Measurement of the Electric Conductivity of a Dense Strongly Nonideal Cesium Plasma

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Results of measurement of the electric conductivity of a dense highly nonideal ($\gamma = e^2 n_e^{1/3}/kT \geq 1$) cesium plasma carried out on two types of experimental arrangements are presented. One assembly is of the "resistance oven" type and the other is a pulsed type of assembly. The experiments are performed at temperatures from 1000 to 10,000 K and pressures from 130 to 350 atm. The results of the experiments show that heating of a dense plasma results in a sharp drop of the electric conductivity in the vicinity of the low temperature $T \approx 2000°$; at higher temperatures $5000° \leq T \leq 10{,}000°$K the electric conductivity becomes anomalously high, close to the values of the metal. There are indications that with increase of pressure the electric conductivity drop decreases. A brief analysis of the physical effects which may occur in the plasma under the conditions of the experiments is presented.

EXPERIMENTAL investigation of the dependence of the electric conductivity on the temperature and pressure is of great significance for the study of the kinetics of the dense strongly nonideal plasma ($\gamma = e^2 n_e^{1/3}/kT \geq 1$). Information on the electric conductivity makes it possible to obtain information on the structure (short-range order) of the plasma, on the energy spectrum of the electrons, and also on quantum-mechanical phenomena peculiar to dense strongly heated media. From the methodological point of view, the electric conductivity is among the plasma properties most accessible to experimental research. This is of no little significance in the study of the dense plasma, since measurements under high-pressure and high-temperature conditions are extremely difficult.

We have investigated the dependence of the electric conductivity of a dense strongly nonideal cesium plasma on the temperature and pressure. The measurements were performed with plasma sources of two types:

1) A stationary setup of the "ohmic oven" type, with which we measured the electric conductivity at low temperatures $1000 \leq T \leq 2500°$K at a pressure $P = 150$ atm; 2) a pulsed setup with the plasma stabilized by a solid transparent wall, on which high-temperature measurements were performed ($T \leq 10\,000°$K, $130 \leq P \leq 350$ atm).

The experiments were performed on cesium in the transcritical state. Cesium, the atom with the largest diameter (smallest ionization potential) is the optimal substance for an experimental investigation of the joint action of pressure and temperature on the equilibrium properties and the kinetics of charged particles in a dense plasma.

1. EXPERIMENTS WITH A STATIONARY SETUP OF THE "OVEN" TYPE

A schematic diagram of the working unit, which is placed inside the high-pressure vessel, is shown in Fig. 1. The measuring section is a cylindrical volume 1 of 9 mm diameter and 15 mm height, made up of a tantalum ampule 2 with wall thickness 2 mm and low-heat-conductivity body 3 with tantalum end piece. A hole 4 of 1 mm diameter and 6 mm length, imitating a black body and intended for optical measurements of the temperature of the investigated volume of cesium, is drilled in the lower part of the measuring volume of the ampule.

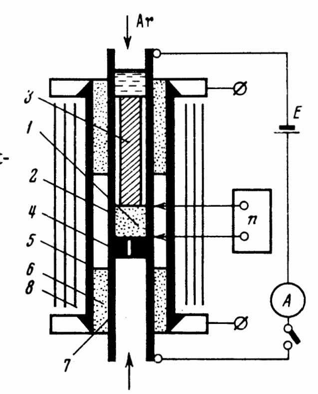

FIG. 1. Schematic diagram of setup of the "resistance oven" type: 1—measuring section, 2—ampule, 3—heat-insulating body, 4—"black body" hole, 5—heater, 6—heat-resistant insulating sleeve, 7—protective tube for pyrometry, 8—heat screens.

The ampule is placed inside a graphite heater fed from an alternating-current source, in such a way that the measuring section of the ampule is in the homogeneous section of the temperature field of the oven. The influence of conductive streams on the temperature field of the measuring section 1 and on the optical image of the hole 4 is eliminated during the pyrometry by using insulating heat-resisting sleeves 6 and continuing the ampule by means of a tube 7.

The resistance of the measuring section 1 was measured by a four-point method. In addition to measuring the potential drop U produced by the flow of the measuring current i, we monitored the thermal emf U_0. The true potential drop due to the flow of the current through the measuring section 1 was determined by subtracting the thermal emf, taken with the proper sign, from the measurements of the potential difference. In the chosen measurement setup, the resistance of the cesium plasma was shunted by the resistance of the ampule material, which was measured for all the employed temperatures prior to filling the ampule with cesium, and also during the time of the experiments, by dropping the argon pressure and retaining the temperature regime of the heater, which was tantamount to making the cesium vapor nonconducting.

Table I

T, °C	i, A	U, mV	U_0, mV	σ_{Ta}, (ohm-cm)$^{-1}$	σ_{Cs}, (ohm-cm)$^{-1}$
980	42.3	3401	555	$1.885 \cdot 10^4$	$4.49 \cdot 10^3 \pm 10\%$
1350	32.3	3384	842	$1.49 \cdot 10^4$	$1.82 \cdot 10^3 \pm 10\%$
1680	32.4	4602	830	$1.226 \cdot 10^4$	$7.42 \cdot 10^2 \pm 20\%$
2080	32.0	8312	−851	$1.036 \cdot 10^4$	$5.76 \cdot 10^2 \pm 26\%$
2200	31.8	8166	−1356	10^4	$1.45 \cdot 10^2 \pm 31\%$

The electric conductivity of the cesium was determined from the expression

$$\sigma = \frac{l}{S} \frac{R_{Ta} - R_{\Sigma}}{R_{Ta} R_{\Sigma}},$$

where l is the length, S the cross section area, and R_{Ta} the resistance of the tantalum wall, and R_{Σ} is the total resistance of the measuring section. The error in the measurement of σ at $T \leq 2000°K$ was 10%.

One of the difficulties arising in the performance of measurements of this type is the allowance for the anomalous growth of the thermal emf of the dense plasma with increasing temperature. Whereas at 1000–1800° the thermal emf does not exceed 400 mV at a growth rate 0.5–1.5 mV/deg, at $T > 1800°K$ the growth rate is approximately 15 mV/deg and the emf at $T = 2300°K$ is 4000 mV. Such behavior of the thermal emf of a dense plasma agrees with the calculated estimate.[1] The superposition of the thermal emf on the true potential difference causes a sharp deterioration in the measurement accuracy with increasing temperature, and the error reached 100% at T = 2400°K. The measurement results are listed in Table I.

2. EXPERIMENTS WITH PULSED SETUP

The purpose of the experiments performed with the pulsed setup was to investigate the behavior of the electric conductivity of a dense strongly nonideal plasma at temperatures greatly exceeding the melting temperature of high-melting point materials ($T \geq 3000°K$). The schematic diagram of the plasma source and of its electric system is shown in Fig. 2a. The main element of the source is a thick-walled quartz tube 1 (with inside diameter 0.7 mm and length l = 20 mm), hermetically clamped between two copper electrodes 2. Liquid cesium is poured under the tube and into the tube itself at the start of the experiment. A volume 4 is left free over the tube for the cesium to expand freely during the course of heating. Pressure is produced over the surface of the cesium by spectrally pure argon and is maintained constant during the course of the experiment. The cesium in the quartz tube is heated by a current pulse shaped by an electric circuit (see Fig. 2a) consisting of a capacitor bank with total capacitance 5000 μF, charged to 400–600 V, an inductance, and a controlled thyristor.

During the course of the experiment, the currents i calculated from the voltage drop across the shunt R, and the voltage U picked off the discharge gap, are recorded with a cathode-ray oscilloscope. At the present time, direct measurement of the temperature field of the plasma is impossible, since the plasma produced is not transparent. It is easy to verify, however, that the dense-plasma source described above ensures in all probability a homogeneous temperature field.

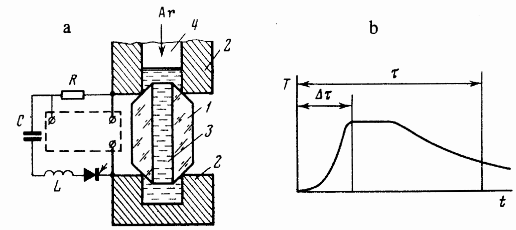

FIG. 2. a) Schematic diagram of pulsed setup: 1—quartz tube, 2—current leads, 3—liquid cesium, 4—argon cushion. b) Schematic time dependence of the plasma temperature.

The radial homogeneity is brought about by the fact that the thermal-conductivity coefficient of a dense cesium plasma is much larger than the thermal conductivity coefficient of the quartz in the entire temperature range (metallic heat conduction at low temperature and radiative at high temperature). In addition, since the electric conductivity decreases with increasing temperature, at least in the low-temperature region, it follows that the volume heat release accompanying the flow of current through the cesium is larger in this case on the periphery of the discharge than at the center, and therefore equalizes the possible radial temperature gradient. Under these conditions, a strong temperature gradient should develop in the tube material (the heating of the tube material is essentially a nonstationary process), and the temperature in the plasma column is high and probably practically constant over the radius. Heat loss from the wall is apparently prevented also by the doubly-charged (thermoelectric) layer produced on the plasma-quartz boundary.[2] This is qualitatively confirmed by the magnified photograph of the quartz tube at the instant of the discharge (Fig. 3a), which shows clearly the zones of heating of the quartz and of the plasma column. The longitudinal temperature homogeneity is the result of the spatial and chemical homogeneities of the liquid cesium column filling the tube at the beginning of the experiment. High-speed motion pictures have shown that a heating regime in which the plasma column is longitudinally homogeneous can be attained.

To produce a stationary, homogeneous, and sufficiently "long-lived" plasma column by the proposed method it is necessary to choose correctly the characteristic plasma heating time $\Delta\tau$ and discharge time τ (see Fig. 2b). On the one hand, the discharge duration τ should be sufficiently short to prevent the temperature waves from penetrating too deeply into the tube material, for this can lead to damage to the tube during the experiment, to considerable absorption of the radiation, and to contamination of the plasma by diffusing particles of molten quartz.

On the other hand, the heating time $\Delta\tau$ should be long enough to satisfy the following conditions:

1. Isobaric expansion of the plasma ($P_{pl} = P_{Ar}$). This means that the pressure drop due to the inertia of the plasma ($\sim \Delta\tau^{-2}$), to viscous friction and surface tension ($\sim \Delta\tau^{-1}$), and to wave losses (the plasma velocity on leaving the tube should be subsonic) should be small compared with the absolute value of P_{Ar}.

2. The plasma should be isothermal, $T_e = T_i$, meaning that $\Delta\tau \gg \tau_{rel}$, where τ_{rel} is the relaxation time of the electrons in the plasma.

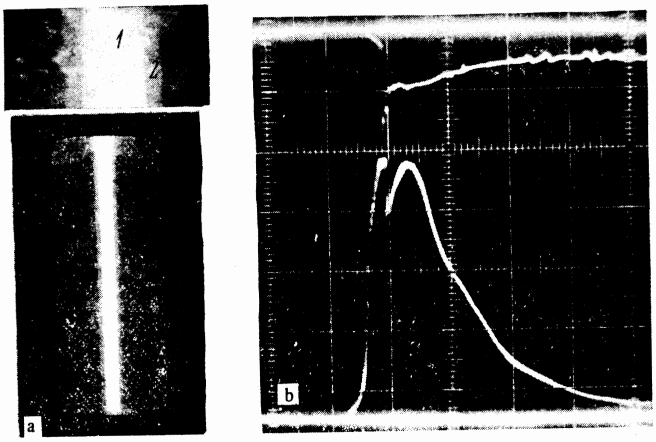

FIG. 3. a) Photograph of discharge: 1—plasma column, 2—heated quartz. b) Oscillogram of discharge at P = 170 atm; top—voltage (U) scale 50 V/cm, bottom—current (i) scale 75 A/cm; time (t) scale 5 msec/cm.

3. The discharge should not be subject to skin effect.
4. The thermal conductivity in the plasma should be radially stationary: $\Delta\tau > \rho C_p \lambda^{-1}(\Phi/2)^2$, where ρ, C_p, λ, and Φ are respectively the density, specific heat, thermal conductivity, and diameter of the plasma column.

Numerical estimates show that the foregoing conditions are satisfied at $\tau \leq 10^{-2}$ sec and $\Delta\tau \geq 3 \times 10^{-3}$ sec. These characteristic times were ensured in the present experiments. The electric conductivity was calculated from the current-voltage characteristics using the formula

$$\sigma = \frac{4l}{\pi\Phi^2}\cdot\frac{i}{U}.$$

Since the generated optically-dense plasma was assumed to be homogeneous, its temperature was estimated from the energy balance under the assumption that the plasma is an absolutely black body. That the radiation corresponds to that of a gray body was verified by photometry of the discharge spectrogram and by comparison with the spectrum of a standard lamp in the 4000–8000 Å range. The measurement data are given in Table II. The maximum random error in the measurements of the electric conductivity does not exceed 25%.[1)] The temperature-measurement error is estimated at 10%.[2)]

3. DISCUSSION OF MEASUREMENT RESULTS

The results of the electric-conductivity measurements obtained in the present study are shown in Fig. 4, which contains also the data of [3,4,8], with which the present results are in qualitative agreement.

The σ(T) plot shows that at low temperatures ($T \sim T_{cr}$) there is a sharp decrease of the electric conductivity with increasing temperature at constant pressure. At high temperature ($T = (6-10) \times 10^3$ °K) the absolute value of the electric conductivity is larger by almost two orders of magnitude than the classical conductivity[5] and approaches the conductivity of a metal. It is interesting to note that an increase of the conductivity with increasing temperature is observed for P = 130–170 atm in the temperature region T ~ 8000°K, and the inverse dependence is observed for P = 350 atm at T ~ 5000°K. The observed dip in the electric conductivity apparently decreases with increasing pressure, as shown qualitatively by the shading in Fig. 4.

The nonmonotonic temperature dependence of the electric conductivity of a strongly nonideal plasma should also give rise to an essential nonmonotonicity in the current-voltage characteristics of the discharge during the course of heating of the plasma. Such a phenomenon was observed regularly in the experiments with the pulsed installation, as is evidenced by Fig. 3b, which shows one of the characteristic oscillograms illustrating this fact.

The behavior of the electric conductivity of a dense plasma is determined primarily by the concentration of the conduction electrons: at low temperature, the decrease of the plasma density due to the growth of the temperature at constant pressure leads to a vanishing of the overlap of the ground-state energy levels of the cesium atoms, to a smaller decrease of the ionization potential connected with the polarization interaction of the electron-atom and electron-ion type[6] and to an in-

Table II

i, A	U, V	$\sigma\cdot10^3$, (ohm-cm)$^{-1}$	T, °K
P = 130 atm			
124	35.0	1.95	7050
192	38,5	2.70	7300
228	41.7	3.24	7750
P = 170 atm			
178	27.0	3.45	7150
320	41.5	4.0	8050
352	40.1	4,6	8800
P = 350 atm			
97.6	9.35	5.4	4150
124	15.0	4.3	4960
160	19.3	4,3	5780

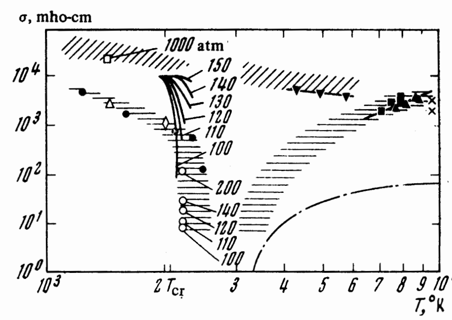

FIG. 4. Temperature dependence of the electric conductivity of a dense nonideal plasma. Our data: ●—150 atm ("oven"-type installation); ■—130 atm, ▲—170 atm, ▼—350 atm (pulsed installation); data of [3]: △—25 atm (liquid), ◇—200 atm, ○—100–200 atm (recalculation), □—1000 atm, X—[8]; continuous curves—according to [4], dash-dot—calculation for the case of an ideal plasma (extrapolation of [5] to 100 atm). Horizontal shading—assumed behavior of electric conductivity at P = (1–2) × 10^2 atm; inclined shading—the same for larger pressures.

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1)The latter consists of the errors in the measurement of the current (10%) and the diameter and length (5%), and is practically the same for all measurements.

2)This estimate does not contain the error due to the deviation of the degree of blackness of the plasma from unity, which is difficult to estimate, but this error can hardly change fundamentally the conclusions of the present work, in view of the weak sensitivity of the temperature to the degree of blackness ($T \sim \epsilon^{1/4}$).

crease of the energy barrier between the atoms and the ions, i.e., to a decrease of the quantum-jump probability. All three effects cause an exponential lowering of the conduction-electron concentration. However, with further increase of the temperature, the concentration of the conduction electrons can increase strongly as a result of the filling of the "bands" corresponding to the excitation levels of the atoms.[7]

This phenomenon, however, can hardly account completely for the anomalously large value of the electric conductivity of the dense cesium plasma, observed in the present experiments in the $5 \times 10^3 \leq T \leq 10\,000°K$ band, since at these temperatures the cesium is already fully ionized thermally, and therefore the "band" mechanism does not lead in practice to an increase in the concentration of the conduction electron. It is probable that the nonideality of the plasma, which causes the short-range order of the ions, will affect the conduction-electron mobility itself.

It is of interest in this connection to compare our results with Robinson's experimental data[8] on the measurement of the electric conductivity of water vapor at $T = 10^4 °K$ and $P = 10^5$ atm ($n \sim 10^{23}$ cm^{-3}). As shown in Fig. 4, the results of both investigations agree in order of magnitude, in spite of the difference between the nonideality parameters:

$$\gamma_{H(O)} / \gamma_{Cs} \approx 6-7.$$

It is curious to note that the ratio of the dimensions of H(O) and Cs is equal to the ratio of the average distances between particles ($n^{-1/3}$) in both experiments, i.e.,[3)]

$$\frac{r_{Cs}}{r_{H(O)}} = \frac{3.5 \cdot 10^{-8}}{0.56 \cdot 10^{-8}} = 6.3, \qquad \left(\frac{n_{H(O)}}{n_{Cs}}\right)^{1/3} \sim \left(\frac{10^{23}}{3 \cdot 10^{21}}\right)^{1/3} = 6.7.$$

It is possible that the latter is an indication that quantum effects connected with the structure of the ions play an important role in the kinetics of the conduction electrons of a dense plasma under these conditions.

The authors take the opportunity to thank V. A. Ryabyĭ and B. M. Kovalev for useful discussions and for help with the experiments.

[3)]At $T \sim 7000°K$ and $P \sim 200$ atm, the density of the cesium plasma estimated according to [9] equals 3×10^{20} cm^{-3}. This estimate agrees with the experimental results obtained in a shock tube in[10].

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