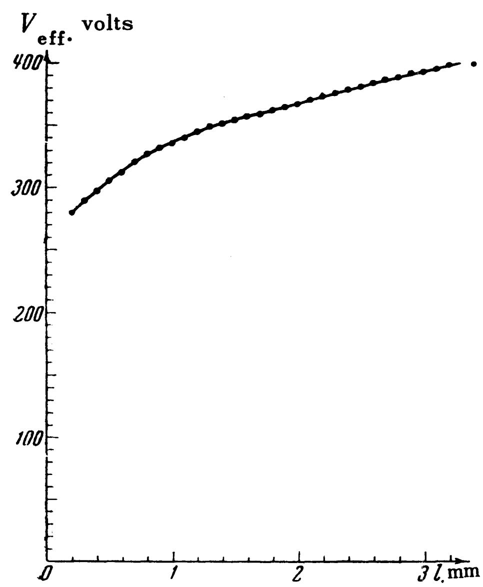


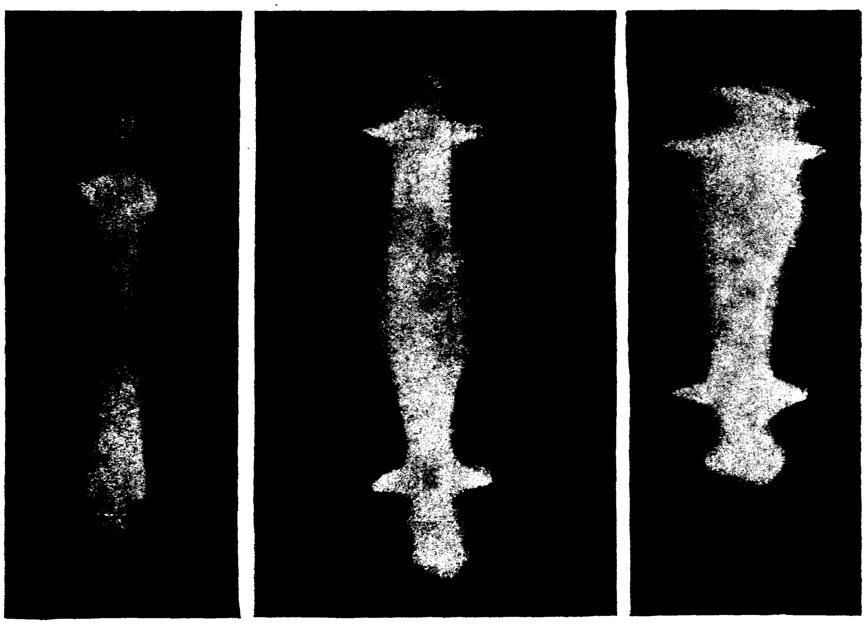
FIG. 3. Dependence of the ignition potential on the electrode separations. Air: f = 35-36 mc.

All the above data on the external form and dependence of the ignition potential on the length of

* It should be noted that this method of determining the field intensity in the canal of a discharge is evidently the only possible one. It does not appear possible to apply probe measurements in the given pressure range (and at such high frequencies) to the measurement of the field intensity of the radiofrequency field. Optical measurements on line splitting (Stark effect) also fail to give decisive results, since the relatively small magnitude of the field intensity would lead to insignificant line splitting, and the detection of these latter would require extraordinarily high resolving power on the part of the spectral apparatus.

the high-frequency discharge applies to a discharge at 35-36 mc. The radiofrequency generator had limited power, which did not permit a study of the discharge in a wide range of rf power in the secondary circuit, in which the discharge occurred.

To obtain a radiofrequency discharge at a frequency of 1.5 mc, a generator with two tubes GK-3000 was employed. This arrangement provided far more power than the generator employed at 35-36 mc. This generator made it possible to obtain the discharge under conditions of a much greater range of rf power in the circuit. Variation in the rf power in the circuit was produced by variation of the filament voltage of the generator tubes. The external form of the discharge depended essentially on this power. The external form of the discharge is shown in Fig. 4 at a frequency of 1.5 mc for different values of the rf power W in the secondary circuit. If this power is not large (W_1), then the external form of the discharge differs but little from the discharge at 35 mc. The difference lies only in the dimensions of the brightness below the near-electrode layer. These are larger at 35 mc than at 1.5 mc (Fig. 4*a*). For higher rf power in the secondary (W_2), an increase is observed in the size of all portions of the discharge, with a broadening of the canal at its middle (Fig. 4*b*). For still higher rf power (W_3), the external form of the discharge is shown in Fig. 4*c*. The significant broadening of the canal and the increased intensity of all parts of the discharge are noteworthy features. The discharge is not stationary, and over long periods of time, a scorching of the electrodes is observed.



a *b* *c*

FIG. 4. Two electrode high-frequency discharge at 1.5 mc and atmospheric pressure for different powers W of the electromagnetic signal in the circuit. a = power W_1 in circuit; b = power W_2 in circuit; c = power W_3 in circuit ($W_1 < W_2 < W_3$).

The dependence of the potential at the electrodes on the distance between them, for various output powers of the generator, is shown in Fig. 5. Under all circumstances, the potential increases with increase in separation. Measurement of the longitudinal field intensity in the canal of the discharge was possible only in the case of a low power discharge, when broadening of the canal did not take place (Fig. 5, curve *a*). In this case the value of the field intensity amounted to 850 eff. volts/cm. For higher powers (Fig. 5, curves *b*, *c*), it was not possible to draw any conclusions as to the field intensity in the canal, since the canal itself had a clearly demonstrated inhomogeneity of structure along its length.

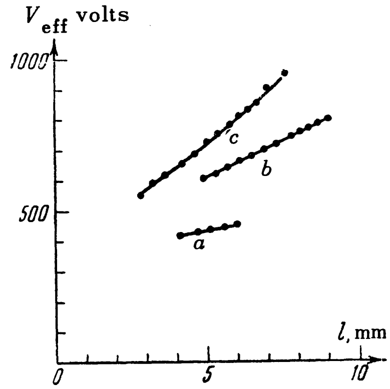


FIG. 5. Dependence of the ignition potential on the electrode separations (air; $f = 1.5$ mc) for different powers W of the electromagnetic signal. a = power W_1 in circuit, b = power W_2 in circuit, c = power W_3 in circuit ($W_1 < W_2 > W_3$).

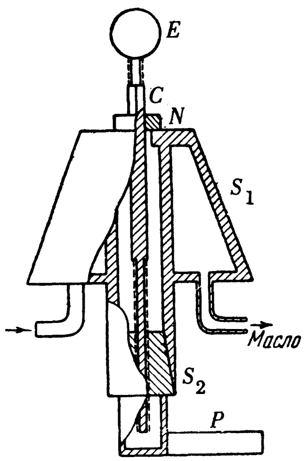


FIG. 6. Section with movable electrode; E = electrode, S_1 = principal section, which is inserted into discharge tube, S_2 = section for movement of the electrode, C = threaded rod, N = control, P = shaft.

2. RADIOFREQUENCY DISCHARGE AT LOWER PRESSURES (100-760 mm Hg) IN AIR, NITROGEN AND ARGON

A special tube was necessary for the investigation of the discharge at reduced pressures. It had metallic (telescoping) sections, which permitted a smooth moving of one electrode relative to the other and the accurate measurement of the distance between them.

The upper electrode E (Fig. 6) was rigidly clamped to the rod C, one end of which was a rectangular parallelopiped of square cross section, while the other was a spiral thread with a pitch of 0.7 mm. Upon rotation of the inner section S_2 by means of the shaft P, the end of the rod with the thread screwed into or out of the section S_2. The rod C itself, which was held by the controls N, could not rotate. As a consequence, rotation of the section S_2 led to a forward motion of the rod, and therefore to forward motion of the electrode also. The second electrode was not movable. The distance between the electrodes was determined by the number of turns of the screw. The electrodes were made of copper in the form of spheres of diameter 30 mm. The tube, which had double walls, and the sections, were cooled with oil, which was driven under pressure successively through the lower section, the tube and the upper section by means of a rotary pump.

The dependence of the ignition voltage of the discharge on the length of the discharge gap was investigated for various pressures in air, nitrogen (impurity 0.6% oxygen) and argon (impurity 0.27% nitrogen; 0.1% oxygen) (Figs. 7, 8, 9).

Before the beginning of a series of measurements at some pressure, a definite value of the potential across the discharge gap in the absence of a discharge was established for a fixed distance between the electrodes (3.5 mm). This potential (650 eff. volts) served as a parameter for measurements at different pressures. It bears a well-defined relation with the magnitude of the capacitative current which flows across the discharge gap in the absence of discharge. We thus de-

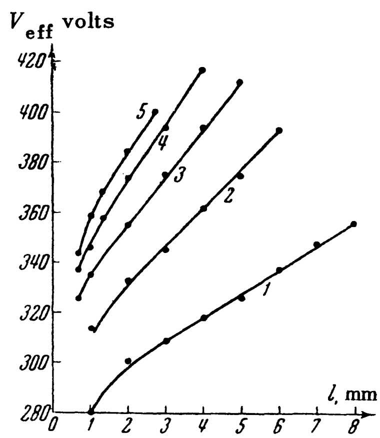


FIG. 7. Dependence of the ignition potential of the discharge in air at 35-36 mc on the distance between the electrodes for various pressures. 1--100, 2--200, 3--300, 4--450, 5--760 mm mercury.

termined the load in voltamperes which the discharge gap represents (in the absence of discharge). This parameter characterized, in known amount, the regime of the rf signal in the circuit, i.e., the source of energy which feeds the discharge under investigation.

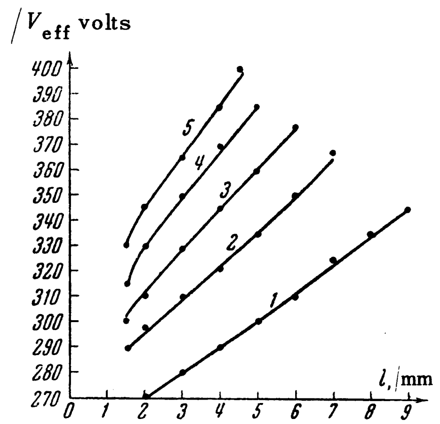


FIG. 8. Dependence of the ignition potential of the discharge in nitrogen at 35-36 mc on the distance between the electrodes for various pressures. *1*--100, *2*--200, *3*--300, *4*--500, *5*--760 mm mercury.

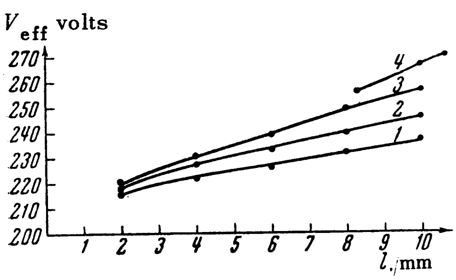


FIG. 9. Dependence of the ignition potential of the discharge in argon at 35-36 mc on distance between the electrodes for various pressures. *1*--760, *2*--100, *3*--300, *4*--400 mm mercury.

The field intensity in the canal of the discharge was determined from the dependence of the ignition potential on the distance between the electrodes for a fixed pressure. As a control, another group of measurements was performed (the dependence of the ignition potential on the pressure was investigated for different fixed distances between the electrodes), from which it was also possible to determine the intensity of the field.

The data for the field intensity in the canal of the radiofrequency discharge (frequency of the field, 35-36 mc) are shown in Fig. 10 for air, nitrogen and argon under different pressures. The potential found in the near-electrode regions of the discharge amounts to several hundred volts, which confirms the presence of strong electric fields in these parts of the discharge, and is in agreement with the presence in the near-electrode layer of spectral lines which correspond to high excitation potentials. This potential has its largest value for the air discharge, and its least for argon. For all three gases the ignition potential increased upon increase in pressure.

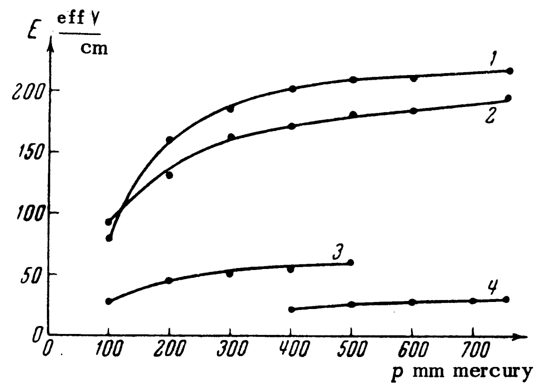


FIG. 10. Dependence of the field strength in the canal of the discharge on the pressure. *1*--air, *2*--nitrogen, *3*--argon, *4*--argon (filamented discharge); $f = 35\text{-}36$ mc.

The external form and structure of the discharges in air and nitrogen for pressures of 100-200 mm Hg are very similar, and are characterized by the presence of a red, sharply bounded canal and bluish near-electrode layers. Upon increase in pressure, the lateral dimensions of all parts of the discharge decrease and a corona appears around the canal in the air discharge. The brightness of the illumination of this corona increases with increase in pressure. Excitation of the corona is connected with the formation of an oxide layer.

The discharge in argon at pressures of 100-500 mm Hg has a diffuse yellowish-blue wide canal and a bluish near-electrode layer. At pressures of 300-760 mm Hg, there takes place a feathering or filamentation of the discharge, which is accompanied by the formation of a very bright bluish-white canal (Fig. 11). In the pressure range from 300 to 500 mm Hg in argon, both filamented and unfilamented discharges could exist. Filamentation of the discharge takes place upon increase in the length of the discharge for constant pressure, or upon increase in the pressure for constant length of discharge. The current density in the filamentation increases more than sixfold. As is evident from Fig. 10, the field intensity in this case is decreased by a factor greater than two.

a *b*

FIG. 11. Discharge in argon: *a*: unfilamented discharge, $p = 200$ mm mercury; *b*: filamented discharge, $p = 300$ mm mercury.

3. DISCUSSION OF THE RESULTS

The experimental results indicate that the field intensity in the canal of a high-frequency discharge changes, for a given range of pressure, upon change in pressure, so that the energy received by the electron in its free path remains constant. This is one of the conditions of similarity which applies both for dc discharge and rf discharge:

$$E/N = C, \tag{1}$$

where E is the field intensity, N the density of the neutral gas, C a constant for a given gas.

The dependence $E = E(p)$ for argon (curves *3*, *4*, Fig. 10) is close to linear. Deviations from linearity are connected with the dependence of the gas density on its temperature:

$$N = p/kT, \tag{2}$$

where p is the pressure of the gas, T the temperature and k Boltzmann's constant.

It follows from Eqs. (1) and (2) that

$$E = Cp/kT, \tag{3a}$$

$$\partial E/\partial p = C/kT. \tag{3b}$$

According to Eq. (3b), the increase in the temperature of the gas, which is observed upon increase in pressure, ought to produce a decrease in $\partial E/\partial p$, i.e., the slope of the tangent in the graph.

In the filamentation of the discharge in argon, there takes place a sharp increase of the current density in the canal. This effect is accompanied by an increase in the temperature of the gas in the filaments of the discharge. In correspondence with Eqs. (3a) and (3b), the magnitude of the field intensity in this case must decrease at fixed pressure. Likewise, the slope of the tangent to the curve $E = E(p)$ must also decrease. Curves *3* and *4* (Fig. 10) show that this is actually the case.

For frequencies which correspond to the very short wavelength of radio waves, and for pressures at which the experiment was conducted, Eq. (1) is equally valid for rf and dc discharge. Actually, under these conditions, the frequency of collision of the electron with the particles of the gas is significantly higher than the frequency of the field; in other words, the electron moves from one collision to another in a slowly changing, "almost constant" field. Diffusion of the electrons along the canal of the discharge does not have to be taken into account, since the canal represents a homogeneous plasma (uniformity of brightness, constancy of longitudinal field intensity).

The law of the change of the field intensity with pressure for discharges in air and nitrogen differs from that for argon (see curves *1* and *2*, Fig. 10).

As was shown by the measurements (carried out by Khokhlov[4]) of the temperature of the gas T in the canal of a two electrode discharge, the dependence of the temperature on pressure has the same form as the dependence of the field intensity on pressure. For pressures of 100-200 mm Hg, E as well as T increases rapidly with pressure; for much higher pressures the increase of E occurs much more slowly (T also hardly changes with further increase in pressure). It follows from this that the rapid increase of E in the canal of the discharge which is open to air is connected with the intensive dissociation of H_2O, with the remaining particles of air, and with the formation of NO which absorbs part of the energy communicated to the electric field by the electron.

The curve $E = E(p)$ for nitrogen is much more sloping. This can explain the fact that in the canal of a nitrogen discharge, a number of processes are missing which take place in air and which

[4] M. Z. Khokhlov, Dissertation, Moscow State Univ., 1954.

prevent the electron from gathering sufficient energy for ionization. Both in air and in nitrogen, part of the energy supplied to the discharge is consumed in the excitation of vibrational and rotational levels of the molecules. These processes do not take place in argon; as a consequence, the field intensity necessary for maintaining the discharge in this gas is less than for nitrogen and air.

Processes connected with losses of energy in the discharge require and increase in the field intensity for their compensation. This explains the deviation of the dependence of $E = E(p)$ for discharges in air and nitrogen from the path of this dependence for discharge in argon. In the latter, condition (1) is satisfied, and an increase in the field intensity is dependent only on the necessity of compensating the decrease in the free path length of the electron.

The high (of the order of hundreds of volts/cm) value of the field intensity is dependent on the fact that, because of the limited supply of energy of electromagnetic vibrations in the oscillatory circuit, the discharge in its regime corresponds to a glow discharge of high pressure with comparatively small current density (hundreds of milliamperes).

CONCLUSIONS

1. It is established that the field intensity in the canal of a high-frequency discharge increases upon increase in pressure from 100 mm Hg to atmospheric in the range 75-220 eff. V/cm (air), 90-200 eff. volts/cm (nitrogen), which corresponds to a regime of glow discharge of high pressure.

2. For pressures above 300 mm Hg there takes place a filamenting of the canal of the discharge in argon. Here the current density increases severalfold, both for increase in the length of the discharge (pressure fixed) or for increase in the pressure (fixed length of discharge). In the pressure range 300-500 mm Hg, both filamented and unfilamented discharges could take place.

3. The field intensity in the canal of the discharge in argon for pressures from 100 to 500 mm Hg amounts to 25-60 eff. volts/cm. In the pressure range 400-760 mm Hg (filamented discharge) the field intensity has the value 20-30 eff. volts/cm.

4. Increase in the field intensity with pressure is determined by the necessity of compensating, first the decrease in the free path length of the electron, second, the losses of energy at the express of the processes of dissociation and chemical reactions, and also the excitation of vibrational and rotational levels of molecules and the loss of free electrons at the expense of the formation of negative ions.

In conclusion, we consider it our duty to express our gratitude to Prof. N. A. Kaptsov for his valuable advice during the work and for his criticisms of the present research.

Translated by R. T. Beyer
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