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New Apparatus and Methods of Measurement

LOW-VOLTAGE HALOGEN COUNTERS

(Mechanism of Discharge)

V. V. VISHNYAKOV, T'ANG HSIAO-WEI, and A. A. TYAPKIN

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INTRODUCTION

GEIGER and Haxel[1] proposed the use of halogens as a quenching additive in counters as early as 1937. However, many others regarded the presence in counters of electronegative gases capturing electrons to be inadmissible. Apparently this explains why the first attempt to fill counters with a mixture containing an admixture of halogens[2] was not made until ten years later. It was soon discovered[3-6] that self-quenching counters obtained at a low halogen concentration possess a number of undisputed advantages compared to ordinary counters which contain an admixture of organic vapors: a low breakdown potential (200 — 300 v), ability to operate at low temperatures (down to $-80°$ C), a practically unlimited working lifetime and the preservation of counting characteristics after an accidental discharge. Therefore, in spite of the complexity of their preparation halogen counters have attained widespread use.

Phenomena in halogen counters differ essentially from phenomena occurring in ordinary self-quenching counters containing organic vapors. The present concepts of the discharge in halogen counters explain a number of characteristic features of such counters.

Thus, the low working voltage of halogen counters is explained by the ionization which occurs in Penning type[7] mixtures as a result of collisions of the second kind. Low voltage halogen counters contain in addition to the principal gas neon small admixtures of argon ($\sim 0.1\%$) and of a halogen ($\sim 0.1\%$). In neon at a comparatively low electric field the electrons begin effectively to produce metastable atoms with an excitation potential of 16.57 ev. This is associated with the fact that the level in question is the lowest excited level and the electrons which experience only elastic collisions accumulate energy in the field until they become capable of producing metastable neon atoms. In pure neon, or in neon with an admixture of organic vapors, the metastable atoms are destroyed without producing charged particles in the gas. When a small admixture of argon is present in the neon, the argon atoms become ionized since the ionization potential of argon (15.7 ev) is less than the excitation potential of the metastable neon state. From available experimental data[7] it is known that ionization of argon takes place in almost every gas-kinetic collision of an argon atom with a metastable neon atom. Ionization of halogen atoms in collisions with metastable neon atoms occurs with a lower efficiency, since the excitation energy has a greater probability to be expended in dissociating the halogen molecules.

Production of metastable neon atoms begins at a comparatively low electric field, since an electron undergoing only elastic collisions accumulates over a path length of hundreds of mean free paths the energy required for the excitation of the metastable neon level which is the lowest excited level. When an admixture of argon is present in the neon ionization occurs, naturally, at low voltages sufficient for the production of metastable neon atoms. In this case the admixture of argon must be sufficiently small so that collisions of electrons with the argon atoms would have a low probability. Otherwise the electrons will expend their energy in exciting metastable levels of argon atoms, and this will lead to an increase in the voltage required for producing a discharge. For the development of such a discharge it is necessary that over a considerable part of the counter volume there should exist an electric field sufficient for the production of metastable atoms. In this connection it becomes clear as to why there should be no dependence of the counting threshold in low voltage halogen counters on the diameter of the wire, as had been observed in one of the earliest papers.[3] In halogen counters usually a comparatively thick wire is used (diameter ~ 1 mm), which leads to a more uniform distribution of the field in the counter. The use of a thin wire leads only to a deterioration in the counting characteristics.

The ability of halogen counters to operate at low temperatures is explained by the fact that the pressure of saturated halogen vapors becomes comparable with the low partial pressure of the halogens in the counters only at a low temperature.

The indefinite working lifetime and the recovery of the counter properties after a continuous discharge are explained by the conservation of the quenching admixture, since the halogen atoms formed in the course of the discharge recombine again into diatomic molecules.

In the investigation of phenomena occurring in halogen counters considerable attention has been devoted to ascertaining the role played by the small admixture of halogens in quenching the discharge. The main role of the quenching admixture consists of eliminating the possibility of the production of secondary electrons after the electric field has been reestablished in the counter. In a non-self-quenching counter these secondary electrons, as is well known, originate in the course of the neutralization of ions at the cathode, and from the metastable atoms remaining in the counter at the expiration of the dead time.

The presence of a halogen in the counter leads as a result of absorption and of chemical action to a considerable increase in the work function of the cathode.[8] As has been noted in references 9, 5, and 10, the ionization potentials of the halogens are lower than that of the argon contained in the counter, and this guarantees the transfer of electrons from the halogen atoms to the argon ions. But neutralization of halogen ions at the cathode occurs without knocking out electrons, since their ionization potential turns out to be less than twice the work function of the cathode subjected to the action of halogens.

As has been already noted, the halogen molecules together with the argon atoms guarantee the destruction of the metastable neon atoms.

In contrast to organic vapors the halogens perform the indicated functions of a quenching admixture even when they are present in the counter in very small quantities (~ 0.1%). The low halogen pressure in the counter results in a low counting threshold, and leads to the fact that the photoeffect at the cathode plays as prominent a role in the development of the discharge as in non self-quenching counters. But the discharge in halogen counters differs from the discharge in ordinary self-quenching counters not only by the existence of a photoeffect at the cathode. The discharge in low voltage halogen counters has a number of specific peculiarities the lack of a single unified explanation of which indicated a deficiency in the existing concepts of the discharge mechanism in these counters.

Thus, the delays of pulses in halogen counters have a completely different character compared to ordinary counters. They can be explained neither by electron drift nor by the drift of negative ions.

An explanation is also needed for the very specific phenomenon of the so-called near-threshold oscillations which had been observed already in the earliest investigations of halogen counters.[3,5,6] This peculiar phenomenon consists of the repetition of discharges which occurs only at voltages close to threshold.

In reference 11 it was shown that a low-voltage halogen counter fed with controlled voltage pulses has characteristics that are completely different from those of ordinary self-quenching counters. It should also be possible to explain this peculiarity of the halogen counter on the basis of a single unified concept of the discharge mechanism in such counters.

FEATURES OF PULSE-FED HALOGEN COUNTERS AND THE DETERMINATION OF THE ROLE PLAYED BY NEGATIVE IONS

In reference 11 results were given of measurements of the efficiency of gas discharge counters in the controlled pulsed supply voltage mode. A high voltage pulse of duration $T_p = 0.8 \times 10^{-6}$ sec was applied to the counter under investigation with a certain delay T_d after an ionizing particle had passed through it. The constant voltage applied to the counter was lower than the threshold voltage, and therefore a discharge occurred in the counter only in the case if at least one electron would remain within the counter volume at the time when the breakdown voltage was applied to the counter.

In the case of ordinary self-quenching counters, there was obtained a completely understandable dependence of the efficiency in the controlled pulsed supply voltage mode on the magnitude of the constant voltage across the counter corresponding to different delays T_d in the supply voltage. Thus, maximum efficiency was observed when the constant field sweeping away the electrons was absent from the counter. As the constant voltage was increased the efficiency diminished, and at a certain value of the voltage (which depended on the value of the delay T_d) the efficiency became equal to zero. At this voltage a complete sweeping away of the electrons occurred during the time T_d. As the constant voltage was increased further the efficiency, naturally, remained equal to zero. The efficiency became different from zero, and then rapidly increased to unity, only for voltages close to the threshold voltage, when the discharge in the counter began prior to the application of the high voltage pulse.

A completely different dependence of the efficiency on the magnitude of the constant voltage was obtained in the case of the low voltage halogen counter of type STS-8.* As can be seen from Fig. 1 (curve 1), for

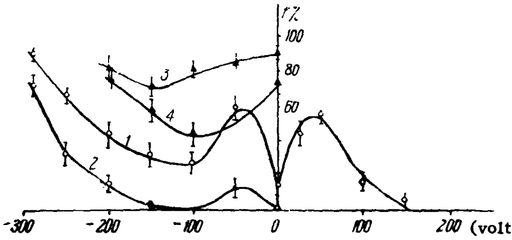

FIG. 1. Dependence of efficiency on the constant voltage applied to the counter:

$1 - T_d = 0.6$ μsec, $2 - T_d = 1.1$ μsec: $t = 20°C$

$3 - T_d = 0.6$ μsec, $4 - T_d = 1.1$ μsec: $t = -196°C$

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*Counters of type STS-8 have a cathode diameter of 1.8 cm, and a wire diameter of 0.06 cm. The total pressure of the mixture is 140 mm Hg (99.2% neon, ~ 0.4% argon and ~ 0.4% bromine). Before filling the counter the cathode is conditioned in a chlorine atmosphere.

$T_d = 6 \times 10^{-7}$ sec the minimum value of the efficiency is observed when there is no electric field in the counter. The presence in the counter of a small electric field of either sign leads to a sharp increase in efficiency. As the constant voltage is increased further, a decrease in efficiency begins to be observed.

Another characteristic feature of halogen counters in the controlled pulsed supply voltage mode is that when the constant negative voltage on the counter cathode is increased the efficiency begins, without attaining a zero value, to increase once again at values of the voltage considerably smaller than the threshold value.

No explanation for these peculiarities of the halogen counters has been found in reference 11. In order to determine the reasons for the observed anomalies, in reference 12, on the basis of the fact that the pulsed supply voltage mode is equally well applicable to self-quenching as to non-self-quenching counters, the efficiency of the same counter was measured after the halogen had been removed from it by cooling it to liquid-nitrogen temperature. The observed dependence of the efficiency on the value of the constant voltage is shown in Fig. 1 (curves 3 and 4).

From a comparison of the characteristics shown in Fig. 1 it follows that a sharp decrease of efficiency at low voltages is due to the presence in the counter of the electronegative gases bromine and chlorine, while the second peculiarity of the characteristics of a halogen counter is exhibited to an even greater degree by a counter filled only with neon with an admixture of argon.

In principle there are two possibilities of explaining the decreased efficiency in the presence of a halogen in the counter. The first of these possibilities noted in reference 11 is that electrons produced by the ionizing particle passing through the counter are rapidly captured by the halogen atoms, and when there is no electric field in the counter the negative ions so formed effectively recombine with the positive ions. Since there exists no theory of this type of recombination,* when neutralization occurs of charges formed from the same atom it is impossible to verify this hypothesis by calculation. From the literature it is known only that such a form of recombination has been observed in gases contaminated by electronegative gases at a pressure[13] of 5 — 10 atm.

The other possibility of explaining the observed decrease in efficiency is to assume that in the absence of an electric field in the halogen counter electronegative ions are effectively formed which do not disintegrate, and do not give a discharge even when a voltage of 1300 v is applied to the counter in the pulsed supply voltage mode.

The choice between these two possibilities was made on the basis of the following measurements. A sensitive meter was used to measure the current passing through a group of halogen counters irradiated by γ rays from Co^{60}. If preferred recombination of ions was occurring in the counters, then at voltages $\lesssim 20$ v a sharp decrease in the current should have been observed. Measurements did not confirm the hypothesis of the occurrence of considerable ion recombination in this range of voltages.

Consequently the sharp decrease in the efficiency of halogen counters in the range of low constant voltages is due to the formation of negative ions which do not break up at the high voltage used for the pulsed supply voltage. The efficiency of the counter was measured for different values of the pulsed high voltage supply. When no constant electric field was present in the counter the efficiency of the counter remained low and did not depend on the amplitude of the supply pulse. Only starting with a voltage equal to 2 kv was an increase in counter efficiency observed associated with the breakup of the electronegative halogen ions.

It should be noted that type STS-8 halogen counters differ considerably from one another by the extent of the drop in efficiency in the range of low constant voltages. In some individual counters there is no decrease at all of the efficiency in this range of voltages (cf. Fig. 2, curve 1). However, a decrease in efficiency appears after such counters have been heated for an hour to a temperature of 120° C (cf. Fig. 2, curve 2). It is clear that these effects are associated with the large differences in the quantity of halogen in the counters. Owing to the strong chemical activity of halogens, the measurement of pressure when the counters are being filled does not characterize the true halogen concentration in the counter. According to the data of reference 14, the true halogen pressure may vary from zero up to twice the value measured at the time of filling.

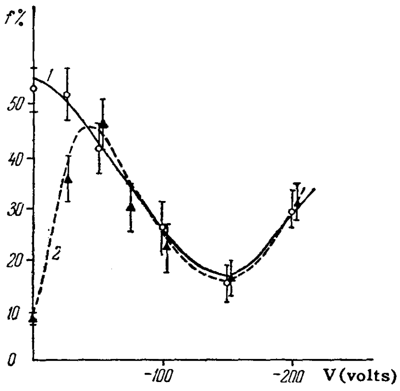

FIG. 2. Effect of heating on the efficiency of a halogen counter.

Thus, we can regard it as established that the electrons produced by the ionizing particle effectively stick to halogen atoms only when there is no electric field

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*The theory of the so-called preferred recombination reduces to the unsolved mathematical problem of the diffusion in a gas of two particles mutually attracted in accordance with Coulomb's law.

present in the counter. This sticking effect is unimportant in low voltage halogen counters at their working voltage. In reference 5 a decrease in counter efficiency was observed down to 70% as the partial pressure of bromine was increased up to 2 mm of Hg. This result shows that at such halogen pressures the formation of electronegative ions becomes appreciable when a fairly high electric field is present in the counter, and simultaneously confirms our conclusion that negative ions do not break up under the action of electric fields existing in the counter.

The breakup of negative ions in collisions with molecules and with atoms was specially studied in reference 15. In accordance with the data of that article the threshold for the removal of the electron from the Br^- ion in neon lies at approximately 100 ev.

NON-SELF-MAINTAINING DISCHARGE AND ITS DEVELOPMENT IN TIME

As has been noted previously, the second peculiarity of the counting characteristic of a halogen counter in the pulsed supply voltage mode is due to the presence in it of neon with an admixture of easily ionized argon. The existence of an efficiency different from zero at constant voltages considerably lower than the threshold voltage indicates that even at these voltages there occur in the counter secondary processes whose duration exceeds the value of the minimum delay in the pulsed supply voltage $T_d = 6 \times 10^{-7}$ sec. These secondary processes, which determine the non-self-maintaining discharge in the neon-argon mixture, cannot be associated with the direct ionization of atoms by electron impact, since such ionization occurs at high fields in which an electron acquires over one mean free path an energy greater than the difference between the ionization potential of the neon atom (21.51 ev) and the lowest excited level (16.57 ev). The only possible secondary processes leading at such low voltages to the initiation of a non-self-maintaining discharge in the counter can be processes associated with the formation of metastable neon atoms.

The probability of spontaneous radiation from a metastable level is exceedingly small, and in pure neon the decay of metastable atoms occurs primarily as a result of rare thermal collisions in which the metastable atom acquires an energy sufficient for a transition to the lowest excited level. The metastable neon atoms can also decay as a result of collisions with the counter cathode. In the case of such a decay of metastable atoms ejection from the cathode of secondary electrons occurs[16] with a probability of 1 — 2%.

In inert gases containing organic vapors, a rapid decay of metastable atoms occurs as a result of collisions with polyatomic molecules. In this case the decay of metastable atoms occurs without ionization of atoms. Ejection of electrons from the cathode also does not occur, since the metastable atoms decay without having time to reach the electrodes.

In neon containing an admixture of easily ionized gases, however, the decay of metastable atoms is accompanied by the ionization of the atoms of the admixture, and this leads to the initiation of a non-self-maintaining discharge at low voltages.

Glotov has shown[17] that small additions of argon to neon not only considerably diminish the starting potential for a self-maintaining discharge, but also lead to the initiation of a non-self-maintaing discharge at exceedingly low voltages. According to his data the coefficient of gas amplification begins to differ from unity starting with a voltage of 17 — 20 v across the electrodes.

It now remains to investigate the time characteristics of the non-self-maintaining discharge which occurs as a result of the formation of metastable atoms and of the subsequent ionization by these atoms of the atoms of the admixture. The mean lifetime of the metastable atoms in a halogen counter is inversely proportional to the number of collisions experienced by an atom per second, and to the concentrations of the argon and of the halogen. On expressing the mean number of collisions per second in terms of the absolute temperature T and of the gas pressure in the counter, we obtain

$$\tau \approx \frac{1}{4\sqrt{\pi}\sqrt{\frac{kT}{m}}\, d^2 N_0 (P_a + P_h)}, \qquad (1)$$

where k is the Boltzmann constant, N_0 is the Loschmidt number, m is the reduced mass of the colliding atoms, d is the effective impact parameter for the collision of a neon atom with the atoms of the admixture, and $P_a + P_h$ is the partial pressure of the argon and the halogen.

For a type STS-8 halogen counter we obtain from relation (1) $\tau \approx 2 \times 10^{-7}$ sec. As a result of their cascade nature, the duration of secondary processes leading to the appearance of electrons in the counter may be considerably greater than the mean lifetime of the metastable atoms.

Indeed, let the ionizing particle create in the counter $n_e(0)$ electrons near the cathode at the initial time t = 0. In traveling to the wire, each electron creates on the average $n_{m,1} = \int_{r_a}^{r_c} \alpha(r)\,dr$ metastable atoms of the first generation, where $\alpha(r)$ is the probability of formation of metastable atoms per unit length, r_c and r_a are respectively the radii of the cathode and of the anode of the counter. On colliding with the argon atoms and the bromine molecules, these metastable atoms gradually decay and form new electrons. In an argon-neon mixture the decay of metastable atoms occurs only at the expense of ionization of argon atoms. In colliding with the halogen molecules the decay of metastable atoms will occur partially without leading to ionization, but accompanied by the breakup of a halogen molecule. Let the quantity δ determine the fraction of metastable atoms which decay by ionizing the atoms of the admixture. Then the number of first generation electrons appearing at the instant t during the time interval dt, will be given by

$$n_{e,1}(t)\,dt = n_e(0)\,\delta n_{m,1} e^{-\frac{t}{\tau}} \frac{dt}{\tau}.$$

In their motion towards the counter wire, the first-generation electrons produce metastable atoms of the second generation. If we neglect the time during which the electrons move prior to the formation of metastable atoms, and take into account only the time during which the metastable neon atoms diffuse prior to colliding with argon or halogen atoms, then electrons from the metastable atoms of the second generation will appear in the counter in accordance with the following distribution

$$n_{e,2}(t) = n_e(0)\frac{(\delta n_{m,1})^2}{2}\frac{t}{\tau^2}e^{-\frac{t}{\tau}}.$$

For electrons of the i-th generation, the following distribution in time will hold:

$$n_{e,i} = n_e(0)\frac{(\delta n_{m,1})^i}{i!\,(i-1)!}\left(\frac{t}{\tau}\right)^{i-1}\frac{e^{-\frac{t}{\tau}}}{\tau}. \qquad (2)$$

This relation takes into account the fact that as the ordinal number of the generation increases the electrons appear ever closer to the wire and each electron produces an ever smaller number of metastable atoms. In deriving this we have neglected the displacement of the metastable atoms due to diffusion. It is clear that under these conditions the avalanche must be limited each time. The total number of electrons of different generations which appear in the counter at the instant t will be given by the sum

$$N_e(t) = \sum_{i=1}^{i=\infty} n_{e,i}(t) = n_e(0)\sum_{i=1}^{i=\infty}\frac{(\delta n_{m,1})^i}{i!\,(i-1)!}\left(\frac{t}{\tau}\right)^{i-1}\frac{e^{-\frac{t}{\tau}}}{\tau}. \qquad (3)$$

On integrating this expression with respect to time from 0 to ∞ we obtain, as in the case of an ordinary avalanche, a series which reduces to an exponential. Thus, the total number of electrons in the avalanche is equal to

$$N_e = n_e(0)\left[1 + \sum_{i=1}^{i=\infty}\frac{(\delta n_{m,1})^i}{i!}\right] = n_e(0)\,e^{\delta n_{m,1}},$$

and, consequently, the coefficient of gas amplification for an individual avalanche is equal to

$$K_a = \frac{N_e}{n_e(0)} = e^{\delta n_{m,1}} = e^{\delta\int_{r_a}^{r_c}\alpha(r)dr}, \qquad (4)$$

where the coefficient $\alpha(r)$, analogous to the first Townsend coefficient, refers, however, not to ionization, but to the excitation by the electrons of the metastable neon level.

Thus, a characteristic feature of the non-self-maintaining discharge in neon containing an easily ionizable admixture is its slow development in time, since each ionizing event is preceded by the time of diffusion of a metastable atom prior to its encounter with an atom of the admixture. The experimental investigations of a discharge in Penning mixtures generally did not deal with the time properties of the discharge. But in studying the properties of low-voltage halogen counters we are dealing with just this uninvestigated property of the discharge. We shall see later that the difficulties in the explanation of a number of strange properties of halogen counters were associated with the fact that no account was taken of the slow development of the discharge brought about by collisions of the second kind.

The average number of electrons appearing during the time interval dt is proportional to the number of metastable atoms present at a given instant:

$$N_e(t)dt = \delta N_m(t)\frac{dt}{\tau}.$$

Figure 3 gives curves showing the change with time of the average number of electrons corresponding to several values of the product $\delta n_{m,1} = \ln K_a$ and $n_e(0) = 1$.

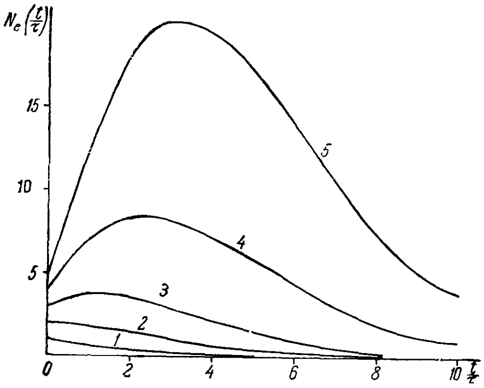

FIG. 3. Distribution in time of the average number of electrons. The numbers labelling the curves in the diagram show the values of the quantity $\ln K_a$ for the corresponding curves.

As may be seen from Fig. 3 the duration of the avalanche increases as the quantity $\delta n_{m,1}$ is increased. The average time for the development of an individual avalanche is equal to $\bar{t} = \delta n_{m,1}\tau$. The number of metastable atoms in the counter for $\delta n_{m,1} > 2$ increases with time, attains a maximum value and then falls off to zero relatively rapidly.

The efficiency of the counter in the pulsed supply voltage mode in the domain of constant voltages smaller than the Geiger threshold is determined by the probability of the appearance of at least one electron during the time interval from T_d to $T_d + T_p$

$$f = 1 - \exp\left[-\int_{T_d}^{T_d+T_p} N_e(t)\,dt\right]. \qquad (5)$$

As the constant voltage is increased the coefficient of gas amplification K_a also increases. Since in this case the duration of an avalanche increases proportionally to ln K_a the efficiency of the counter increases correspondingly. When the halogen is frozen out in a type STS-8 counter the mean lifetime of the metastable atoms τ increases by a factor of two and, moreover, the coefficient δ increases to unity. Therefore, the efficiency of the counter increases sharply as the halogen is frozen out.

THE DEVELOPMENT OF THE SELF-MAINTAINING DISCHARGE AND THE DELAY OF PULSES IN A HALOGEN COUNTER

The first measurements of the delay of pulses in halogen counters were carried out in reference 18. The distribution of the delay times obtained in these measurements turned out to be very strange. The maximum of the distribution occurred at 5.3 μsec, and no delays smaller than 3.5 μsec were observed. The maximum delay time amounted to 9.3 μsec. The existence of a minimum delay time of appreciable magnitude represents the main peculiarity of pulsed delays in low voltage halogen counters.

The observed pulse delay times are greater by factors of several times ten than the possible electron drift times in the counter, and are considerably smaller than the negative ion drift time. Moreover, in the case of delays due to negative ion drift time it is impossible to explain the statistical distribution of delays characterized by a maximum at 5 μsec. In references 19 and 20 Éig attempted to explain the pulse delays in halogen counters by the combined effects of electron and negative ion drift. He develops the concept that the electrons produced by the ionizing particle are captured by the halogen atoms as they move towards the counter wire, while the negative ions break up in the stronger electric field into electrons and neutral atoms after having covered only a part of their path towards the wire. In accordance with this scheme, a calculation is given in his paper of the mean delay time of the discharge and measurements are made of the delay times of the pulses corresponding to different voltages applied to the counter.

The assumption of the disintegration of negative ions by electric fields existing in low-voltage halogen counters contradicts the data given above. But, moreover, the concept of the delay of the discharge developed in references 19 and 20 contradicts the experimental data obtained in the same references. Calculations of the mean delay time in accordance with the adopted scheme resulted in a smooth dependence on the absolute value of the counter voltage which, as should have been expected, did not in any way involve the value of the threshold voltage. However, measurements have shown that the mean delay time of the pulses increases sharply as the voltage approaches the threshold voltage, i.e., it depends not on the absolute value of the voltage, but on the overvoltage applied to the counter.

It should be noted that in reference 19 extensive and valuable material has been accumulated on the development of the technique of preparation and on the investigation of properties of low-voltage halogen counters. In presenting the material on the discharge mechanism in such counters, the author has restricted himself primarily to the discussion of the role played by the halogen admixture in quenching the discharge, without emphasizing the fact that it is just those properties, which distinguish halogen counters from ordinary ones, that have remained unexplained. Thus, no explanation was given for the occurrence of oscillations of the discharge near the threshold voltage, and an incorrect explanation was given for the unusual delay of the pulses which contradicts the experimental data obtained in the same paper.

Van Zoonen's paper[21] is also devoted to a discussion of the causes of the occurrence of pulse delays in halogen counters. In rejecting one by one the various possible assumptions regarding the cause for pulse delays, the author arrives at the conclusion that the delay is associated with the participation in the discharge of metastable states. However, this correct conclusion has remained unnoticed by other investigators of halogen counters, and attempts were made, as before, to explain the pulse delays in terms of negative ions.

We have seen in the preceding section that the cascade process of the increase in the number of metastable atoms in the counter leads to the fact that each individual avalanche of a non-self-maintaining discharge has been spread out over a time of the order of 1 μsec. It is clear that in the regime of the self-maintaining discharge when a repetition of avalanches occurs the time for the development of the discharge may be considerably increased. A self-maintaining discharge occurs in the counter due to the photoeffect at the cathode. The photoelectrons ejected from the cathode give rise to new avalanches occurring later in time. Under certain conditions this repetition of avalanches leads to an unrestricted growth of the discharge. In this case the discharge ceases only after a sufficiently large number of ions has accumulated within the counter volume, and the electric field has been significantly decreased by their space charge.

A characteristic feature of low-voltage halogen counters is that due to the insignificant absorption of photons the role played by the photoeffect in the development of the self-maintaining discharge turns out to be just as great as in non-self-quenching counters. This peculiarity manifests itself, in particular, in the fact that the conditions for the initiation of a self-maintaining discharge in low-voltage halogen counters begin to be satisfied at a comparatively low value of the coefficient of gas amplification in an individual avalanche. It has been noted in many papers that in low-voltage halogen counters there is no domain of proportional or of limited proportional amplification, and the pulses are observed to have the same magnitude from the outset. The domain of proportional amplification appears only when the quantity of halogen is increased, when the counters cease to be low-voltage counters. In actual fact the halogen counter possesses a wide range of proportional amplification, but the coefficient of amplication in this whole domain remains exceedingly low. Figure 4 shows the dependence of the coefficient of gas amplification on the voltage in the case of a type STS-8 counter. This dependence was obtained on the basis of measuring the current through the counter irradiated by γ quanta from Co^{60}.

FIG. 4. Dependence of the coefficient of gas amplification on the voltage applied to the counter.

As may be seen from the figure, even at voltages close to the Geiger threshold the gas amplification remains of the order of 100. It is clear that such insignificant amplification cannot be observed directly using an ordinary oscillograph. The initial stage of the development of a self-maintaining discharge has also remained unobserved. Therefore, the time of development of the discharge in this concealed stage has been interpreted as a delay of the discharge in the counter. Since in actual fact the discharge develops slowly, it would be more correct to speak of the delay of the pulse, rather than of the delay of the discharge in the counter.

It can be seen from Fig. 4, that in the range of voltages up to 280 v a linear dependence of ln K on the voltage V is observed. A more rapid increase in the coefficient of gas amplification at high voltages applied to the counter can be, naturally, explained by the appearance of repeated avalanches due to the photoeffect at the cathode. The total coefficient of gas amplification K, can be expressed, as is well known, in terms of the amplification coefficient K_a for an individual avalanche by the relation

$$K = \frac{K_a}{1 - \gamma K_a}, \qquad (6)$$

where γ is the probability of the production of a photoelectron at the cathode expressed per electron of the avalanche.

As the voltage across the counter is increased not only does the coefficient of gas amplification in the individual avalanche show an increase, but the probability of production of a photoelectron γ also increases. This is associated with the fact that as the voltage increases the electrons in moving towards the counter wire acquire a relatively greater probability of exciting the lowest level of the neon atom, and this leads to an increase in the number of photons per electron of the avalanche.

The smooth curve of Fig. 4 corresponds to relation (6) in which we have taken

$$\left.\begin{array}{l} \ln K_a = 2.70\cdot10^{-2}\ V = -4.05 \\ \text{and} \\ \gamma = 2.5\cdot10^{-3} \ln K_a. \end{array}\right\} \qquad (7)$$

The self-maintaining discharge in the counter occurs for $\gamma K_a \geq 1$, where the equality sign corresponds to the Geiger threshold. Using the adopted values for K_a and γ we obtain the Geiger threshold $V_g = 317$ v. The directly obtained counting threshold for this counter is equal to 320 v.

Let us now consider the time development of a discharge in a counter taking into account the repetition of avalanches due to the photoeffect. For the solution of this problem it is useful instead of the complicated expression (3) to utilize a simplified description of an individual avalanche, expressing it by means of an exponential function. In doing this the average time for the development of an avalanche must be preserved equal to $\bar{t} = \delta n_{m,1} \tau$, the initial number of metastable atoms must be equated to a certain effective value $N_m(0) = [n_e(0)/\delta^2 n_{m,1}] \exp(\delta n_{m,1})$, chosen to satisfy the condition that the total number of electrons in the avalanche should remain equal to $n_e(0) \exp(\delta n_{m,1})$. By foregoing the exact description of the development of an individual avalanche, we significantly simplify the solution of the problem of the self-maintaining discharge, for the time development of which the characteristic phenomenon is the superposition of repeatedly originating avalanches.

We now set up the differential equation which describes the variation with time of the number of metastable atoms in the counter. We suppose that at a certain instant t there are $N_m(t)$ metastable atoms within the volume of the counter. This number of metastable atoms must vary with time for a number of reasons. First of all, the number of metastable atoms will diminish due to their decay by an amount $\Delta N_{m(\text{decay})} = N_m(t)\, dt/\tau$. But the decay of metastable atoms leads to the appearance within the counter of $\delta \Delta N_{m(\text{decay})}$ electrons, the motion of each towards the wire will directly give rise on the average to q new metastable atoms. In making this calculation we neglect the time taken by the electrons in their motion towards the wire. Moreover, the electrons moving towards the wire of the counter given rise to photons, and this leads to the appearance at the cathode on the average of $\gamma \delta \Delta N_{m(\text{decay})}$ photoelectrons. But the ejection of a photoelectron from the counter cathode is equivalent to the appearance of $(1/\delta^2 n_{m,1})\exp(\delta n_{m,1})$ new metastable atoms corresponding to the initial number of metastable atoms in the new avalanche brought about by one electron $n_e(0) = 1$.

Thus, the total change in the number of metastable atoms will be given by

$$dN_m(t) = -N_m(t)\frac{dt}{\tau} + q\delta N_m(t)\frac{dt}{\tau} + \frac{1}{\delta n_{m,1}} e^{\delta n_{m,1}} \gamma N_m(t)\frac{dt}{\tau}. \tag{8}$$

The value $q = (1 - 1/\delta n_{m,1})/\delta$ corresponds to the exponential function chosen to describe an individual avalanche. In this case the solution of equation (8) has the following form:

$$N_m(t) = \frac{n_e(0)K_a}{\delta \ln K_a}\exp\left[-\frac{t}{\tau \ln K_a}(1-\gamma K_a)\right]. \tag{9}$$

By multiplying the obtained number of metastable atoms by δ/τ we obtain the average number of electrons $N_e(t)$ appearing at the instant t in the counter in the presence of repeated avalanches due to the photoeffect at the cathode.

For $\gamma K_a < 1$ we have a non-self-maintaining discharge in the counter which decays with an average decay time $\bar{t} = \tau \ln K_a/(1-\gamma K_a)$. As expected, an account of the repetition of the avalanches has led to an increase in the duration of the non-self-maintaining discharge, which, in particular, manifests itself in the sharp increase in the counter efficiency in the pulsed supply mode as the threshold voltage is approached (cf. Fig. 1, curves 1 and 2).

The value $\gamma K_a = 1$ corresponds to the beginning of the region of the self-maintaining discharge (Geiger threshold). For $\gamma K_a > 1$ the number of electrons and of metastable atoms in the counter increases exponentially; an increase by a factor of e occurs during the time $T = \tau \ln K_a/(\gamma K_a - 1)$.

Consequently, for voltages close to the Geiger threshold when the product γK_a exceeds unity by only a small amount, the self-maintaining discharge in the counter is characterized by very slow development in time. The discharge in the counter is recorded after the number of electrons has built up to some definite value R. The average time of delay of recording the discharge will in this case be equal to

$$t_d = \frac{\tau \ln K_a}{\gamma K_a - 1}\left[\ln R - \ln\frac{n_e(0)K_a}{\ln K_a}\right]. \tag{10}$$

From this relation we see that the time of delay of recording the pulse increases sharply as the overvoltage applied to the counter is diminished.

The delay time is proportional to the mean time of decay of metastable atoms τ and, consequently, increases as the halogen concentration is decreased. The average time of pulse delay, moreover, depends on the initial ionization.

The calculation which we have carried out has shown that at a voltage equal to the threshold voltage ($\gamma K_a = 1$) the discharge should last indefinitely without damping and without growing. However, we should keep in mind that owing to fluctuations which have not been taken into account in the calculation this repetition of avalanches must cease. The fluctuations must manifest themselves also at voltages higher than the threshold voltage. For $\gamma K_a > 1$ the number of repeated avalanches must gradually increase and the discharge, which until then is concealed due to the low value of the multiplication coefficient, now becomes capable of being recorded. Owing to fluctuations, the repetition of the avalanches in the initial stage of the discharge may cease in a number of cases, and the discharge will then remain unrecorded. Calculations show that the probability of the termination of the discharge due to fluctuations in the process of repetition of avalanches is expressed by the relation

$$\Phi = p^{n_e(0)}, \tag{11}$$

where p is the solution of the transcendental equation

$$p = e^{-\gamma K_a(1-p)}.$$

From this relation it follows that the efficiency of recording the discharge in the counter $F = 1 - \Phi$ must diminish as the overvoltage on the counter is decreased. This decrease in efficiency, which had not been noted earlier by investigators of low-voltage halogen counters, is still another peculiarity of such counters. On an oscillograph screen the pulses from low-voltage halogen counters are always observed to be of the same size, but it turns out that the probability of their appearance must diminish sharply as the threshold voltage is approached.

Our measurements confirm the considerable decrease in efficiency at low overvoltages. In Fig. 5 curves 1 and 2 show the dependence of the mean delay time and of the efficiency F on the overvoltage across the counter calculated on the basis of relations (7), (10), and (11). In this case for the delay time t_d we have taken the time for the growth of the pulse up to a value equal to 5% of its amplitude, $n_e(0)$ was taken equal to 5 and $\tau = 2 \times 10^{-7}$ sec.

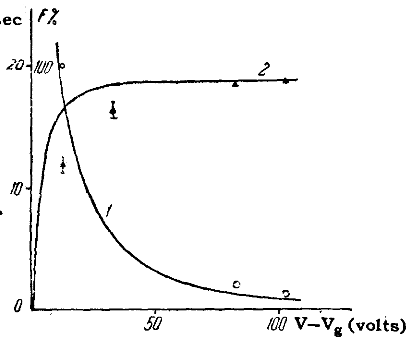

FIG. 5. Dependence of the mean delay time and of the efficiency on the overvoltage applied to the counter.

Figure 5 also shows the results of measurements for a type STS-8 counter of the mean delay time of the pulses and of the efficiency for four different values of the overvoltage. Figure 6 shows the statistical distributions of the delay times of the pulses obtained in the course of these measurements. The scatter in the delay times of the pulses observed for the same value of the voltage may be due to differences in the initial ionization, and also to the fluctuations in the development of the discharge in time which were not taken into account.

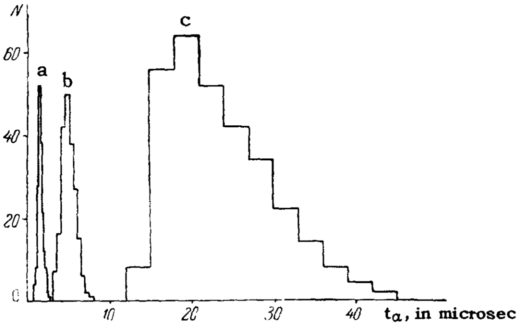

FIG. 6. Distribution of pulse delay times: a) $V - V_g = 103$ v, b) $V - V_g = 33$ v, c) $V - V_g = 13$ v.

The existence of a dependence of the delay time on the initial ionization $n_e(0)$ [cf. (10)] opens up a completely unexpected possibility of utilizing halogen counters for measuring the ionizing power of particles. In this connection it becomes necessary to investigate the possible accuracy of such measurements, and to compare it with the accuracy of measurements made with the aid of ordinary proportional counters.

NEAR-THRESHOLD OSCILLATIONS OF THE DISCHARGE

In the earliest investigations of halogen counters[3-6] the strange phenomenon of the repeated occurrence of the discharge was observed; it occurred only at voltages close to the threshold voltage. Usually several repeated discharges following one another are observed. The frequency of these oscillations depends on the concentration of the halogen and amounts to approximately 10 kc/sec. As the voltage across the counter is increased, the amplitudes of the repeated pulses increase and their number decreases; beginning at a certain voltage, the repeated discharges in the counter disappear completely. It has been established that the near-threshold oscillations are observed only for low halogen concentrations ($\lesssim 0.1\%$), with the range of voltages in which such oscillations occur becoming greater as the halogen admixture is diminished. In particular, this circumstance hinders the construction of counters with a counting threshold lower than 250 v in which the admixture of halogen must be less than 0.1%.

The phenomenon of near-threshold oscillations must also be taken into account in selecting counter construction. Thus, it has been found[22] that as the length of the counter is increased the range of voltages within which near-threshold oscillations occur is also increased.

In spite of the fact that the near-threshold oscillations have been investigated in a number of papers,[3-6, 19,23] this phenomenon, which is characteristic of low-voltage halogen counters, has remained unexplained until very recently. In actual fact no attempts of explaining this phenomenon were made even in papers devoted to the investigation of the mechanism of discharge in such counters. Only in Le Croissette's paper[23] was an attempt made to find an explanation for these near-threshold oscillations. In this paper the occurrence of repeated discharges is associated with the ejection of electrons from the cathode by argon ions and with the formation of metastable atoms which have a certain probability of not decaying during the dead time and of producing an electron within the volume of the counter after the electric field has been reestablished in it. However, it can be easily seen that, taken by itself, the fact of the formation of metastable atoms, without account of the description in time of the repeated occurrence of individual avalanches of metastable atoms and electrons, cannot explain the cessation of the oscillations as the voltage across the counter is increased. Indeed, as the voltage is increased the number of metastable atoms formed in the counter is also increased and, consequently, the probability of producing an electron after the end of the dead time is also increased. Taking into account the ejection of electrons from the cathode also leads to the same dependence of the probability of the occurrence of a repeated discharge. But the specific characteristic feature of near-threshold oscillations consists of their cessation as the voltage across the counter is increased. The effects considered in reference 23 are indeed the cause of the occurrence of repeated discharges, but not near the threshold, but for large values of the overvoltage at the end of the counter plateau.

As we have seen, the self-maintaining discharge in the halogen counter at voltages close to threshold voltages is characterized by an extremely slow development. Therefore, the attempt[12] was quite natural to associate the near-threshold phenomena with this special feature of a discharge developing as a result of collisions of the second kind. As the number of ions in the counter increases, the discharge which inincreases slowly and exponentially must then go over into a slowly damped discharge, owing to the decrease in the electric field. From the fact that at a low value of the overvoltage the delay time of the pulses in a halogen counter attains a value of several tens of microseconds, it follows that the time for the development and the decay of the discharge in the counter can exceed the time of reestablishment of the electric field in the counter associated with the motion of the ions towards the cathode. Obviously, in this case the damping of the discharge must be replaced by a repeated development of the discharge.

As the overvoltage applied to the counter is increased, a more rapid growth of the discharge occurs, which is then also replaced by damping. The explanation of the near-threshold oscillations presented here can be accepted only if it is shown that the rapid growth of the discharge is necessarily accompanied by a rapid damping of the discharge.

In order to investigate this question it will be necessary to consider the development of the discharge taking into account the screening action of the space charge of the ions produced.

In the general case the discharge in the counter is described by the equation

$$dN_m(t) = \varepsilon N_m(t) \frac{dt}{\tau \ln K_a}, \qquad (12)$$

where

$$\varepsilon = \gamma K_a - 1.$$

In the preceding section we solved this equation by treating the parameter ϵ as a constant quantity determined by the overvoltage on the counter. For $\epsilon < 0$ a gradually damped discharge takes place in the counter, corresponding to voltages smaller than the threshold voltage. For $\epsilon > 0$ the solution of the equation leads to an unlimited exponential growth of the discharge. It is clear that this solution describes the discharge only during the initial period of time, when we can neglect the decrease in the electric field due to the space charge produced in the counter. For a complete description of the discharge in the Geiger domain it is, evidently, necessary to take into account the decrease in the value of ϵ as the number of ions in the counter increases. For initial values of $\epsilon_0 \ll 1$ corresponding to the domain of voltages close to the threshold voltage this diminution of ϵ can be described in the first approximation by a linear function of the number of ions formed in the counter

$$N_i(t) = \delta \int_0^t N_m(t') \frac{dt'}{\tau}, \text{ i.e., } \varepsilon(t) = \varepsilon_0 - \beta N_i(t);$$

here β is a coefficient of proportionality, whose value can be determined by measuring the total quantity of charge deposited on the counter wire. By taking the total number of ions formed by the time t we neglect the fact that each ion moving towards the cathode participates in the quenching of the discharge only during a certain effective time associated with the value of the counter dead time.

Let us examine the process of the damping of the discharge with quenching taken into account to this degree of approximation. The integral equation

$$\frac{dN_m(t)}{dt} = \left[\varepsilon_0 - \beta\delta \int_0^t N_m(t')\,dt'\right] \frac{N_m(t)}{\tau \ln K_a} \qquad (13)$$

reduces after the change of variables $y = \int_0^t N_m(t')\,dt'$ to the following differential equation:

$$y'' = \left(\varepsilon_0 - \frac{\beta\delta}{\tau} y\right) \frac{y'}{\tau \ln K_a}. \qquad (14)$$

On solving this equation we find, after neglecting the initial number of metastable atoms, that

$$\varepsilon_{t=\infty} \approx -\varepsilon_0. \qquad (15)$$

Thus, the quenching of the discharge by the space charge leads to a decrease of the parameter ϵ, but not down to zero value at which any further growth of the discharge ceases, but to a negative value equal in absolute value to the initial value of ϵ_0. This occurs because of a peculiar inertia in the quenching of the discharge. At the moment when the number of ions accumulated in the counter is sufficient to stop any further growth of the discharge and the parameter ϵ has become equal to zero, the counter contains a large number of metastable atoms which on decaying lead to a further increase in the number of ions in the counter. Consequently, the electric field in the counter continues to decrease, and the parameter ϵ in assuming a negative value now characterizes the rate of decay of the discharge in the counter.

After leaving out the negligibly small contribution to quenching made by the initial number of metastable atoms $N_m(0)$ the solution of (14) assumes the fairly simple form:

$$N_m(t) \approx N_m(0)(D+1)^2 \frac{e^{\frac{t}{T}}}{(e^{t/T}+D)^2}, \qquad (16)$$

where $N_m(0) = (K_a/\delta \ln K_a)\, n_e(0)$, $D = 2\epsilon_0^2/\beta K_a n_e(0)$ and $T = \tau \ln K_a/\epsilon_0$. The current pulse passing through the counter is given by the relation

$$I(t) = \frac{e\delta}{\tau} N_m(t), \qquad (17)$$

where e is the electron charge.

The total number of electrons formed in the counter by the time t is given by

$$N_e(t) = \frac{\delta}{\tau} y(t) \approx \frac{K_a n_e(0)(D+1)(e^{\frac{t}{T}} - 1)}{\varepsilon_0 (e^{t/T} + D)}. \qquad (18)$$

On setting in expression (18) $t = \infty$, we obtain the total charge deposited on the counter wire

$$Q \approx e\frac{2\varepsilon_0}{\beta} + e\frac{K_a n_e(0)}{\varepsilon_0} \approx e\frac{2\varepsilon_0}{\beta}. \qquad (19)$$

From this relation on the basis of measurements of the magnitude of the voltage pulse on the counter wire for a given value of the overvoltage it is possible to determine the value of the ratio $\epsilon_0/\beta = (\gamma K_a - 1)/\beta$. By assuming for γK_a the dependence on the voltage obtained from measurements of the current within the domain of the non-self-maintaining discharge, it becomes possible to make an estimate of the value of the coefficient β. Thus, for a type STS-8 counter the coefficient β determined in this manner has turned out to be equal to 5×10^{-9}. It is quite obvious that the coefficient β must be inversely proportional to the length of the counter.

The number of metastable atoms in the counter increases with time, attains a maximum value at $\exp(t_m/T) = D$, and falls to the initial value $N_m(0)$ within the time $t_p = 2t_m$. Consequently, the time

$$t_p = \frac{2\tau \ln K_{\mathbf{a}}}{\varepsilon_0} \ln \frac{2\varepsilon_0^2}{\beta K_{\mathbf{a}} n_e(0)} \tag{20}$$

can be regarded as the duration of the discharge occurring in the counter. As can be seen from this relation, the duration of the discharge increases sharply as the parameter ϵ_0 approaches zero, i.e., near the Geiger threshold. In Fig. 7 curves 1 and 2 show on a logarithmic scale the time dependence of the number of metastable atoms in the counter for two initial values of the parameter ϵ_0 (0.1 and 0.3). It can be seen from the diagram that the rapid growth of the discharge (curve 2) is replaced by a similarly rapid damping.

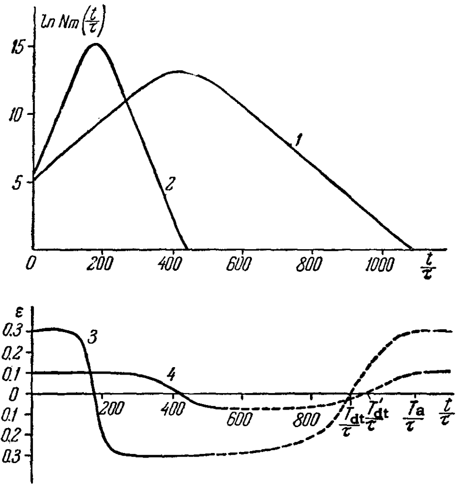

FIG. 7. Dependence of the mean number of metastable atoms and of the parameter ε on the time.

As has been noted earlier, a proof of this peculiarity of the quenching of the discharge gives us an explanation of the disappearance of repeated discharges as the overvoltage applied to the counter is increased.

The relations given above describe the self-maintaining discharge in the counter taking into account the screening effect of the space charge in those cases when the duration of the discharge is considerably smaller than the dead time of the counter T_{dt}. But the near-threshold oscillations occur in the counter for $t_p \gtrsim T_{dt}$ and in order to describe them it is necessary to take into account the ion motion. This leads to a considerable complication of the whole problem. The relations which we have obtained can be utilized only to estimate the probability of occurrence of a repeated discharge when $t_p \approx T_{dt}$.

If the duration of the discharge is considerably shorter than the dead time of the counter, then by the time t_p the discharge in the counter practically ceases, and the parameter ϵ characterizing the intensity of avalanche multiplication attains a value $\epsilon(t_p) \approx -\epsilon_0$. Then, the motion of the ions towards the cathode causes reestablishment of the electric field in the counter, and this leads to a gradual increase in the parameter ϵ. Starting at a certain instant, the parameter ϵ goes over into the domain of positive values and a self-maintaining discharge becomes possible in the counter. This time is the dead time of the counter, T_{dt}. If there is no initial ionization in the counter, then further reestablishment of the electric field will lead to an increase in the parameter ϵ up to the initial value ϵ_0. This instant of the complete recovery of the counter corresponds to the time which is usually referred to as the recovery time for the counter. The time dependence of the parameter $\epsilon(t)$ for the case when $t_p \ll T_{dt}$ is shown by curve 3 in Fig. 7.

The value of the dead time T'_{dt} shown in this figure is close to the value of the duration of the discharge occurring for $\epsilon_0 = 0.1$. In this case the picture of counter recovery is qualitatively given by curve 4 (Fig. 7). The parameter ϵ begins to increase without attaining the value $-\epsilon_0$, and becomes equal to zero at a certain instant T'_{dt}. However, the discharge has not completely ceased by this time and, consequently, there is a certain probability of electrons appearing in the counter even after the time T'_{dt}. In this case a further increase in the parameter ϵ can be accompanied by a repeated growth of the discharge in the counter. From the relation (18) we can find the average number of electrons from the initial discharge which appear in the counter after the time T'_{dt}

$$N_e(\infty) - N_e(T'_{dt}) \approx \frac{K_{\mathbf{a}} n_e(0)(D+1)^2}{\varepsilon_0 \left(e^{T'_{dt}/T} + D\right)}. \tag{21}$$

This number of electrons is smaller than the actual average number of electrons, since in determining it we have not taken into account the increase in the parameter ϵ. Consequently, the probability of the appearance in the counter of at least one electron after the time T'_{dt} must be greater than the quantity

$$W = 1 - \exp\left[N_e(T'_{dt}) - N_e(\infty)\right]. \tag{22}$$

The probability of occurrence of a repeated discharge may be taken proportional to the quantity W. In determining this probability we must also take into account the probability of the cessation of the discharge due to the fluctuations in the development of the avalanches. Relations (21) and (22) can be utilized only for a qualitative investigation of the effect of the different factors on the near-threshold oscillations.

As the quantity W approaches unity we should observe a decrease in the number of single pulses and an increase in the number of repeated discharges following one another.

Figure 8 shows oscillograms of pulses in a type STS-8 counter for the same value of the voltage close to the threshold voltage. As may be seen from the diagram, both single pulses and pulses with a different number of repeated cycles are observed. Usually the subsequent pulses have a magnitude somewhat lower than that of the first one. This is due to the fact that the repeated discharge develops in an electric field which has been somewhat weakened by the ions from the preceding discharge.

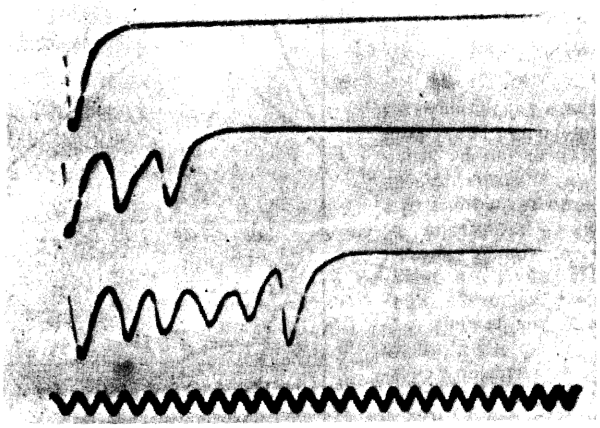

FIG. 8. Oscillograms of pulses at a voltage close to the threshold voltage. The frequency of the calibration sinusoidal curve is 10kc/sec.

It follows from relations (21) and (22) that the range of voltages for which near-threshold oscillations occur increases as the lifetime τ of metastable atoms is increased and as the coefficient β is decreased. Consequently, the near-threshold phenomena must be intensified as the concentration of the easily ionized admixture is diminished and as the counter length is increased, and this is in agreement with experimental data. It also follows from relations (21) and (22) that the probability of occurrence of a repeated discharge decreases as the initial ionization is increased.

CONCLUSION

Thus, a whole series of specific properties of low-voltage halogen counters receives a unified explanation on the basis of taking into account the peculiarities of the time development of the discharge governed by ionization produced as a result of collisions of the second kind. The characteristic feature of such a discharge consists of each ionization event being preceded by a certain time of diffusion of a metastable neon atom prior to its encounter with an atom of the ionizable admixture. Therefore, such specific properties of halogen counters as the appearance of near-threshold oscillations and the sharp increase in the average delay time of pulses as the voltage approaches the threshold voltage, manifest themselves clearly only at a low concentration of the halogen and of argon ($\lesssim 0.1\%$), when the average time of decay of the metastable neon atoms is large. The changes in the properties of the counters occurring as the halogen concentration is increased also become comprehensible in the light of the foregoing concepts of the discharge mechanism in halogen counters.

An increase in the amount of the halogen admixture leads to an increase in the value of the threshold voltage. This effect was studied in detail in reference 14. The observed increase in the threshold voltage is due first of all to an increase in the absorption of photons by the halogen molecules which leads to a diminution of the probability of the ejection of photoelectrons from the cathode. Moreover, due to the increase in the number of inelastic collisions the average energy of the electrons decreases, and this leads to a diminution in the number of metastable neon atoms produced at a given voltage. Another reason for the increase in the threshold voltage is the decrease in the coefficient δ which characterizes the fraction of metastable atoms whose breakup is accompanied by ionization of the atoms of the admixture.

The increased photon absorption leads in turn to an increase in the values of the coefficients of gas amplification attained within the regime of the non-self-sustaining discharge. The latter manifests itself in the appearance of the domain of proportional amplification which can now be detected by means of visual observation of pulses on an oscillograph screen.[5]

In reference 5 it was found, moreover, that the dead time of the counter increases as the quantity of bromine is increased. This effect should be related to a decrease in the mobility of the ions.

In references 5 and 14 it was observed that as the halogen pressure is increased the counter efficiency diminishes. As has been noted earlier, this decrease in efficiency is associated with the formation of negative ions.

An increase in the amount of halogen admixture must, naturally, lead to a decrease in the average time of delay of pulses measured at the same value of the overvoltage, corresponding to a decrease in the average time of decay of the metastable atoms.

The near-threshold oscillations are particularly sensitive to the amount of halogen. As the admixture of halogen is increased the domain of near-threshold oscillations is narrowed and then disappears entirely. The sharp dependence of the near-threshold oscillations on the amount of halogen is explained by the simultaneous operation of two causes: a decrease in the duration of the discharge and an increase in the dead time.

Thus, as the amount of halogen is increased the specific properties of low-voltage halogen counters, pertaining to a discharge occurring as a result of the formation of metastable atoms of the principal gas and of the subsequent ionization of the atoms of the admixture by collisions of the second kind, become less and less pronounced. At the same time, as the threshold voltage of the counter increases, ionization of the gas resulting directly from electron impact begins to occur, and its role begins to be more and more prominent as the voltage is increased. For this reason the mathematical description of the discharge in low-voltage counters given above becomes inapplicable at a halogen pressure equal to several millimeters of Hg. At a sufficiently high halogen pressure the counter becomes a high-voltage counter, the discharge in which no longer differs from the discharge in ordinary self-quenching counters.

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