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Primary ionization of noble gases by relativistic electrons

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The specific primary ionization produced by ~2-MeV relativistic electrons in the noble gases helium, neon, argon, krypton and xenon, and also in henogal, is measured with a low pressure wire spark chamber. It is shown that the results of the measurements of the specific primary ionization, carried out under the most favorable conditions, with a streamer chamber and with a low-pressure wire spark chamber, are in agreement with the theoretical predictions, in which the contribution of rapid secondary processes in the gas is taken into account.

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1. INTRODUCTION

While the specific primary ionization of gases under the action of nonrelativistic gases has been studied in sufficient detail, the primary ionization brought about by charged particles of high energy has been measured only for a small number of gases and in the restricted range of values of the Lorentz factor $\gamma = E/mc^2$.[1-12,11] The existing theoretical calculations of the primary ionization by relativistic particles[13-16] also call for verification.

In addition, the data on the primary ionization is of interest for plasma physics, upper atmosphere physics, astrophysics and high energy physics. In the present work, we give the results of measurements of the specific primary ionization of noble gases by relativistic electrons in the region of minimum ionization at $\gamma \approx 4$. The measurements were carried out by means of a spark chamber—a pulsed gas-discharge detector, widely used in high energy physics for the determination of the coordinates of charged particles. As has been pointed out previously,[17-19] the effectiveness of the spark chamber, i.e., the probability of the generation in it of a spark discharge by the passage of a charged particle, should depend on the specific primary ionization. It can therefore be used for the measurement of the latter, similar to what was done in the low-efficiency Geiger–Müller counters. In spite of the obviousness of this idea, attempts at its realization have been undertaken only recently.[11,12]

The spark chamber method has a potential advantage over the other methods of measurement of the primary ionization. Thus, for example, in contrast with the low-efficiency Geiger–Müller counters,[1,2] and also the Wilson chamber[3,4] or the diffusion chamber,[5] where the presence of impurities in the working gas is a condition for the normal operation of the apparatus, the spark chamber can be used with the pure gas. The spark chamber method is much simpler than that with the streamer chamber,[6-10] where electron-optical amplification of the light of the streamers is necessary, and, as will be shown below, it allows us to make the

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measurements also in gases with a high coefficient of electron diffusion.

2. EFFICIENCY OF THE SPARK CHAMBER AND PRIMARY IONIZATION

Thanks to the random character of the collisions of charged particles with the gas atoms, the probability F_j of formation of j primary pairs of ions in a spark gap of a chamber of length l obeys a Poisson distribution with mean value

$$n=l(dn/dx)_{P,T}=(273/T)Pl(dn/dx), \quad (1)$$

where $(dn/dx)_{P,T}$ and dn/dx stand respectively for the specific primary ionization of a gas of charged particles at a pressure P(atm) and temperature T(K) and under normal conditions ($P=1$, $T=273$). If, only a single free electron is sufficient for the evolution of the spark breakdown, then the efficiency η of the spark chamber is connected with the primary ionization by the simple relation:

$$\eta=1-F_0=1-e^{-n}=1-\exp\left[-l(dn/dx)_{P,T}\right] \quad (2)$$

or

$$dn/dx=-\frac{\ln(1-\eta)}{(273/T)Pl}\ [\text{cm}^{-1}]\ . \quad (3)$$

The standard error in the determination of the efficiency

$$\langle\Delta\eta\rangle=[\eta(1-\eta)/N]^{1/2}, \quad (4)$$

where N is the number of measurements, corresponds to a binomial distribution relative to two possibilities, firing or non-firing of the spark chamber. Here the relative accuracy of measurement is

$$\frac{\langle\Delta(dn/dx)\rangle}{dn/dx}=-\frac{\{\exp[-\ln(1-\eta)]-1\}^{1/2}}{N^{1/2}\ln(1-\eta)}\ . \quad (5)$$

The maximum accuracy of measurement of the primary ionization corresponds to the value[20]

$$n=-\ln(1-\eta)=1.6, \quad (6)$$

i.e., $\eta=0.80$ and at $N=10^3$ is equal to 3.9%. It should be noted however, that the quantity $\langle\Delta(dn/dx)\rangle/(dn/dx)$ changes little in the interval $0.5<\eta<0.95$ and does not exceed 4.6% at $N=10^3$.

If we are interested only in the expected values of dn/dx for relativistic particles at the minimum of the ionization,[14,15] then the optimal conditions of measurement of the primary ionization in all gases at $l\approx 1$ cm will be pressures below atmospheric (from ~0.5 atm for He to ~0.04 atm for Xe). Another alternative is a decrease in the interelectrode distance at $P=1$ atm—which is undesirable in view of the deterioration of the front of the high-voltage pulse because of the increase in the self-capacitance of the spark chamber and difficulties associated with the necessity of keeping the interelectrode distance exactly constant. Therefore, in all our experiments, low pressure spark chambers were used with $l=1$ cm, Table I.

TABLE I. Gas pressure in a wire spark chamber with interelectrode distance $l=1$ cm, used for the measurement of the specific primary ionization in noble gases.

Investigated gas	P, atm.	Investigated gas	P, atm.
He	0.4: 0.6	Kr	0.06
Ne	0.15	Xe	0.05
Ar	0.07	30% He+70% Ne (henogal)	0.15

3. METHOD OF EXPERIMENT

As was shown by the authors previously,[12] the use of spark chambers with plane solid electrodes is not suitable for measurement of the primary ionization for the following reasons. Part of the electrons produced by the charged particles as a result of ionization of the gas, of the diffusion during the delay time t_d of the high-voltage pulse, and also of the drift of the electrons in the electric field at the front of the high-voltage pulse, lands on the electrodes and does not participate in the creation of the spark discharge. These effects are especially marked in gases with high diffusion coefficients and mobilities, and increase with decrease in the gas pressure.

The transition to wire electrodes with transparency of ~90% significantly increases the efficiency of the spark chamber, since the diffusion of the electrons from the interelectrode gap is compensated for by the reverse diffusion of electrons formed outside this gap. The drift of the electrons at the front of the high-voltage pulse is also practically eliminated thanks to the high intensity of the electric field near the wires ($E\approx 40$ kV/cm at $U=10$ kV and wire diameter 0.1 mm), which leads to the appearance of a discharge in the gas regardless of the place of formation of the electron.

The construction of the spark chamber with three wire electrodes is shown in Fig. 1. The electrodes are wound of wire of beryllium bronze BrB-2 of diameter

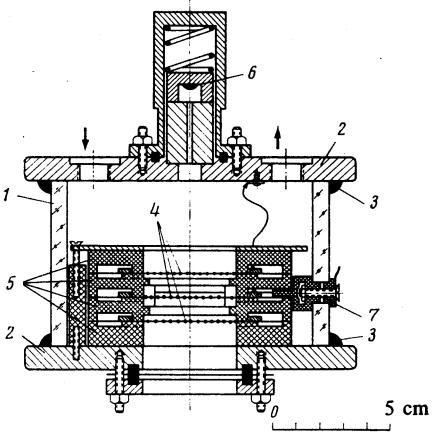

FIG. 1. Construction of the low pressure spark chamber: 1—glass case, 2—chamber cover, 3—vacuum cement, 4—wire electrodes, 5—teflon rings, 6—radioactive source (Sr^{60}_{38}), 7—high-voltage lead.

90 μ, with pitch of 1 mm on, a ring-shaped brass frame. The distance between the electrodes was fixed by Teflon rings of thickness 10 ± 0.01 mm, in which windows were cut for observation of the spark discharge. The spark chamber could operate both in a three-electrode configuration (the central electrode serving as the anode) and also in a two-electrode one (the voltage is applied to the central electrode and one of the outer electrodes). In the latter case, the capacitance of the chamber amounted to ~ 30 pf. Sealing of the glass cylinder with duraluminum covers was carried out by means of specially prepared vacuum cement.[12] The mechanical strength of the construction was assured by the difference between the internal and external pressure. The pressure and the temperature of the gas in the course of filling the spark chamber was monitored to within 0.3%.

The spark chamber was filled with a noble gas of high purity; however, the contamination of the gas in the course of operation changed significantly the efficiency of the spark chamber because of ionization of the impurities with low ionization potentials in collisions with the excited atoms of the main gas. To avoid this effect, the gas was continuously circulated through calcium chips heated to 450–500 °C. The calcium vapor was collected in a trap filled with zeolite. Periodic monitoring of the purity of the gas with a KhLM-2MD chromatograph showed that the partial pressure of any impurity did not exceed 10^{-5} atm. Because of this, it was possible to achieve excellent stability of the efficiency of the spark chamber.

Irradiation of the spark chamber was achieved by electrons with energies 1.7-2.2 MeV from the β source Sr^{90}_{38}. The specific primary ionization created by these electrons differed from the minimum on average by no more than 0.5%.[14,15] The passage of the electrons through the spark chamber was recorded by two scintillation counters. A synchronization signal triggered the circuit of the pulse supply to the spark chamber. The time constant of the high-voltage pulse and the minimum time of its delay amounted to 200 nsec. The spark discharge was recorded by a miniature photomultiplier FEU-68. At all the gas pressure values used, a distinct spark was observed, surrounded more or less by a bright halo. Because of the large "dead" time of the low pressure spark chamber filled with pure noble gas, due to the long-time existence of metastable atoms in its volume,[21] we used a blocking time $\gtrsim 5$ sec.

4. MEASUREMENT OF THE PRIMARY IONIZATION IN THE SPARK CHAMBER

The efficiency of the spark chamber is determined in the experiment by the ratio of the number of ignitions N' and the total number N of passages of charged particles through it:

$$\eta_{meas} = N'/N. \tag{7}$$

After each cycle of measurements ($N \geqslant 10^3$) the efficiency η_Φ of recording phonon events was determined. For this purpose, the spark chamber was triggered by the pulse generator and the frequency of breakdowns, brought about by the random coincidences of the high-voltage pulse with the ionizations of the gas generated by the β source. The quantity η_b varied, as a function of the gas composition and the amplitude of the high-voltage pulse, in the range 0.05–0.2, (in the absence of the β source, $\eta_b < 0.01$.) The real efficiency of the spark chamber under conditions of statistical independence of the noise is

$$\eta = (\eta_{meas} - \eta_b)/(1 - \eta_b). \tag{8}$$

For each gas, the dependent of the efficiency $\eta(U)$ was plotted as a function of the amplitude of the high-voltage pulse (counting characteristic). All the obtained curves have the characteristic gently sloping region—a plateau with an extent of 2–3 kV, where the efficiency of the spark chamber does not depend on the applied voltage, see Fig. 2. The presence of the plateau indicates that the probability of development of a spark discharge remains constant, in spite of the sharp increase in the first Townsend ionization coefficient $\alpha(U/P)$. This fact serves as proof that in the region of the plateau a single free electron is sufficient for generation of the spark discharge. This conclusion is very important for demonstrating the possibility of measurement of the primary ionization in gas-discharge devices. It is also confirmed by the data obtained in streamer chambers.[6–10] All measurements of primary ionization were carried out at the middle of the plateau of the efficiency of the spark chamber.

As was pointed out above, the loss of part of the secondary electrons by diffusion to the electrodes of the spark chamber can greatly influence the results of mea-

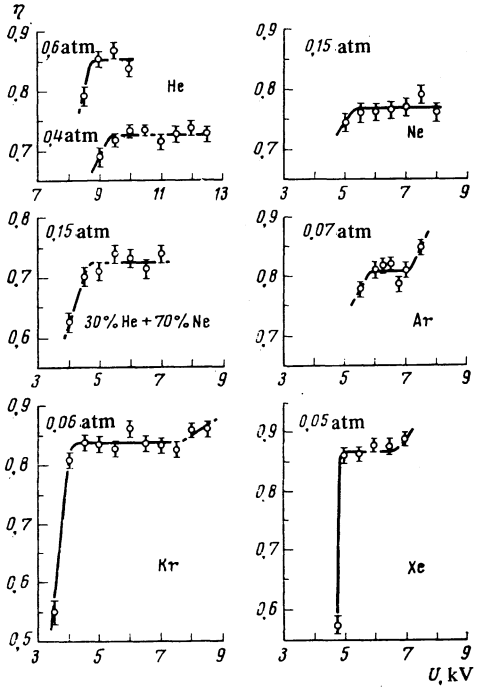

FIG. 2. Dependence of the efficiency η of a low-pressure spark chamber filled with a noble gas on the amplitude U of the high-voltage pulse ($RC = 0.2$ μsec, $t_d = 0.2$ μsec, $t = 20$ °C).

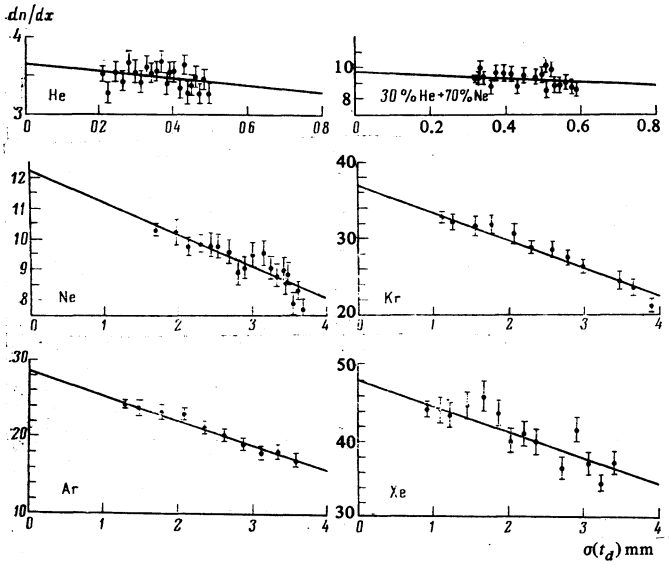

FIG. 3. Dependence of the specific primary ionization dn/dx, cm^{-1}, on the calculated diffusion mean square displacement $\sigma(t_d)$ of the electrons, formed by the charged particle in the gas (the results of one of cycles of measurements referred to normal conditions, are shown).

surement of the primary ionization. The use of wire electrodes, while reducing the role of the diffusion, does not eliminate it completely. The effect of diffusion on the measured primary ionization is seen in Fig. 3. A correction for diffusion can be introduced by extrapolating to the point $t_d = 0$ the time dependence of the primary ionization, measured at different delays of the high-voltage pulse. In this case, the extrapolation law should take into account the change in the diffusion coefficient of the electrons in the process of their thermalization, i.e., the slowing down as a result of elastic collisions with the gas atoms, from an energy on the order of 10 eV, obtained at the instant of generation, to thermal energies. As is shown in the Appendix, the primary ionization turns out to be a linear function $\sigma(t_d)$ of the calculated mean squared deviation of the electron in the course of thermalization from the point of its generation. Thus, the dependence of the measured specific primary ionization on the time of delay of the high-voltage pulse is of the form (Fig. 3)

$$dn(t_3)/dx = dn(t_3=0)/dx\,[1-\text{const}\cdot\sigma(t_3)]. \qquad (9)$$

The desired values of $dn(t_d = 0)/dx$ were found by approximation of the experimental values by the dependence (9) by the method of least squares. All the calculations were carried out on a high-speed computer.

The results of the measurements of the specific primary ionization of noble gases at the minimum of the ionization under normal conditions, obtained in the present research, together with the data of other experiments and theoretical predictions, are given in Table II. (Only the statistical errors are shown; the systematic errors, however, can be of the same order of magnitude.)

5. DISCUSSION

In a comparison of the experimental data with the results of calculations, one must take into account the contribution of the fast secondary processes in the gas of the detector to the measured primary ionization. The value of the contribution depends both on the nature and purity of the gas and on the chosen method of measurement.[8] In the case of a low-pressure spark chamber with wire electrodes (transparency ~90%), filled with a pure noble gas, the only secondary process that leads to the additional ionization can be the reaction of formation of a molecular ion[2)]

$$X^* + X \to X_2^+ + e^-. \qquad (10)$$

However, only helium, of all the noble gases, has the levels $1s4p$, $1s5p$, ... with an excitation potential higher than the potential (23.3 ± 0.1 eV[22]) at which the molecular ion He_2^+ appears. The characteristic time of the reaction (10) at $P_{He} \approx 0.5$ atm (the reaction cross section is $\sim 2\times 10^{-15}$ cm^2[22]) amounts to $\sim 10^{-10}$ sec. The additional ionization is thus produced almost instantaneously, and it is not possible to separate it experimentally from the primary ionization. The calculated value of the contribution of the reaction (10) amounts to about 4% of the expected primary ionization.[14,16,23]

The primary ionization in 30% He + 70% Ne (henogal) is not equal to the sum of the partial ionizations of helium and neon. In collisions with resonantly excited atoms of He*, the excitation energy of which exceeds the ionization potential of neon or the potential of appearance of molecular ions He_2^+ and $HeNe^+$, an additional ionization is produced

$$He^* + Ne \to He + Ne^+ + e^- \qquad (11)$$

(reaction cross section $\sim 10^{-15}$ cm^2[22]) or

$$\begin{aligned} He^* + He &\to He_2^+ + e^-, \\ He^* + Ne &\to HeNe^+ + e^-. \end{aligned} \qquad (12)$$

The characteristic times of these reactions at gas pressure $P \approx 0.15$ atm is essentially below 0.2 μsec. Therefore it is impossible to separate the secondary ionization caused by them from the primary ionizator.

Analysis of Table II, where the existing data on the primary ionization of noble gases and henogal at the ionization minimum are gathered, allows us to draw the following conclusions:

1. A low-pressure wire spark chamber is suitable for the measurement of the specific primary ionization in gases, even those possessing large coefficients of electron diffusion.

2. By use of the wire spark chamber, measurements can be made of the primary ionization, both in pure gases and in mixtures of gases. In all cases, the possible contribution of secondary processes with part of the excited atoms should be taken into account.

3. Measurements in spark chambers with plane solid electrodes give lower values of the specific primary

TABLE II. Specific primary ionization of noble gases produced by relativistic electrons with energies ~ 2 MeV (minimum ionization) under normal conditions.

Investigated gas	Method of measurement	n, cm^{-1} experiment	n, cm^{-1} theory
He	Low efficiency Geiger-Müller counter[2]	5.02±0.06	3.62[13]
	Streamer chamber[8]	3.83±0.11	3.50[14,15,23]
	Streamer chamber (from the results for He+Ne mixture)[10]	3.54±0.11	3.43[16]
	Spark chamber with plane electrodes[12]	3.44±0.06	3.79*[14,15,23]
	Spark chamber with wire electrodes[12]	3.66±0.06	3.72*[16]
	Spark chamber with wire electrodes	3.65±0.06	
Ne	Low-efficiency Geiger-Müller counter[2]	12.4±0.2	11.4[14,15]
	Streamer chamber (from results for He+Ne mixture)[10]	11.7±0.3	11.75[23]
	Spark chamber with plane electrodes[12]	10.6±0.6	
	Spark chamber with wire electrodes[12]	11.1±0.2	
	Spark chamber with wire electrodes	12.27±0.15	
Ar	Low efficiency Geiger-Müller counter[2]	27.8±0.3	25.9[14,15]
	Wilson chamber[3]	28.6±0.5	26.65[23]
	Diffusion chamber[5]	26.4±1.8	
	Spark chamber with plane electrodes[12]	27.0±1.8	
	Spark chamber with wire electrodes[12]	27.1±0.9	
	Spark chamber with wire electrodes	28.5±0.5	
Kr	Spark chamber with wire electrodes	37.1±0.6	35.4[15,23]
Xe	Spark chamber with wire electrodes	48.0±1.0	49.6[14] 48.1[15,23]
30% He +70% Ne (henogal)	Streamer chamber[6]	10.2±1.0	9.2**[15]
	Spark chamber with wire electrodes	9.6±0.3	9.45**[23]

*) With account of additional ionization in reaction (10).
**) With account of additional ionization in reactions (11) and (12).
Note. The formulas for primary ionization, given in Refs. 14 and 15 and in Ref. 23 (Eq. (6)), differ only in the fact that the summation over the finite number of discrete oscillations in Refs. 14 and 15 is replaced in Ref. 23 by integration over the distribution of oscillator strengths. Therefore, the values of dn/dx calculated according to Ref. 23 should be regarded as more accurate. Values without literature references are those of the present research.

ionization because of electron diffusion and drift to the electrodes of the spark chamber in the electric field of the high-voltage pulse.

4. Measurements of the specific primary ionization, carried out under the purest conditions by method of the streamer chamber (for helium and henogal) and of the wire spark chamber (for all the noble gases and henogal) are in satisfactory agreement with the results of calculations that take into account the contribution of secondary processes in the gas. The present accuracy of the experimental data does not allow us, however, to draw any conclusion on the use of an particular variant of the theory.

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APPENDIX: EFFECT OF ELECTRON DIFFUSION ON THE MEASUREMENT OF PRIMARY IONIZATION

Let F_j be the Poisson probability of formation of j primary electrons along the length l in the gas, and W_k

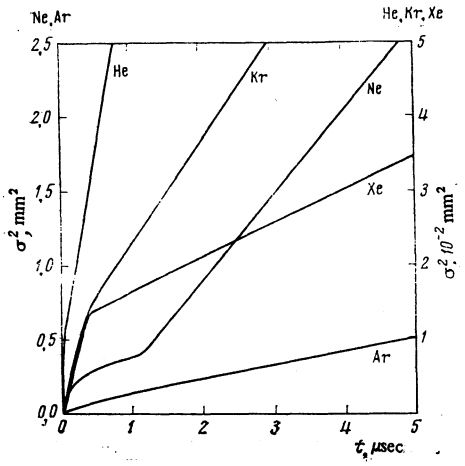

FIG. 4. Dependence of the mean square departure[2] of the electron on the delay time t in noble gases under normal conditions.

be the probability of appearance of k secondary electrons, including the primary one,

$$W_0=0, \quad \sum_{k=1}^{\infty} W_k=1.$$

The inefficiency of the spark chamber is determined by events in which the charged particle either does not form electrons in the interelectrode gap, or all the secondary electrons fall onto the electrode and do not participate in the development of the spark breakdown,

$$1-\eta(t)=F_0+\sum_{j=1}^{\infty} F_j\left[\sum_{k=1}^{\infty} W_k l^{-1}\int_0^l \alpha^k(x_0,t)\,dx_0\right]^j$$
$$=F_0+\sum_{j=1}^{\infty} F_j\alpha^j(t)=\exp\{-n[1-\alpha(t)]\}. \qquad \text{(A. 1)}$$

Here $\alpha(x_0, t)$ is the probability of incidence of an electron, formed at the point $x_0 (0 \leq x_0 \leq l)$, on the electrode of the spark chamber, due to its diffusion in the interelectrode during a time $t \leq t_d$, and

$$\alpha(t)=\sum_{k=1}^{\infty}\alpha_k(t)=\sum_{k=1}^{\infty} W_k l^{-1}\int_0^l \alpha^k(x_0,t)\,dx_0 \qquad \text{(A. 2)}$$

is the mean probability of diffusion in a time t of all the secondary electrons to the electrode of the spark chamber.

To find $\alpha(x_0, t)$ and $\alpha(t)$, we consider the problem of the diffusion of the electron in the gas with account of thermalization. Since the dimensions of the electrodes are much greater than the interelectrode gap, we can neglect the lateral displacement of the electrons and limit ourselves to the one-dimensional equation

$$\frac{\partial u(x,t)}{\partial t}=KD(t)\frac{\partial^2 u(x,t)}{\partial x^2}, \quad 0\leq x\leq l, \quad t\geq 0. \qquad \text{(A. 3)}$$

where $u(x, t)$ is the probability density of finding the electron at the point x at the instant of time t, $D(t)$ is the diffusion coefficient, which depends on the time, since the energy of the electron decreases during thermalization, and $K = d/S$ is the nontransparency of the electrode, which depends on the effective diameter d of the wires and the distance S between them.

The introduction of the nontransparency K in the diffusion equation (A. 3) allows us to specify boundary and initial conditions exactly in the same way as in the case of solid electrodes[12]:

$$u(0,t)=u(l,t)=0, \quad u(x,0)=\delta(x-x_0). \qquad \text{(A. 4)}$$

Employing the usual solution of the diffusion equation (A. 3), we find

$$\alpha(x_0,t)=1-l^{-1}\int_0^t u(x_0,x,t)\,dx$$
$$=1-\frac{4}{\pi}\sum_{m=1}^{\infty}\frac{\sin\{\pi(2m-1)x_0\}}{2m-1}\exp\{-K\pi^2(2m-1)^2\int_0^t D(t)\,dt\}. \qquad \text{(A. 5)}$$

We introduce the quantity

$$\sigma^2(t)=2\int_0^t D(t)\,dt. \qquad \text{(A. 6)}$$

which corresponds to the mean square displacement of the electron in the time t. Data on the cross sections of momentum transfer of electrons with energies ~ 10 eV to thermal energies in elastic collisions with atoms of noble gases[24] have been used and, following Ref. 25, [3)], we find $\sigma^2(t)$; see Fig. 4.

Furthermore, substituting (A. 5) and (A. 6) in (A. 2) and, carrying out numerical integration, we obtain the result that the function $\alpha(t)$ in a broad range of values $0 \leq \alpha(t) \lesssim \frac{1}{2}$ is connected with $\alpha(t)$ by a linear dependence:

$$\alpha(t)=\text{const}\cdot\sigma(t). \qquad \text{(A. 7)}$$

The same result was obtained analytically in Ref. 12 for small $\sigma(t)$, when $(Dt)^{1/2}/l \ll 1$.

Finally, with the help of (A. 6), (2) and (A. 1), we find

$$n(t)=n(t=0)\,[1-\text{const}\cdot\sigma(t)\,], \qquad \text{(A. 8)}$$

or, on the basis of (1),

$$dn(t)/dx=dn(t=0)/dx\,[1-\text{const}\cdot\sigma(t)\,]. \qquad \text{(A. 9)}$$

[1)] We speak of the specific primary ionization, and not of the ionization cross section, since the latter concept loses meaning for particles of high energy. Actually, because of the relativistic increase in the range of impact parameters corresponding to the ionization, the interaction, beginning at a certain energy, is no longer with one but with many atoms.

[2)] The reaction of formation of excited molecules of a noble gas in the triple collisions $X^*+2X \to X_2^*+X$ under our conditions has a chacteristic time of the order of tens of microseconds. In addition, the hard photons, formed as a result of luminescence of X_2^*, pass practically freely through the wire electrodes without producing electron emission.

[3)] In Eqs. (4) and (6) of Ref. 25, we must use not the total but the transport mean free path of the electrons.

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Ionization of high-lying states of the sodium atom by a pulsed electric field

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The critical field intensities are obtained for the S and D states with $n = 12$–19 of a sodium atom excited by radiation from a pulsed dye laser with continuously tunable lasing frequency. The experimentally measured critical intensity agrees well with the calculated one and is proportional to $(n^*)^{-4}$, where n^* is the effective principal quantum number. It is shown that in a field with an intensity higher than critical, the highly-excited atoms are ionized with an ion yield equal to unity. The effective cross section of the atom-ionization process is equal in this case to the cross section for the excitation of the high-lying states.

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1. INTRODUCTION. FORMULATION OF PROBLEM

Much attention is being paid recently to selective stepwise photoionization of atoms by laser radiation. This method is promising for the solution of such problems as isotope separation, nuclear isomers, production of ultrapure substances, etc., since it is universal, i.e., it is applicable practically to all elements and is effective.

The gist of the method consists in the following. The atoms of the chosen species are selectively excited into the intermediate state by narrow-band laser radiation. Additional laser radiation is then used to ionize the excited atoms. This ionization method and its use for separation of atoms was first proposed in[1] and realized in[2] with Rb as an example. This method was then used to carry selective photoionization of the Ca^{40} isotope[3] and a weighable amount of uranium enriched with U^{235} was obtained[4,1)]. In,[7] using a tunable dye laser or by using the emission of a ruby laser and its second harmonic for the ionization, photoionization of rubidium atoms was effected with an ion yield close to unity. The resultant ions and electrons made up a plasma with a maximum charge density $\approx 10^{13}$ cm^{-3}.

Despite the high selectivity and efficiency of the method in individual experiments, its extensive use is difficult. The reason is that, owing to the smallness of the cross section σ_{ion} for the ionization of the atom (σ_{ion}

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