# Electron dynamics in condensed argon and xenon

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(Submitted 3 April 1981; resubmitted 23 November 1981)
Zh. Eksp. Teor. Fiz. **82**, 1114–1125 (April 1982)

From accurate measurements of the drift velocity in condensed argon and xenon over a wide range of temperature (80–135 K for argon, 80–230 K for xenon) and of electric fields ($5–1.5\times 10^4$ V·cm$^{-1}$) the explicit form of the electron energy distribution function has been obtained so that the dynamics of electrons in these materials can be fully described. The description was based on the Lekner "hot" electron theory. The mean electron energies and diffusion coefficients were calculated for different temperatures and electric fields. Values for the scattering cross sections for electrons in condensed argon and xenon at different temperatures were obtained.

PACS numbers: 72.20.Dp

Condensed and highly compressed noble gases are constantly attracting the attention of investigators designing new apparatus for nuclear physics, as possible working materials for radiation detectors. Prediction of the possible characteristics of detectors, especially with electronic data collection, requires a knowledge of the behavior of charge carriers in these materials. Measurement and theoretical calculations of such quantities as the drift velocity of electrons, their mean energy, diffusion coefficient, and the scattering cross section at different temperatures and electric field strengths are also important from the point of view of the physics of condensed matter.

However, experimental results are at present very scanty and contradictory even for argon,[1] which is the gas most studied, while information about the dynamic characteristics of electrons is practically non-existent. Measurements of drift velocity were carried out either for a fixed value of electric field strength in the temperature range from the triple point $T_0$ to the critical temperature $T_c$ (Refs. 2–5), or on the other hand over a wide field range but at a fixed temperature, usually near $T_0$ (Refs. 6–10).

We have earlier[1,11] given preliminary results of studies of drift properties of condensed argon and xenon and, in particular, of an attempt to describe electron drift in argon in the range 70 to 110 K and 0.8 to 8 kV·cm$^{-1}$ with the help of the Davydov distribution. In the present work we give the results of accurate measurements of electron drift velocities in condensed argon (80 to 135 K; 20 to $1.5\times 10^4$ V·cm$^{-1}$) and xenon (80 to 230 K; 5 to $1.5\times 10^4$ V·cm$^{-1}$) and also the results of calculations of the dynamic characteristics of electrons based on the experimental results obtained.

## METHOD AND EXPERIMENTAL ERRORS

Measurements of drift velocity were carried out with apparatus similar to that described earlier.[12] We used a modified Townsend pulsed discharge method, firstly, as the most direct time-of-flight method of measuring the drift velocity and, secondly, as the most direct method of measuring and controlling the purity of the condensed matter.[13,14] In this method the electron component of the current or voltage pulse which arises in a two-electrode ionization chamber[11] on irradiation from the lower electrode side by a short pulse of x rays is amplified and analyzed with, for example, an oscilloscope. It can be shown that for an amplifier time constant $RC \gg t$ (where $t$ is the drift time) an accurate value of the drift velocity is

$$V=\frac{L}{t'}\left\{1+\frac{\tau-\tau_R}{2}\left[\frac{1}{RC}+\frac{1}{t'}\left(1-\frac{L}{D}\right)\right]-\frac{\tau}{2t'}\right\},$$

where $L$ is the drift distance, $\tau$ the duration of the x-ray pulse, $\tau_R = L_R/V$, $L_R$ is the effective penetration depth of the x-ray beam into the material under investigation, defined as the tenfold attenuation layer, $t'$ is the rise time of the voltage pulse, measured by the intersection of the extrapolation of the linear part of the pulse front with the zero and maximum amplitude levels, and $D$ is the mean electron path before capture, inversely proportional to the concentration of electronegative impurities (mainly oxygen). As can be seen from the above expression, neglect of the correction in the curly brackets can lead to a considerable error in measurements of the drift velocity. In our experiments $RC = 400$ $\mu$s, $t = 2$ to 50 $\mu$s, $\tau \ll 0.3$ $\mu$s, $L = 1$ to 2 cm, the x-ray pulse energy if 50 MeV·$\mu$s$^{-1}$, the maximum energy of the x ray quanta is 23 keV, $L_R = 30$ to 80 $\mu$m, and $L/D \leqslant 0.03$. The overall error in the measurement is governed also by the following factors:

1. The uncertainty in the distance between the electrodes. If the geometrical dimensions are measured with an accuracy of 0.1 mm and $L = 1$ cm, the error in the drift velocity is 1%.

2. The error in measuring $t'$ on the oscilloscope screen is not worse than 1.5%.

3. The error in calibrating the horizontal oscilloscope sweep is not more than 3%.

4. The uncertainty $\Delta U = \pm 0.1$, ±60, and ±150 V in the value of the voltage applied to the chamber in the ranges 0–1, 1–3, 3–15 kV, respectively.

5. The error in temperature measurement. The temperature could be measured to an accuracy no worse than ±0.5 K and could be stabilized to no worse than 0.1 K by using a tempeature control system similar to

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that described by Voronova *et al.*[12] The temperature gradient over the chamber height did not exceed 1 K.

The positive space charge which is formed near the cathode by the extremely small ionic (hole) mobility ($\sim 10^{-2}$ cm$^2\cdot$V$^{-1}\cdot$s$^{-1}$) and weakens the external field can introduce an appreciable error when working in weak fields. The drift velocity then obtained corresponds to some total field, the value of which is not known, while the mobility $\mu_0 = V/E$ is less than the true value. In the present work the x-ray pulse produced $\leq 10^5$ electron-ion pairs in the chamber. Under these conditions the current pulse observed in fields $< 100$ V$\cdot$cm$^{-1}$ was rectangular at an x-ray pulse repetition frequency 0.1 to 1 Hz. Increasing the repetition frequency led to distortion of the current pulse shape (or to a nonlinear voltage pulse front), which indicated field distortions in the gap between the electrodes. For comparison, the radiation-pulse repetition frequency used by Miller *et al.*[8] was 50 Hz and the charge produced by a pulse was not less than $2 \times 10^5$ electron-ion pairs.

The total error in a single measurement of the drift velocity at a fixed field value thus did not exceed 3.5%.

## EXPERIMENTAL RESULTS

The results of this investigation are shown in Figs. 1 to 4 and in Table I, and the main conclusions are as follows.

1. The doubly-logarithmic plot of drift velocity vs electric field strength has some clearly defined linear sections (Figs. 1 and 2), so that in each section the drift velocity can be well approximated by the expression $V = BE^{\alpha}$, where $B$ and $\alpha$ are constants for a given temperature. As the field strength increases, $\alpha$ changes from 1 ($V = \mu_0 E$) to 0 ($V = V_s = \text{const.}$).

2. The linear section $V = \mu_0 E$ was reliably measured and contains 20 to 30 experimental points for each temperature. The mobility $\mu_0$ was determined from the value of the drift velocity at the intersection of the extrapolation of the linear section $V = \mu_0 E$ on the doubly logarithmic plot with the ordinate axis at $E = 1$ V$\cdot$cm$^{-1}$. As noted before,[2-5] the temperature dependence of $\mu_0$ (Fig. 3) is very nonmonotonic; the maximum electron mobility (8500 cm$^2\cdot$V$^{-1}\cdot$s$^{-1}$) is reached in liquid xenon at 220 K. In solid xenon, $\mu_0$ increases monotonically with decreasing temperature from 2900 cm$^2\cdot$V$^{-1}\cdot$s$^{-1}$ at $T = 155$ to 6000 cm$^2\cdot$V$^{-1}\cdot$s$^{-1}$ at $T = 80$ K.

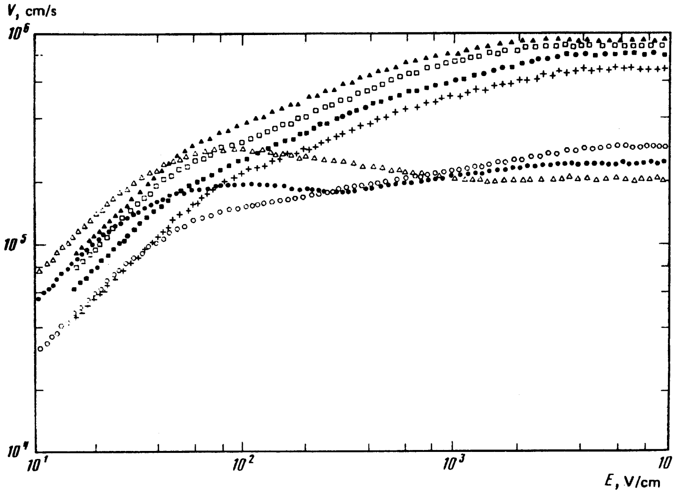

FIG. 1. Electric field dependence of the drift velocity of electrons in condensed xenon at the following temperatures: liquid: ○—165; ●—200; △—230 K. Crystal: +—155; ■—140; □—120; ▲—100 K.

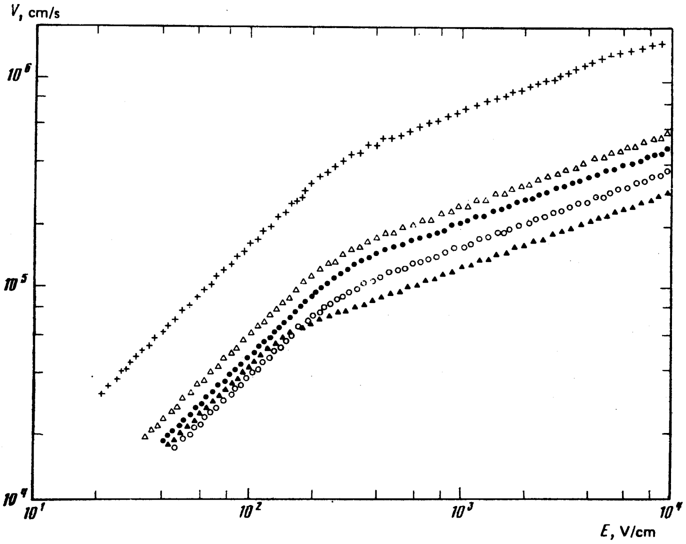

FIG. 2. Electric field dependence of the drift velocity of electrons in condensed argon at the following temperatures: liquid: △—85; ●—100; ○—120; ▲—130 K; crystal: +—80 K.

3. The form of the electric field dependence of the electron drift velocity does not change with temperature, except for liquid xenon where there is a characteristic dip at $E = 10^2$ to $10^3$ V$\cdot$cm$^{-1}$ (Fig. 1) far from the triple point in the region of the maximum of the $V(E)$ curve; this dip is absent for gaseous noble gases. The electron drift velocity in liquid argon evidently behaves in a similar way near 145 K.

4. In condensed xenon the drift velocity reaches saturation in fields above 2 to 4 kV cm$^{-1}$, and the satura-

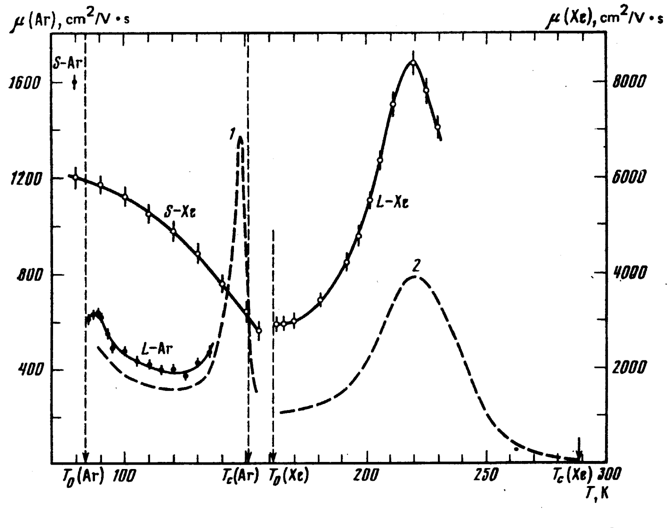

FIG. 3. Temperature dependence of electron mobility in the limit of zero field; $L$—liquid, $S$—crystal. Dashed lines—results of earlier work: 1—Ref. 3, 2—Ref. 5.

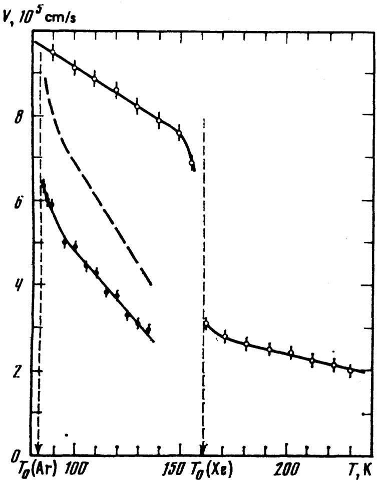

FIG. 4. Temperature dependence of drift velocity at saturation: ○—xenon, $V_s$; ●—argon, $V(10^4\ \mathrm{V\cdot cm^{-1}})$, dashed line—argon, $V_s$. In solid argon $V_s = 1.8\times10^6\ \mathrm{cm\cdot s^{-1}}$ at $T = 80$ K.

tion limit shifts to lower values of $E$ as the temperature is raised or lowered relative to the critical point. The saturation effect in the drift velocity was observed[8,9] in condensed argon in fields above 60 kV cm$^{-1}$, so that it was not reached in our measurements. However, on the assumption that measuring conditions in different studies influence mainly the absolute magnitude of the drift velocity, while relative results are quite reliable, to determine the drift velocity in condensed argon at saturation the drift velocity at $E = 10^4$ V·cm$^{-1}$ measured by us was multiplied by the ratio $V_s/V$ ($10^4$ V·cm$^{-1}$) taken from Refs. 8 and 9, where it was really found to be very close to 1.63 and 1.6. As can be seen from Fig. 4, $V_s$ increases with decreasing temperature and changes at the liquid–crystal transition not abruptly, but over a temperature interval $T_0 + 10$ K, where it depends sharply on temperature. This fact explains partially the difference between our results and those published earlier. However, comparison of the results in Table I shows that even at equal temperatures, the values of drift velocity and of mobility are appreciably higher than those in the literature, apparently as a consequence of the more reliable method and experimental technique.

TABLE I. Drift velocity at saturation $V_s$ and zero field mobility.

| Substance | $T$, K | $\mu_0$, cm² · V⁻¹ · s⁻¹ | $V_s$, cm · s⁻¹ | Reference |
|---|---|---|---|---|
| Liquid argon | 87 | 400±50 | 6.4 | [9] |
| | 87 | 520 | – | [2.3] |
| | 85 | 475 | 7.5 | [8] |
| | 87 | – | 6 | [7] |
| | 87 | – | 8 | [6] |
| | 90 | 501 | – | [4] |
| | 85 | 625±15 | 9.1±0.3 | Our work |
| Solid argon | 82 | 1000 | 13,8 | [8] |
| | 80 | 1600±30 | 18.0±0.6 | Our work |
| Liquid xenon | 165 | 2000±200 | 2.6 | [9] |
| | 163 | 2200 | 2.9 | [8] |
| | 167 | 1100 | – | [5] |
| | 165 | 2950±50 | 2.95±0.05 | Our work |
| Solid xenon | 157 | ~4500 | 5.5 | [8] |
| | 155 | 2900±50 | 6.8±0.1 | Our work |

5. The electron drift velocity and mobility in argon and xenon crystals do not depend, within the limits of experimental error, on the rate of crystal growth (i.e., on the crystal quality) in the range from 1 to 10 mm·s$^{-1}$.

## ELECTRON SCATTERING CROSS SECTIONS IN CONDENSED NOBLE GASES

The behavior of electrons in matter in an external electric field is described by an electron distribution function in momentum, $F(\mathbf{p})$, or in energy, $F(\varepsilon)$, that satisfies the Boltzmann equation, with its exact form depending on the type of scattering (elastic or inelastic). Calculation of the main feature of the electron dynamic characteristics is not difficult if the form of the function and the values of the parameters entering into it are known. The transport coefficients, the drift velocity $V$, the mean energy $\bar{\varepsilon}$, and the electron diffusion coefficient $D$ are given by the expressions

$$V = \frac{eE}{3}\left(\frac{2}{mkT}\right)^{1/2}\frac{1}{\mathcal{N}}\int_0^\infty x\lambda(x)\frac{\partial}{\partial x}F_0(x)\,dx, \tag{1}$$

$$\varepsilon = kT\frac{1}{\mathcal{N}}\int_0^\infty x^{3/2}F_0(x)\,dx, \quad D = \frac{1}{3}\left(\frac{2kT}{m}\right)^{1/2}\frac{1}{\mathcal{N}}\int_0^\infty x\lambda(x)F_0(x)\,dx, \tag{2}$$

$$\mathcal{N} = \int_0^\infty x^{1/2}F_0(x)\,dx,$$

where $x = \varepsilon/kT$, $m$, and $e$ and $\varepsilon$ are the electronic mass, charge and energy, $k$ is Boltzmann's constant, $T$ is the absolute temperature, $E$ is the electric field strength, $\lambda(x)$ is the electron mean free path for momentum transfer, and $F_0(x)$ is the isotropic part of the distribution function.

In 1967 Lekner[15] obtained, by solving the Boltzmann equation for elastic electron scattering, the distribution function in the following form

$$F_0(x) = \exp\left[-\int_0^x \frac{x}{x+b(x)}\,dx\right], \quad b(x) = \frac{(eE)^2\lambda_0(x)\lambda_1(x)}{6(m/M)(kT)^2} \tag{3}$$

and extended this result to gases, liquids, and solids. In Lekner's solution, which takes the structure factor $S(\mathbf{k})$ into account ($\mathbf{k}$ is the electron wave vector), the mean free paths for energy transfer ($\lambda_c$) and momentum transfer ($\lambda_1$) are different in condensed matter and only become close in value in a gas or for very hot ($\varepsilon \gg kT$) electrons, when $S(k) \to 1$.

In a pure noble gas at not too strong fields, the electron dynamics is determined by elastic scattering, since interelectron scattering can be neglected at the electron densities ($\lesssim 10^{13}$ cm$^{-3}$) typical of drift measurements, so that the dynamic characteristics of an electron is condensed argon and xenon can be calculated from Eqs. (1) to (3). The main difficulty lies then in the evaluation of $\lambda_0$ and $\lambda_1$. This problem can be solved either by quantum-mechanical calculations or by determining $\lambda_0$ and $\lambda_1$ directly from experimental data.

Methods of calculation of the mean free paths (scattering cross sections) of electrons in a weakly ionized gas are now fairly well developed (see, for example, Ref. 16), especially for the case of only elastic scattering. The most accurate analysis method is based successive approximations in which a power law dependence of the cross-section $\sigma$ on $\varepsilon$ is used as the first approximation. For this purpose the transport coefficients are calculated and compared with those measured, after which corrections are applied to the calculated cross section to give the best agreement between calculation and experiment in the repeated calculation.

There are no restrictions in principle on the application of these methods to condensed matter if the electron distribution function in energy is known. Since this sort of analysis has until now been carried out for condensed noble gases, we shall discuss this question in more detail and show, in particular, that even the first approximation gives completely satisfactory results.

The simple theory of elastic scattering of electrons in semiconductors leads to a differential cross section independent of electron energy.[17] This is, evidently, also valid for the liquid state if the liquid is considered as a system with short-range order, having a corresponding phonon spectrum. Lekner's calculations,[18] using an effective scattering potential, show that $\lambda_0$ in liquid argon depends extremely weakly on electron energy. Similar results have been obtained[9] for liquid argon, krypton, and xenon. In condensed noble gases, $\lambda_0$ is thus independent of energy at a given temperature.

Since the Maxwell distribution function is valid for weak electric fields, such that $V=\mu_0 E$, while Lekner's theory gives $\lambda_0=\lambda_1 S(0)$ for hot electrons, we have from Eq. (1)

$$\lambda_0=\frac{1}{N\sigma_0}=\frac{3}{2}\left[\frac{\pi mkT}{2}\right]^{1/2}\frac{\mu_0}{c}S(0), \tag{4}$$

where $S(0)=NkT\chi_T$, where $\chi_T$ is the isothermal compressibility.

For convenience, the masses and $kT$ are expressed in eV in all expressions here and further on; $c$ is the velocity of light.

The electron scattering cross section relative to energy transfer, $\sigma_0$, calculated from Eq. (4) with the substitution of $\mu_0$ as measured by us, has in liquid argon and xenon a sharp minimum at temperatures corresponding to the peak in the mobility (Fig. 5). As the temperature increases, $\sigma_0$ tends to the value calculated for the gas at the critical point. On the left of $T_m$, $\sigma_0$ increases as the temperature decreases both in the liquid and in the crystal. Lekner[19,20] explained the nonmonotonic behavior of $\sigma_0$ and $\mu_0$, showing that the effective electron scattering length $\tilde{a}$, the sign of which depends on the nature of the scattering potential, is negative in a gas but positive in a liquid near the triple point. There must, therefore, exist a temperature region in the interval $T_0$ to $T_c$ where $\tilde{a}\to 0$ and $\sigma_0=4\pi\tilde{a}^2$ has a minimum while $\mu_0$ is a maximum. Unrestricted growth of the mobility is prevented by the scattering of the electrons by thermodynamic fluctuations of the electron-atom potential[20] or by its tails, which do not completely overlap.[21] A liquid is evidently a system with short-range order, i.e., a quasi-crystal at $T<T_m$ and going over gradually at $T>T_m$ into a system of individual scattering centers. The problem of the mobility peak is still not completely resolved and continues to attract interest. An attempt has been made,[22] for example, to attribute this phenomenon to the existence of percolation channels, which are regions of high mobility that thread through the liquid at $T=T_m$.

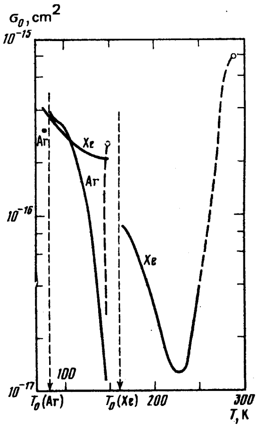

FIG. 5. Temperature dependence of electron scattering cross section for energy transfer: ○—$\sigma_0$ at $T=T_c$, calculated from the mobility $\mu_0$.

Having determined $\lambda_0$, we pass to the calculation of $\lambda_1$, which now depends on energy. Suppose that for some range of electron energy $\lambda_1$ is approximated by the power series $\lambda_1(x)=ax^n$. Substituting this expression in Eq. (3) and neglecting the thermal term in $F_0(x)$, i.e., considering the field region where $\varepsilon\gg kT$, we obtain from Eq. (1)

$$V=(4akT/3\lambda_0 M)^{1/2}c(2-n)^{1/2}[A(2-n)]^{(n+1)/2(2-n)}\Gamma\left(\frac{3}{2-n}\right)\Big/\Gamma\left(\frac{3}{2(2-n)}\right), \tag{5}$$

where $A=b(x)/x^n$, and $\Gamma$ is the gamma-function.

If the experimental dependence of the drift velocity on the electric field, for a certain range of $E$, is approximated by the expression $V=BE^\alpha$, then equating the latter with Eq. (7) we obtain the relations connecting the experimental values of $B$ and $\alpha$ with the approximation parameters $\lambda_1=ax^n$, in particular

$$n=(2\alpha-1)/(\alpha+1). \tag{6}$$

Since $\alpha=0$ in the saturation region, we have $n=-1$ and the effect of saturation of the drift velocity in condensed gases is simply explained by the hyperbolic dependence of mean free path for momentum transfer on electron energy. The scattering cross section increases linearly with energy. For the gaseous state, when $b\sim\lambda_1^2$, $n=1-\frac{1}{2}\alpha$. The drift velocity of electrons in a gas cannot, therefore, reach saturation in a noticeable range of electric field change, as confirmed by experimental results.[6] This method of calculation, first applied to condensed noble gases, gives thus immediately good qualitative results, explaining in a simple way the saturation of the drift velocity.

In general, analysis methods based on a power-law approximation of the scattering cross section are not considered very suitable in the case of a strong dependence of cross section on electron energy, for example near a Ramsauer-Townsend minimum in heavy

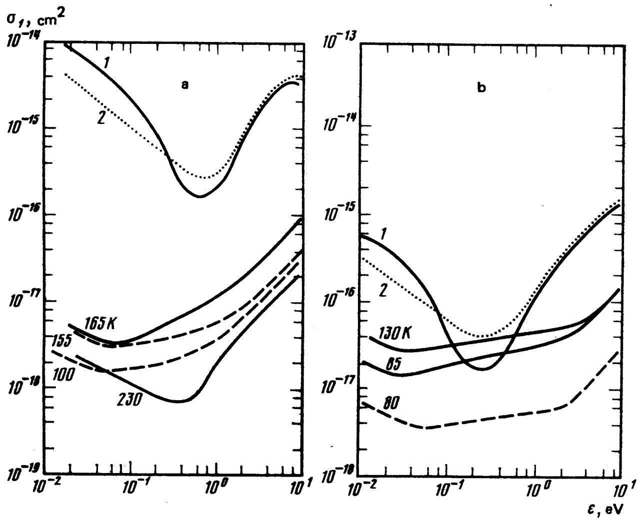

FIG. 6. Electron-energy dependence of electron scattering cross section for momentum transfer in liquid (full lines) and solid (dashed lines) xenon (a) and argon (b); 1—$\sigma_1$ in the gas[23]; 2—the same, calculated by the method of successive approximation.

monatomic gases such as argon, krypton and xenon. As can be seen from Fig. 6, good agreement is achieved only to the right of the Ramsauer minimum. However, if the ultimate aim of the calculations is the determination of not so much the scattering cross section as other features, such as the characteristic or mean energy, the agreement between calculation and experiment is appreciably better.

In condensed argon and xenon $\alpha$ ranges from 1 to $-0.15$, so that $n<0$ and the cross section is an increasing function of electron energy if $\varepsilon \gg kT$. On the other hand, it was pointed out earlier that either the Ramsauer minimum is completely absent in condensed noble gases[18] or that it exists, at least in liquid argon at low energies $\sim 2\times10^{-2}$ eV, but is shallow.[24] At first sight, the analysis method considered cannot give information about the behavior of the cross section at such energies. However, energy considerations lead to the conclusion that the Ramsauer minimum does exist in the condensed phase. If we equate the electron energy loss in a single elastic scattering event

$$(2m/M)\varepsilon F_0(\varepsilon)\varepsilon^{1/2}d\varepsilon$$

to the gain in energy from the external electric field between collisions

$$\lambda_0 E\frac{V}{(2\varepsilon/m)^{1/2}}F_0(\varepsilon)\varepsilon^{1/2}\,d\varepsilon$$

and carry out an integration for the Maxwell distribution function, an expression can be obtained for the electric field strength $E_0$, for which the relation $V=\mu_0 E$ is preserved:

$$E_0 \leqslant \frac{c}{\mu_0}\left[\frac{2kT}{MS(0)}\right]^{1/2}. \tag{7}$$

The values of $E_0$ calculated from Eq. (7) are appreciably lower than the experimental values (Fig. 7). At the same time, thermodynamic equilibrium is not an essential condition for a linear dependence of drift velocity $E$, since it follows from Eq. (6) that $\alpha=1$ if $n=\frac{1}{2}$; the distribution function may then not be Maxwellian and the mean energy may differ from $(\frac{3}{2})kT$.

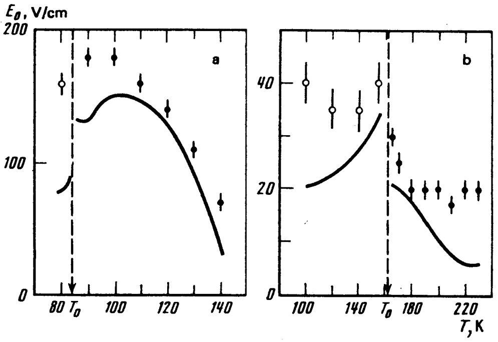

FIG. 7. Temperature dependence of limiting field strength $E_0$ for argon (a) and xenon (b). Solid lines—calculated from Eq. (7).

The considerations given are, essentially, equivalent to a second approximation in the analysis i.e., to a correction of the calculated cross sections after comparing the experimental and calculated drift velocities.

The Ramsauer minimum in the electron cross section for momentum transfer (Fig. 6) is in fact shallow, while its position (about 0.025 eV) in liquid argon agrees with the predictions. Its minimum shifts to higher energies as the temperature is raised, while its depth increases.

The considerable difference in the behavior of the scattering cross-section in argon and xenon on going from gas to liquid is also interesting. While for argon the cross section in the liquid is close to the value at the minimum for the gas, for xenon it is less by several orders of magnitude, especially in the low-energy region.

In conclusion, we note that although the electron scattering cross section in condensed noble gases can be

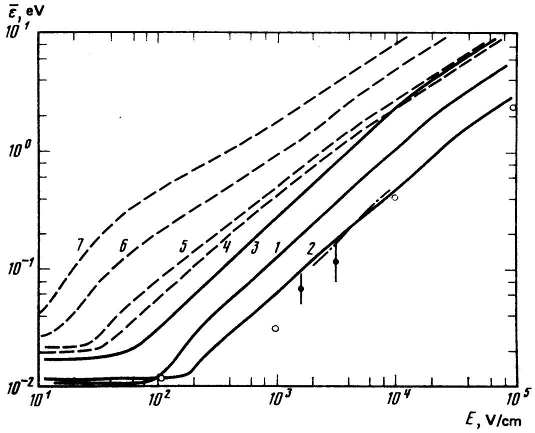

FIG. 8. Electric field strength dependence of mean electron energy. Solid lines—argon: solid—1 (80 K); liquid—2 (85), 3 (140 K). Dashed lines—xenon: solid—4 (155 K); liquid—5 (165), 6 (200), 7 (230 K). Dash-dot line and ●—experiment[25] (85 K), ○—calculated[18] (84 K).

TABLE II. Mean energy (eV) and diffusi coefficient ($cm^2 \cdot s^{-1}$) of electrons, calculated.

| $E$, $V \cdot cm^{-1}$ | Solid argon $T$, K | Liquid argon $T$, K | | | Solid xenon $T$, K | | | | Liquid xenon $T$, K | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 80 | 85 | 110 | 130 | 100 | 120 | 140 | 155 | 165 | 180 | 200 | 230 |
| | | | | | Mean energy | | | | | | | |
| 0 | 0.01 | 0.011 | 0.014 | 0.017 | 0.013 | 0.016 | 0.018 | 0.02 | 0.021 | 0.023 | 0.026 | 0.03 |
| $3 \cdot 10^2$ | 0.04 | 0.021 | 0.024 | 0.04 | 0.165 | 0.18 | 0.165 | 0.15 | 0.19 | 0.25 | 0.42 | 0.9 |
| $1 \cdot 10^3$ | 0.125 | 0.062 | 0.073 | 0.125 | 0.5 | 0.5 | 0.5 | 0.43 | 0.5 | 0.6 | 0.96 | 1.8 |
| $3 \cdot 10^3$ | 0.35 | 0.17 | 0.20 | 0.35 | 1.25 | 1.25 | 1.25 | 1.05 | 1.4 | 1.65 | 2.1 | 3.7 |
| $1 \cdot 10^4$ | 1.05 | 0.5 | 0.62 | 1.10 | 2.8 | 2.8 | 2.8 | 2.4 | 2.6 | 3.2 | 5.0 | 8.2 |
| $3 \cdot 10^4$ | 2.3 | 1.35 | 1.5 | 2.8 | 5.8 | 5.8 | 5.8 | 5.0 | 5.4 | 6.6 | 10 | 17 |
| $1 \cdot 10^5$ | 5.0 | 3.0 | 3.4 | 6.0 | 12.5 | 12.5 | 12.5 | 11.5 | 12 | 14 | 22 | 35 |
| | | | | | Diffusion coefficient | | | | | | | |
| 0 | 11 | 4.5 | 4.0 | 4.6 | 50 | 51 | 47 | 39 | 42 | 53 | 91 | 140 |
| $3 \cdot 10^2$ | 43 | 9.0 | 7.0 | 8.5 | 290 | 210 | 200 | 150 | 110 | 140 | 650 | 1840 |
| $1 \cdot 10^3$ | 71 | 13 | 11 | 13 | 360 | 315 | 270 | 190 | 110 | 120 | 200 | 520 |
| $3 \cdot 10^3$ | 104 | 18 | 15 | 19 | 520 | 510 | 460 | 201 | 120 | 130 | 160 | 350 |
| $1 \cdot 10^4$ | 150 | 24 | 22 | 28 | 360 | 340 | 310 | 230 | 100 | 120 | 170 | 230 |
| $3 \cdot 10^4$ | 190 | 33 | 27 | 36 | 250 | 235 | 210 | 160 | 70 | 80 | 110 | 160 |
| $1 \cdot 10^5$ | 130 | 34 | 29 | 38 | 170 | 150 | 140 | 110 | 50 | 50 | 70 | 100 |

determined, as shown above, from experimental results for only a single transport coefficient (the drift velocity in the present case), a comparison of the calculated and experimental values of any other quantity, for example the characteristic energy, also provides a valuable check on the correctness of the analysis method and on the calculated cross section.

## MEAN ENERGY AND ELECTRON DIFFUSION COEFFICIENT

After the electron distribution function has been determined and the connection between its parameters and the experimental values of $B$ and $\alpha$ established, there is no difficulty in calculating the mean energy and the diffusion coefficient for electrons. The results of the calculations are shown in Fig. 8 and in Table II. Over the temperature range studied, the mean electron energy in the liquid increases monotonically with increasing temperature in line with the reduction in $\sigma_0$ and $\sigma_1$. In crystalline xenon the mean energy is practically independent of temperature in the range 80 to 160 K. At the liquid-crystal transition, $\bar{\varepsilon}$ in argon increases while in xenon it decreases slightly.

Only the characteristic energy $D/\mu$ in liquid argon in the range of fields 2 to 10 $kV \cdot cm^{-1}$ has been determined experimentally.[25] We used the Townsend relation in the form

$$D/\mu = F\bar{\varepsilon}$$

to compare $\bar{\varepsilon}$ and $D/\mu$, where $F$ is a dimensionless coefficient. In weak fields, obviously, $F = \frac{2}{3}$. If $\varepsilon \gg kT$, in general $F$ depends on $\varepsilon$. Calculation gives $F = 0.82$ in liquid argon for $E \sim 10^3$ $V \cdot cm^{-1}$, so that $\bar{\varepsilon} \approx 1.2 D/\mu$. Taking this into account, the agreement between the experimental values of $\bar{\varepsilon}$ and those calculated by us is very good.

Finally, if we consider how the accuracy in the measurement of drift velocity and mobility $\mu_0$ influences the results of subsequent calculations, it follows from the relations

$$\bar{\varepsilon} \sim \left(\frac{V\mu_0 E}{\alpha+1}\right)^{2/3} T, \quad D \sim \left(\frac{VE\mu_0}{\alpha+1}\right)^{5/3} \frac{T}{\mu_0 E^2}$$

that every percent error in measuring $\alpha$, $V$, $E$, $\mu_0$ and $T$ introduces an error of several percent in $\bar{\varepsilon}$ and especially in $D$.

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Translated by R. Berman