SOVIET PHYSICS
JETP

SOVIET PHYSICS JETP VOLUME 3, NUMBER 2 SEPTEMBER, 1956

Investigation at Low Gas Pressure of an Intermediate Frequency Discharge Occurring Between High Frequency and Low Audio Frequency Discharges

N. A. POPOV AND N. A. KAPTSOV
Moscow State University

(Submitted to JETP editor November 15, 1954)
J. Exptl. Theoret. Phys. (U.S.S.R.) 30, 68-76 (January, 1956)

An experimental investigation was made of the lower frequency limit at which high-frequency discharge can occur in tubes filled with hydrogen, neon, or krypton at a pressure of several mm. mercury. It was found that high-frequency discharges and discharges at low audio frequencies are separated by an intermediate frequency region within which the discharge exhibited properties commom to both types of discharge; the lower limit of the transition region is several hundred cycles. The time dependence of the drop in emission intensity of the discharge plasma during the de-ionization of hydrogen and krypton was obtained, and it was shown that with increasing frequency the duration of the de-ionization phenomenon is a principal factor in the transformation of the a-c discharge into a high-frequency discharge.

1. INTRODUCTION

THE purpose of our investigation was to determine at what frequencies the discharge typical of low audio frequencies stops and the high-frequency discharge begins, and to explain what elementary processes play a principal role in the transformation from the low-audio-frequency discharge to the high-frequency one.

It is known that the glow of a 50-cycle electric discharge produced in a rarefied gas is seen by the eye as two simultaneous d-c discharges with overlapping cathode and anode portions; in this case the discharge arc is ignited and extinguished within the same half cycle. If the frequency of the voltage applied to the low-pressure gas-discharge tube is 100 kc and above, the discharge glows continuously and there is no overlap of the cathode and anode portions[1-4]. Investigators of high-frequency discharges have noted that the ignition voltage drops sharply at frequencies above 10^5-10^6 cycles, but all indicated that the ignition voltage is independent of frequency below 10^5 cycles[5-6]. No detailed experimental investigation of an a-c discharge at frequencies below 10^5 cycles but above 50 cycles has been made up to now*.

The distribution function of the electrons in high-frequency and commercial-frequency discharges was analyzed theoretically by Margenau and Hartman[7-8]. It follows from their work that the distribution function for electrons in a discharge is continuous over a frequency range from zero (d-c discharge) to several megacycles (high-frequency discharge). If this be so, there should

---

[1] N. A. Kaptsov, *Electric Phenomena in Gases and in Vacuum*, Gostekhizdat, Moscow-Leningrad, 1950.

[2] E. Hiedemann, Ann. Physik. 85, 649 (1928); 2, 221 (1929).

[3] E. Hiedemann, Phys. Rev. 37, 978 (1931).

[4] J. J. Thomson, Phil. Mag. 23, 1 (1937).

* Note added in proof: With the exception of a recently published article by G. Francis, Proc. Phys. Soc. (London B68, 137 (1955).

[5] L. Rohde, Ann. Physik 12, 569 (1932).

[6] H. Bocker ,Archiv Elektrotech. 31, H. 3, 1937.

[7] H. Margenau, Phys. Rev. 73, 297 (1948).

[8] H. Margenau and L. Hartman, Phys. Rev. 73, 309 (1948).

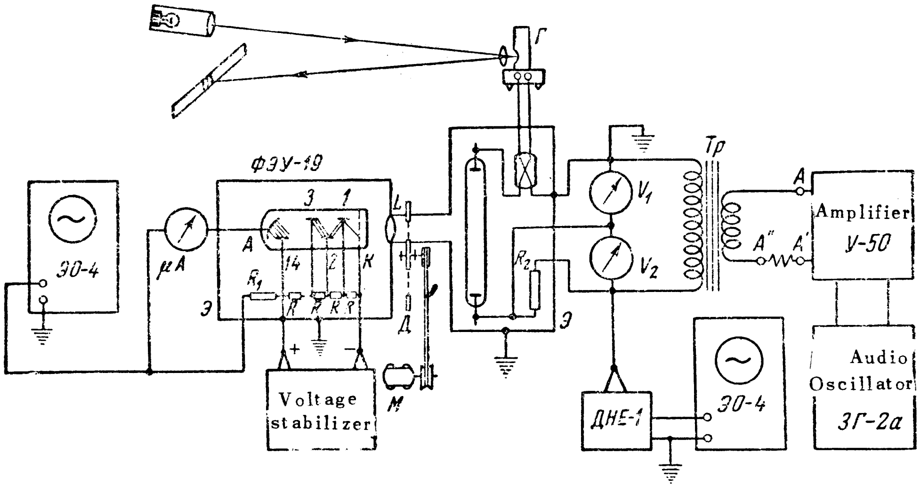

FIG. 1. Diagram of Experimental setup.

be a smooth transition between both types of discharge (commercial- and high-frequency) as the frequency is varied in either direction.

Restricting ourselves to low pressure, we shall from now on call a high-frequency discharge any discharge occurring in a tube operating at any radio frequency, provided first, that the alternation of the applied voltage causes no observable flicker in the intensity of the discharge, and second, that the character of the ignition and glow of the discharge remain the same when either internal or external electrodes are used. We shall call an a-c discharge one occurring in a tube operating at audio frequencies, provided first that the intensity of the discharge changes noticeably with the voltage alternations, and second that the type of electrodes used (external or internal) affects substantially the character of the ignition and glow of the discharge.

The frequency dependence of the ignition and glow of an a-c discharge in tubes with external electrodes was studied by us with the aid of oscillographs of the discharge emission[9]. It was established in that investigation that at low frequencies individual flashes of a nonself-maintaining discharge occur in tubes with external electrodes. Such unstable discharges can be changed into ordinary stable ones by increasing the frequency, or by increasing the voltage across the electrodes. At frequencies of several tens of kilocycles the discharge ignition and glow characteristics become practically the same for internal and external electrodes and thus, in this respect, the discharge behaves like a high-frequency one.

2. EXPERIMENTAL PROCEDURE

In this work, which is a continuation of the earlier investigation[9], we employed a further modification of the older method of oscillographing the discharge emission, adapted from the work by Huxford and Platt[10] and by Beese[11].

The principle diagram of the experimental setup is given in Fig. 1. The audio-frequency source was the same as in Ref. 9, as were the methods of measuring the current and voltage. The light from the central portion of the discharge tube was made to pass through lens *L* and semi-transparent antimony-cesium cathode of electrostatically electron-focussed photomultiplier FEU-19. Voltage was applied to the plates of the photomultiplier through a voltage divider, connected to a stabilized rectifier with a smoothly variable output voltage. The output current of the photomultiplier was monitored with a microammeter and recorded with an EO-4 oscillograph. A DNE-1 capacitative voltage divider and another EO-4 oscillograph were used to monitor the waveform of the voltage across the discharge tube. A systematic check showed the voltage waveform to be sinusoidal in all the experiments. All the set-up elements, including the photomultiplier

---

[9] N. A. Kaptsov and N. A. Popov, J. Exptl. Theoret. Phys. (U.S.S.R.) **27**, 97 (1954).

[10] W. Huxford and J. Platt, J. Opt. Soc. Am. **37**, 10 (1947).

[11] N. S. Beese, J. Opt. Soc. Am. **36**, 555 (1946).

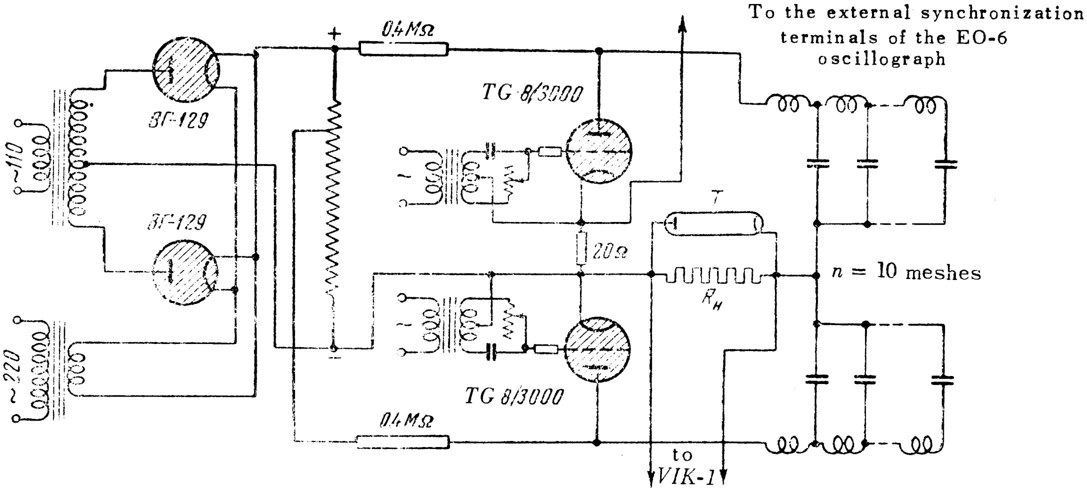

FIG. 2. Diagram of pulse generator.

and the discharge tube, were thoroughly shielded to prevent interference. Shield *E* was made of tin and the outer braid of the shielded conductors was grounded.

To investigate the emission of a pulsed discharge, we assembled another variant of the experimental setup, in which the source of voltage was a rectangular pulse generator (Fig. 2). The circuit of this generator was adapted by us from one described in an article by Gavrilov [12]. With the aid of two TG-8/3000 thyratrons and two artificial lines, this generator formed two identical rectangular voltage pulses from each positive sinusoidal half-cycle of the voltage fed to the thyratrons from the rectifier, which in turn employed VG-129 gas-filled diodes. The time interval between these two rectangular pulses could be varied with two phase shifters.

The artificial lines were made up of ten meshes each and formed pulses of 20 microsecond duration. A noninductive resistance, equal to the characteristic impedance of the line (600 ohms), was connected in parallel with the discharge tube, The voltage on the discharge tube was measured with a VIK-1 pulse voltmeter. Type EO-6 oscillographs with driven sweep were used. The peak working voltage of the pulse was 800.

According to our preliminary assumptions, the duration of the de-ionization of the gas, occurring in the discharge tube at the instant of voltage polarity reversal. is of great importance in the transformation of the a-c discharge into a high-frequency discharge with increasing frequency. We therefore filled the discharge tubes with hydrogen, neon, and krypton. Hydrogen is the lightest gas and furthermore is a molecular one, and the de-ionization phenomenon in hydrogen was thoroughly studied by Gavrilov [12]. From the work of Ardonova it is known [13] that the de-ionization rate in neon is noticeably different from that of krypton.

The hydrogen was obtained electrolytically, and was then purified of all possible organic impurities water vapor, and oxygen. The mercury vapor was frozen out with liquid nitrogen. A spectral check showed the absence of other gases from the hydrogen-filled tubes. Neon and krypton were obtained in glass flasks from the All- Union Electrotechnical Institute.

The discharge was investigated both in sealed-off discharge tubes as well as in tubes joined to the setup. After degassing, the tube was filled with hydrogen and a glow discharge lasting not less than one hour was started. The hydrogen was then removed, the tube again degassed and refilled with the investigated gas, and the discharge restarted in the fresh gas. This conditioning procedure was carried out again for not less than an hour and only then was the tube sealed off (or the discharge studied with the tube attached). The observations covered the central portion of the discharge in symmetrical tubes with internal nickel electrodes. The spacing between electrodes was 300-400 mm,

---

[12] S. N. Gavrilov, Dokl. Akad. Nauk SSSR **71**, 265 (1950).

[13] S. I. Ardonova, J. Exptl. Theoret. Phys. (U.S.S.R.) **22**, 981 (1952).

and the internal diameter of the tube was 25 mm.

A series capacitor is connected in the input of the vertical amplifier of the EO-4 oscillograph. This means that the oscillograph screen shows only the a-c component of any periodic process that contains both d-c and a-c components. Therefore, in order to observe the total photoelectric current on the oscillograph screen, the light emitted by the discharge tube and incident on the photomultiplier cathode is interrupted by disk *D*, rotated by electric motor *M* (Fig. 1). The disk has four symmetrical equally-spaced openings of equal size.

This method permitted determining what portion of the total photoelectric current is the a-c component and what portion is the d-c component.

3. RESULTS OF OBSERVATIONS

Figure 3 shows a series of photocell-current oscillograms of an a-c discharge in hydrogen. The first three oscillograms were taken with the disk stationary and with the light passing directly through the lens to the photomultiplier cathode (Figs. 3a-c). The remaining oscillograms were taken with the disk rotating and with the oscillograph sweep synchronized with the frequency at which the light was interrupted by the disk (Figs. 3d-k). In the latter case, the oscillograph shows clearly the zero line corresponding to the absence of photocell current and consequently to the absence of the light in the photomultiplier. We also synchronized the sweep frequency with the frequency of the voltage applied to the discharge-tube electrodes. Both methods of synchronizing the frequencies on the oscillographs are equivalent. and the results obtained are numerically the same. However, in practice it proved more convenient to synchronize the sweep frequency with the light-interruption frequency at low audio frequencies and with the tube-voltage frequency at higher frequencies.

The oscillograms show that starting with 200-300 cycles, a d-c component appears in the photocell current and starts rising rapidly with the frequency. This means that the tube starts glowing continuously at the instant in which the voltage changes polarity. In other words, at these frequencies and above, we deal with a modulated emission at a frequency f' which equals twice the frequency f of the electrode voltage: $f' = 2f$.

In our experiments the waveform of the alternating voltage applied to the discharge tube was strictly sinusoidal. In the first approximation, it is possible to assume that the time variation of the light intensity is also sinusoidal, as can be seen from the accompanying oscillograms (Figs. 3d-k). In this case the intensity of the light coming from the central portion of the discharge tube obeys the following relationship:

$$I(t) = I_0 + I_1 \sin 2\omega t, \qquad (1)$$

where the modulation frequency $2\omega = 4\pi f$. For measurement purposes, it is more convenient to put

$$I(t) = I_{\min} + I_1(1 + \sin 2\omega t), \qquad (2)$$

where $I_{\text{мин}} = I_0 - I_1$ is the minimum intensity of tube emission. If $\omega = \pi n/2$ ($n = 1,2,3\ldots$), $I(t)$ becomes a constant quantity, equal to $I_{\text{peak}} = I_{\min} + 2I_1 = I_0 + I_1$. This last relationship is valid not only for a sinusoidally-varying light intensity, but also for any other variation. The percentage modulation K is given by the following relationship:

$$K = 100\,(I_{\text{peak}} - I_{\min})/I_{\text{peak}}. \qquad (3)$$

The quantities I_{peak} and $I_{\min}$ entering into this expression were determined by us by counting the number of squares on a transparent grid placed on the oscillograph screen, with the rotating disk interrupting the light from the discharge tube.

The measurement procedure chosen permitted us to investigate the transformation of the low-frequency discharge into a high-frequency one in various gases (hydrogen, neon, and krypton) as a function of the discharge current and of the pressure of the gas filling discharge tube.

The graph showing the transformation from the low- to the high-frequency discharge and its dependence on the type of gas is shown in Fig. 4. The discharge was studied in three identical sealed-off discharge tubes with hydrogen, neon, and krypton at a pressure of 2 mm mercury and at a discharge current of 2 ma. Flat electrodes, 15 mm in diameter and 300 mm apart, were placed inside the tube. The internal diameter of the tube was 25 mm. The abscissa of the graph indicates the frequency in kc and there are two ordinate scales. One indicates the ratio of the fraction T_2 of the period during which no discharge glow is observed in the tube to the total period T. The frequency dependence of this ratio T_2/T is represented graphically by the descending branches in the curves in the frequency range from 50 to 200 cycles. The ascending branches of the curves for the same gases correspond to the second ordinate scale, shifted to the right for convenience, which represents the percentage modulation K of the light from the discharge

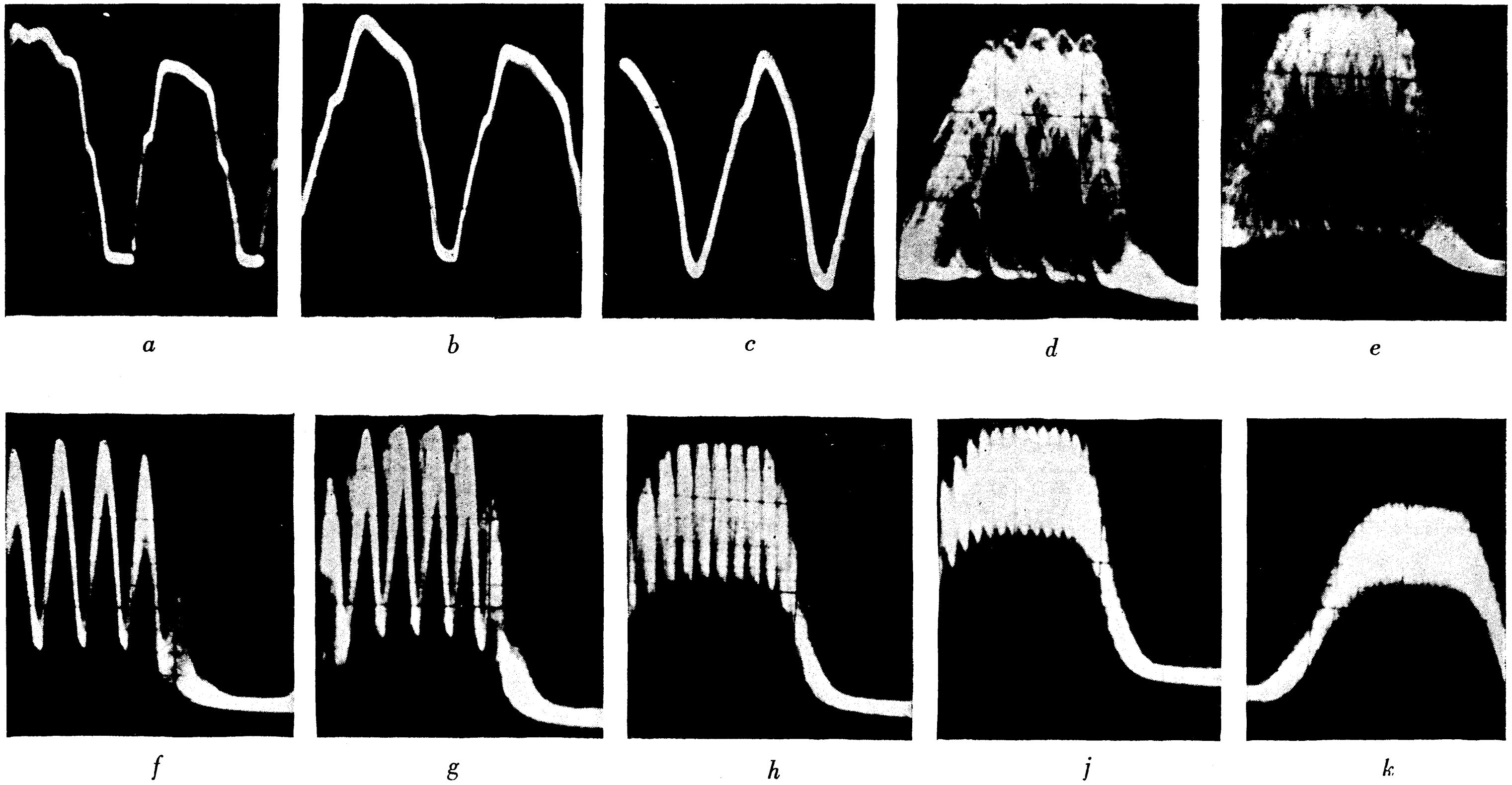

FIG. 3. Oscillographs of photocell current. Discharge in hydrogen at various frequencies of voltage applied to discharge-tube electrodes: *a* – 50 cycles; *b* – 100 cycles; *c*, *d*, – 200 cycles; *e* – 400 cycles; *f* – 800 cycles; *g* – 1 kc; *h* – 2 kc; *j* – 3 kc; *k* – 5 kc.

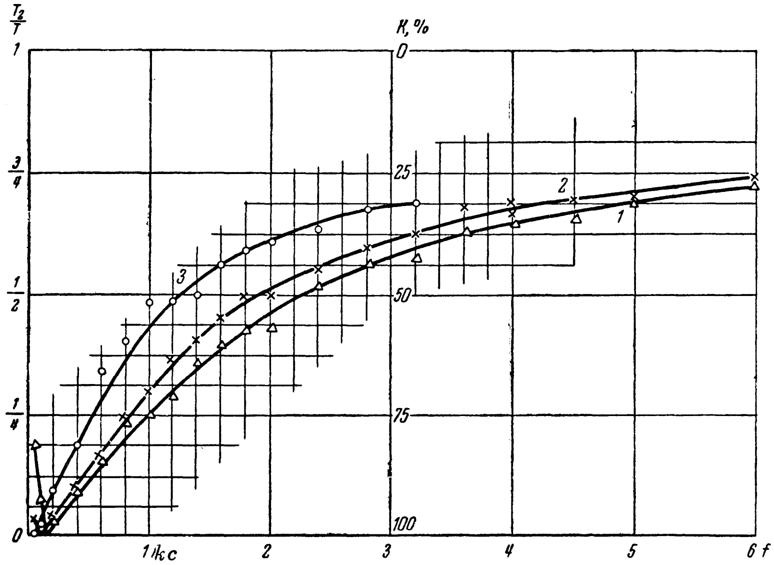

FIG. 4. Graph showing transition between low- and high-frequency discharge for different gases. 1 — hydrogen; 2 — neon; 3 — krypton; $i = 2$ ma; $p = 2$ mm mercury.

tube.

It is evident from this graph that even at frequencies as low as 200 cycles the discharge cannot become completely distinguished within a single cycle in any of these three gases. This means that at these frequencies (50-200 cycles, depending on the type of gas) the ratio T_2/T vanishes and the photocell current starts containing a d-c component proportional to the light intensity. Even at 2.5 kc the modulation factor of the constant light flux from the discharge tube is less than 50% for all three gases. Characteristically, for different gases, the higher the atomic number of the element, i.e., the longer the de-ionization time of a given gas, the higher the position of the right-hand branch of the curve, other conditions being equal.

For all three gases, a detailed study was made of the transformation of the a-c discharge into a high-frequency one, both as a function of the discharge current, as well as a function of the gas pressure, other conditions being equal. The experiments were carried out at gas pressures ranging from 0.8 to 25 mm mercury and at discharge currents from 0.5 to 5 ma. The form of the K vs. f curves is in all cases similar to that of the curves of Fig. 4. The curves in similar graphs run parallel to each other, both when the parameter varied is the pressure and when it is the current.

The sequence in which the curves range themselves on the graphs when the parameter is the discharge current or the gas pressure depends not only on the de-ionization time but also on the ratio between the ignition voltage and the amplitude of the voltage applied to the tube. We increase the latter, thereby increasing the discharge current. The ignition and extinction voltage vary with the pressure. All this leads to a change in the time elapsed from the instant of ignition to the instant of extinction of the discharge within the same voltage half-cycle, and consequently also effects the position of the curves that show the dependence of T_2/T and of K on f.

The form of these curves depends considerably more on the gas pressure in the tube than on the discharge current. The frequency variation of the modulation factor, plotted by us for various pressures of the same gas at a fixed distance between electrodes, has shown that two different relationships hold in this case. On one hand, at lower pressures (region of left branch of ignition characteristic) the K vs. f curves occupy higher and higher positions as the pressure is increased. On the other hand, at higher pressures (region of right branch of the same characteristic), this relationship is reversed; starting with a certain pressure, the curves occupy lower and lower positions as the pressure increases. Investigations of the transformation of the a-c discharge into a high-frequency discharge, made at various values of the discharge current, show that the higher the discharge current in these gases, the higher the position of the K vs. f curves. In our experiments, over the entire range of variation of the current and of the gas pressure, the point on the frequency axis corresponding to $T_2/T = 0$ or $K = 100\%$ never lies beyond 500 cycles.

Measurements were made of the frequency dependence of T_2/T and K in two sealed-off discharge tubes of identical internal diameter and 40 and 30 cm long filled with hydrogen at a pressure of 2 mm mercury. The curves obtained for identical discharge currents are in sufficiently good agreement over their entire length. This experimental fact is well explained by the de-ionization theory developed by Granovskii[14]. In fact, plasma in the de-ionization stage exhibits ambipolar diffusion of electrons and ions from the plasma to the walls of the tube and to the electrodes. On the other hand, in the central portion of the tube there is ambipolar diffusion of electrons and ions only to the walls. Since both tubes had the same internal diameter, the speed of plasma de-ionization and consequently also the intensity of emission from the plasma in the de-ionization stage were the same for both tubes. This evidently also caused the corresponding frequency-dependence curves of T_2/T and K to be the same for tubes of different lengths.

To obtain more details on the mechanism of the transformation of the low-frequency discharge into a high-frequency one with increasing frequency, we investigated the drop in intensity of emission of a pulsed discharge with time in the de-ionization stage in hydrogen and krypton. The presence of two periodically repeating light pulses in the photocell-current oscillograms has led to a sufficiently accurate determination of the time behavior of the drop in the intensity of emission from the plasma in the central portion of the discharge tube with hydrogen and krypton at pressures of 2-3 mm mercury (Fig. 5). The fact that the curves of Fig. 5 differ insignificantly from straight lines is an indication that at these pressures the intensity of emission from the discharge tube in the de-ionization stage drops nearly exponentially. There is therefore every reason for assuming that in our experiments the charged particles become diverted from the plasma principally by diffusion onto the wall[14].

Knowing the discharge ignition and extinction voltages, and knowing also the amplitude of the sinusoidal voltage applied to electrodes, we determined graphically the time interval between the instant when the diminishing sinusoidal voltage becomes equal to the discharge extinction potential in a given half cycle and the time the voltage rises to the value of the ignition potential in the next half cycle. The plasma becomes de-ionized during this time interval, which depends on the frequency. Knowing the drop in emission intensity of the discharge in the de-ionization stage, it was easy to calculate to what minimum value should the emission intensity of the a-c discharge decrease during the polarity reversal.

The K vs. f curves thus computed for hydrogen and krypton agree sufficiently well with similar curves obtained directly by measuring I_{peak}/I_{min} on the oscillogram for the same gases, other conditions being equal. This result confirms the previously-made assumption that the duration of the plasma de-ionization plays a substantial role in the transition between the low-and high-frequency discharges as the frequency is increased.

If the electrode voltage varies sinusoidally, the de-ionization in the post-discharge period takes place first in a diminishing direct field and then in an increasing reverse field. In this case, as shown in references 15 and 16, the plasma breaks up, mostly in the vicinity of the electrodes, owing to the formation of an ever-increasing space charge layer, consisting of positive ions. The space charge is initially formed at the cathode, and after the voltage passes through zero it is formed at the former anode. For the discharge tube and for the gases, voltages, and electrode spacing used in our investigations, the plasma breaks up before the space charge boundary manages to approach it. Consequently, in our case the speed of de-ionization is independent of the electrode-voltage amplitude.

When the drop in intensity of emission from a pulse discharge in the de-ionization stage is used to plot analytically the curves showing the frequency dependence of the modulation factor of an a-c discharge, it turns out that it is possible to compute these curves, to a certain approximation, up to frequencies of 10^5 cycles. The results obtained are plotted in Fig. 6.

4. CONCLUSIONS

The experimental material gathered in this investigation of fluctuations in the emission of a discharge at alternating current, in tubes with internal electrodes, as well as the material on the ignition

---

[14] V. L. Granovskii, *De-ionization of Gas.* From the collection *Electron and Ion Instruments*, edited by P. V. Timofeev, Gosenergoizdat, 1941, p. 93.

[15] B. G. Mendelev and L. A. Sviatoezerskaia, J. Exptl. Theoret. Phys. (U.S.S.R.) 21, 18 (1951).

[16] V. D. Andreev, V. E. Levina and B. G. Mendelev, J. Exptl. Theoret. Phys. (U.S.S.R.) 21, 149 (1951).

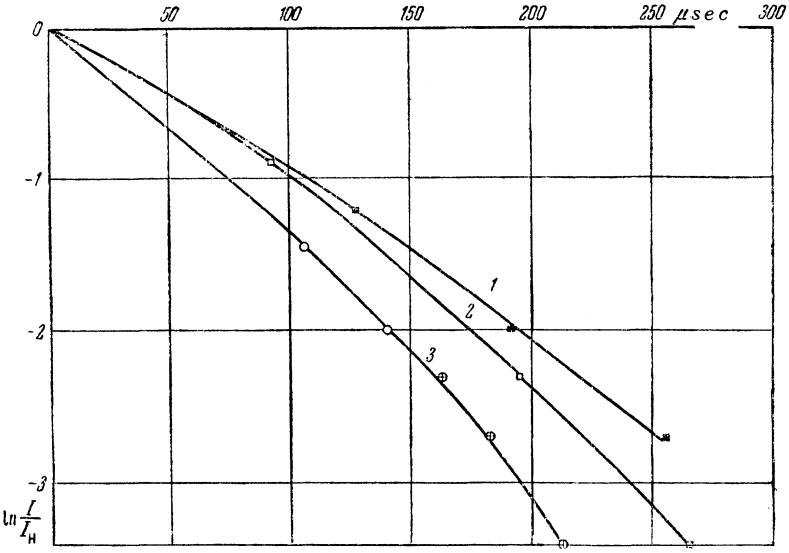

FIG. 5. Semi-logarithmic plot of the drop in emission intensity *I* of a discharge in the de-ionization stage with time. I_H — initial emission intensity. *1* — krypton, 2.8 mm mercury; *2* — 1.5 mm mercury; *3* — hydrogen, 2.1-3.1 mm mercury.

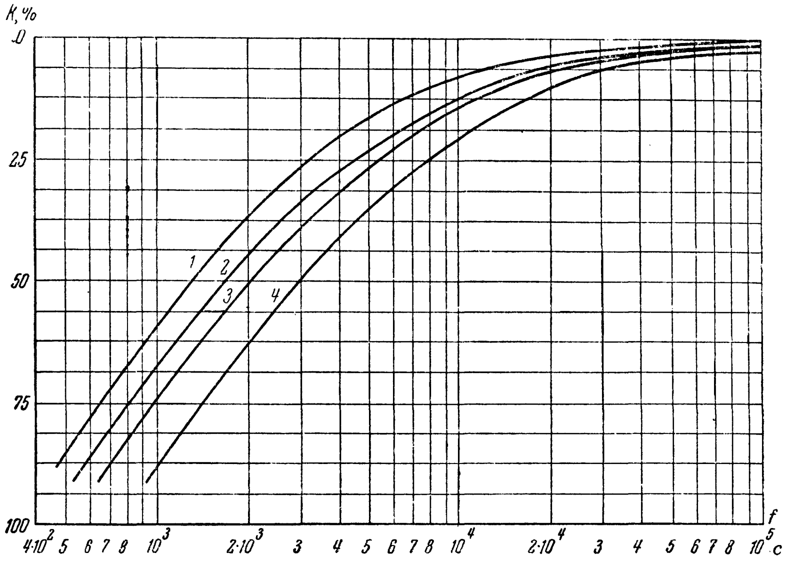

FIG. 6. Graph showing frequency dependence of modulation factor *K* of the a-c discharge emission intensity. Krypton: *1* — 2mm mercury; *2* — 2.7 mm mercury; Hydrogen: *3* — 2 mm mercury; *4* — 2.5 mm mercury.

of discharge tubes with internal and external electrodes in audio-frequency circuits, obtained by us in Ref. 9, leads to the following deductions:

1. There is no sharp boundary between an a-c discharge and a high-frequency discharge. Between these two types of discharge there is a transition region within which the discharge exhibits properties of both types of discharge.

2. The positions of the boundaries of the transition region depend on the pressure and on the type of gas. The lower limit of the transition region is several hundred cycles. The upper limit cannot be established accurately, for with increasing frequency the discharge in the intermediate frequency region approximates asymptotically in its basic properties the high-frequency discharge.

3. As the a-c discharge changes into a high-frequency one, and as the frequency is increased, a substantial role is played by the finite time of deionization occurring in the plasma of the a-c discharge when the voltage reverses polarity.

Translated by J. G. Adashko
10

SOVIET PHYSICS JETP VOLUME 3, NUMBER 2 SEPTEMBER, 1956

The Structure of Superconductors. IX. Roentgenographic Determination of the Structure of ∝ - Bi_4Rh

V. P. GLAGOLEVA AND G. S. ZHDANOV
Moscow Physico-engineering Institute

(Submitted to JETP editor December 29, 1954)
J. Exptl. Theoret. Phys. (U.S.S.R.) 30, 248-251 (February, 1956)

We have determined the structure of the low temperature modification of Bi_4Rh, which belongs to the space group O_h^{10}— $Ia3d$, with a lattice period $a = 14.928$ A. The positions of the bismuth and rhodium atoms were determined by a very precise method of constructing the cross sections and projecting the series of interatomic vectors (F^2-series) and the series of electron densities (F-series).

IN the work of one of us and Zhuravlev[1] it was shown that the compound Bi_4Rh has three modifications; ∝, β, and γ. The low temperature modification has a cubic lattice with a period $a = 14.928$ A and belongs to the space group O_h^{10}— $Ia3d$. In the simple lattice there are 120 atoms: 96 atoms of bismuth and 24 rhodium atoms. Alekseevskii[2] has shown that the low temperature modification ∝ - Bi_4Rh does not exhibit superconductivity down to a temperature ~ 0.1 K, whereas the two other modifications - β - Bi_4Rh and γ - Bi_4Rh pass over into the superconducting state. In the same manner as in white and gray tin, the superconductivity in Bi_4Rh is a property of the high temperature modification which is metastable at low temperatures. The compound Bi_4Rh, having a considerable number of modifications and various superconducting properties, appears to be interesting, since a study of the structure of its polymorphic modifications may enable one to explain the connection between polymorphism and superconductivity. The problem in question in this work[3] was to determine the atomic structure of one of these modifications (∝-Bi_4Rh), which contains a large number of atoms in the elementary cell. A short report of the results of this work was published previously[4].

An analysis of the regularity of the extinctions and the possible atomic positions shows that the bismuth atoms may occupy just the general position 96 h and the rhodium atoms – the one of the two 24 – fold positions 24 c or 24 d.

For determining the positions of the bismuth atoms, which forms the framework of the structure, we selected the method of constructing the cross sections of the F^2-series. A three dimensional assembly of the reflected intensity received from a series of oscillating-crystal roentgenograms, was taken by the method of irradiating in a RKV camera 86 mm in diameter. We derived the layer lines from zero to an eighth with a total number of independent reflections equal to 235. The reflected intensity was measured by a visual comparison of the spots for quality of blackening. For calculating $F^2(hkl)$ we took only angular factors into account; temperature and absorption factors were not considered.

The sections of the F^2-series were selected so that the number of maxima were as small as possible, with a small probability of overlapping, so that the connection between the coördinates of the maxima and the atomic coordinates was of a very simple form. There are three types of maxima: Bi-Bi,

---

[1] N. N. Zhuravlev and G. S. Zhdanov, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 228 (1955); Soviet Phys. JETP **1**, 91 (1955).

[2] N. E. Alekseevskii, G. S. Zhdanov and N. N. Zhuravlev, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 237 (1955); Soviet Phys. JETP **1**, 99 (1955).

[3] V. P. Glagoleva, Dissertation. MIFI (Moscow Physico-Engineering Institute), 1954.

[4] G. S. Zhdanov, Works (Trudy) of the Crystallograph. Inst. **10**, 243 (1954).