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Electric conductivity of a non-ideal plasma

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Results are presented of measurements of the electric conductivity of a dense plasma with strong interparticle Coulomb interaction. Experiments with air, neon, argon and xenon were carried out with an explosive nonideal-plasma generator. A four-point probe recording technique was used. The Coulomb component of the electrtic conductivity is compared with that predicted by theories of a non-ideal plasma.

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1. INTRODUCTION

Electric conductivity is one of the most essential plasma characteristics that determine its dissipative heating and the interaction with the electromagnetic field in the operation of magnetohydrodynamic and magnetocumulative generators, thermonuclear, laser, and other pulsed devices that require a considerable energy concentration.[1] In view of the high charge density, the average electrostatic-interaction energy turns out to be of the order of the kinetic energy of particle motion, so that deviations of the plasma from ideal determine the equilibrium and kinetic properties of such a medium.[2]

At the present time, a consistent theoretical calculation of the transport characteristics of disordered electron systems can be carried out only in the case of weak interaction at $\Gamma = e^2/kTr_D \ll 1$ $(r_D = \sqrt{kT/8\pi n_e e^2})$ on the basis of the kinetic equations or by the method of time-dependent correlation functions.[3,4] As the deviation from ideal increases, however, it becomes quite difficult to justify the initial kinetic equations and the methods for their solutions. In particular, in view of the strong collective interaction in a dense plasma it is impossible to separate unambiguously the characteristic times of the elementary processes, and the time of evolution of the system under the influence of an external field is no longer, generally speaking a Markov process.[4] Allowance for the bound states in a partly ionized plasma[3] constitutes a special problem, owing to the absence of the corresponding kinetic equations and transport cross sections that would permit the use of approximate semi-empirical methods. The results of the theoretical calculations of the low-frequency $(\omega_2 \lesssim \omega_p^2 = 4\pi n_e e^2/m_e)$ conductivity of the plasma therefore begin to differ noticeably starting with $\Gamma \sim 0.1$.[5] Extrapolation of these theories to the region $\Gamma \gtrsim 1$ of increased deviation from ideal, as a rule, leads to unphysical divergences that are connected with the use of a finite number of Sonine polynomials when solving the corresponding kinetic equations by the Chapman-Enskog method.

The difficulties in the experimental study of the electrophysical properties of a non-ideal plasma are connected with the need for highly concentrating the energy, and with the absence of well-developed methods for measurements in optically dense media. The region of parameters up to $\Gamma \sim 0.7$ can be reached relatively easily in stationary (see[5]) and in pulsed[6–9] experiments, the results of which, however, frequently contradict each other because of considerable experimental errors and interpretation inaccuracies.[10] The transition to increased deviations from ideal entails great difficulties in the generation and the diagnostics of the plasma. The number of pertinent experiments is quite limited[11–15] and most are of qualitative character, in view of the lack of directly recorded and reliable information on the physical parameters of the plasma.[11–13]

We present here the results of the measurement of the electric conductivity of a dense low-temperature plasma in a wide range of non-ideality parameters $\Gamma \sim 0.3–4.5$. The absence of complicated molecular and ion-molecular formations, the fact that the cross sections of the elementary processes have been investigated in detail, and the high molecular weight have dictated the choice of inert gases as the investigation

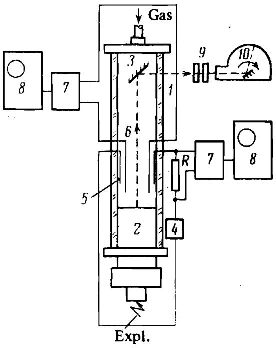

FIG. 1. Schematic diagram of conductivity measurement. 1—channel of explosive shock tube, 2—explosive charge, 3—mirror, 4—dc source, 5, 6—current and potential electrodes, 7—differential amplifiers, 8—oscilloscopes, 9—optical system, 10—high-speed motion picture camera.

objects. The latter circumstance makes the dynamic heating of these gases effective, so that a plasma with high degree of ionization can be obtained, thereby decreasing the uncertainty concerning its thermodynamic composition, and most importantly, making possible a reliable separation, from the measurement results, of the Coulomb component of the conductivity due to the scattering of electrons by the charged particles. The experiments were performed with different gases (xenon, argon, neon, air) and in parameter ranges that overlapped partially both with one another and (in the weakly non-ideal region) with other measurements. This made it possible to trace the variation of the conductivity for a wide and continuous variation of the Coulomb interaction in the system.

2. PLASMA GENERATION AND DIAGNOSTICS

In view of the need of high energy concentration, we used for the generation of a strongly non-ideal plasma a dynamic method[16] based on compression and irreversible heating of the gas in the front of a high-power ionizing shock wave. To produce shock waves of optimal intensity in pre-compressed gases we used an explosive non-ideal plasma generator[16] with a high-power condensed explosive as the active element (Fig. 1). The shock wave was produced by the expansion of the products of the explosive detonation in the investigated gas; these products had high initial parameters (after completion of the detonation in the condensed phase), namely $P \sim 300$ kbar, $T \sim 5\times10^3$ °K, and $\rho \sim 2.3$ g/cm^3. The flow of the shock-compressed plasma was made one-dimensional and quasistationary by a suitable choice of the dimensions of the generator elements (the diameter of channel 1 was 6 cm, and the thickness of the glass wall was 0.5 cm) and of the parameters of the active charge 2. The hydrodynamic properties of the generator operation, and also the homogeneity and thermodynamic properties of the non-ideal plasma cluster were investigated beforehand by optical[16] and x-ray diffraction[17] methods. The presence of a high-power explosive charge has caused the generator to be destroyed in each experiment, and called for appropriate measures to protect the measuring apparatus. The physical parameters of the shock-compressed plasma were varied by changing the initial gas pressure P_0 and the distance from the measurement section to the explosive charge.

The shock-wave front velocity D was determined in a special series of experiments by optical and electric-contact basic methods with accuracy ~1.5%. In addition, the construction of the measuring electrodes has made it possible in each experiment to measure, besides the electric conductivity, also the shock-wave velocity.

The high electric conductivity and the short ($\sim 5\times10^{-6}$ sec) lifetime of the shock-compressed plasmoid result in a plasma skin-layer thickness of several millimeters, making it impossible to use electromagnetic methods to measure the conductivity, in view of the considerable crowding out of the external magnetic field by the plasma. We measured the electric conductivity with a four-point probe method (see Fig. 1), which had a high spatial resolution and was relatively simple to realize under conditions of a one-shot dynamic experiment. The transport electric current I from a specially developed source 4 was applied to the plasma by copper electrodes 5 placed along the shock-tube channel. To improve the dynamic characteristics of the system, the stabilized current source was placed in the immediate vicinity (at an approximate distance of 1 m) of the explosive generator. The voltage drop due to this current was registered by potential electrodes 6 placed parallel to the plasma stream; these electrodes were connected to the inputs of differential amplifiers 7 with input resistances (~1 MΩ) much larger than the plasmoid resistance. Such system leads to small electric currents in a measurement circuit and consequently to negligible voltage drops in the vicinity of the measuring electrodes 6, which in this case registered the true potential difference in the plasma. To exclude the distortion due to the electric layers at the electrodes, the potential probes were located 1 cm away from the nearest current electrode,[1)] a distance greatly exceeding the electric-potential inhomogeneities due to the phenomena next to the electrodes when a large ($\sim 10^3$ A) transport current is fed to the plasma. To eliminate the electric noise, the current and potential measurement systems were at a floating potential relative to ground.

The geometric factor that takes into account the spreading of the stream lines was measured in a special series of calibrating experiments under stationary conditions using $NiSO_4$ and NaCl electrolytes and in a dynamic regime using shock-compressed air[18] and the detonation products of condensed explosives.[19] The plasma-mirror dimensions needed to determine the electric conductance were determined on the basis of x-ray diffraction and optical experiments,[17] and were additionally monitored against gas dynamic calculations.[20]

The working voltage applied to the current electrodes varied from 10 to 300 V, a range in which the isothermal character of the plasma was not disturbed ($eEl/kT \ll 1$, where l is the electron mean free path in the field E). Figure 2 shows plots of the voltage drop U in the plasma, measured in dynamic experiments, against the transport current I. The practically linear character of the current-voltage characteristics shows that in this diagnostic scheme the measured electric conductance is not influenced by electric phenomena

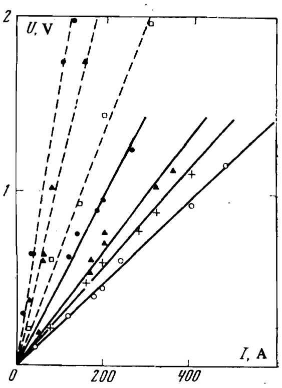

FIG. 2. Current-voltage charactersitics of plasma gap. Dashed—argon, solid curves—xenon. Initial pressure P_0 (in bars): ●—1, ▲—3, □—10, +—15, ○—20.

TABLE I. Results of measurement of the electric conductivity of a non-ideal plasma.

Gas	P_0, bar	D, km/sec	T, 10^3 K	P, bar	Γ	n_e, cm^{-3}	n_0, cm^{-3}	σ, $\Omega^{-1}\cdot$cm^{-1}	σ_K $\Omega^{-1}\cdot$cm^{-1}	$\bar{\sigma}_K$
Ar	0.25	8.4	22.2	270	0.55	$2.8\cdot 10^{19}$	$3.0\cdot 10^{19}$	185	190	0.37
	1	6.9	20.3	700	0.84	$5.5\cdot 10^{19}$	$1.4\cdot 10^{20}$	150	155	0.35
	3	6.0	19.3	1550	1.10	$8.1\cdot 10^{19}$	$4.0\cdot 10^{20}$	160	170	0.42
	10	5.5	19.0	4200	1.50	$1.4\cdot 10^{20}$	$1.3\cdot 10^{21}$	225	255	0.64
	20	5.0	17.8	6800	1.82	$1.7\cdot 10^{20}$	$2.4\cdot 10^{21}$	210	245	0.67
Xe	1	6.4	30.1	2000	1.06	$2.5\cdot 10^{20}$	$3.7\cdot 10^{19}$	445	450	0.57
	3	5.5	27.5	4400	1.82	$5.9\cdot 10^{20}$	$1.9\cdot 10^{20}$	655	680	0.98
	5	5.2	27.0	6700	2.17	$7.9\cdot 10^{20}$	$4.0\cdot 10^{20}$	685	740	1.09
	10	5.0	26.1	12500	3.03	$1.4\cdot 10^{21}$	$8.0\cdot 10^{20}$	630	690	1.07
	15	4.6	25.1	15000	3.45	$1.6\cdot 10^{21}$	$1.6\cdot 10^{20}$	670	780	1.28
	20	4.4	24.6	18500	3.98	$2.0\cdot 10^{21}$	$2.4\cdot 10^{21}$	820	1040	1.75
	30	3.9	22.7	21800	4.46	$2.0\cdot 10^{21}$	$3.9\cdot 10^{21}$	750	930	1.77
Ne	3	7.1	19.8	1000	0.41	$1.1\cdot 10^{19}$	$3.4\cdot 10^{20}$	100	130	0.31
	10	6.8	19.6	3000	0.54	$1.9\cdot 10^{19}$	$1.1\cdot 10^{21}$	100	165	0.40
Air	1	8.0	11.0	720	0.33	$1.3\cdot 10^{18}$	$4.8\cdot 10^{20}$	12	60	0.34

next to the electrodes, an influence that is the main shortcoming of probe measurements in a dense plasma. In the experimental setup the potential probes were ~3 cm longer than the current probes, making it possible to register in each experiment the shock-wave velocity D, thereby monitoring the reproducibility of the parameters and the operating quality of the explosive plasma generator. Approximate calculations and high-speed motion picture photography of the gas dynamic picture of flow around the probe system have shown that the electrodes do not become deformed during the measurement time and introduce no noticeable hydrodynamic perturbations in the plasma stream.

A typical oscillogram of the transport current (a) and of the voltage on the potential electrodes (b) is shown in Fig. 3. The oscillogram shows clearly the "mirror" of the shock-compressed plasma 3, the growth of which as the shock wave moves over the electrodes leads to a certain increase of the transport current (a).

3. MEASUREMENT RESULTS

Our aim was to investigate the electric conductivity of a dense low-temperature plasma in a wide range of non-ideality parameters from $\Gamma\sim 0.3$, where the differences between the theories are relatively small and the amount of experimental data is appreciable,[5] up to the experimenally univestigated region of extremely high $\Gamma\sim 4.5$, in which most theoretical approximations differ from one another. We note that the largest attainable values of Γ are close to the maximum possible ones for a nondegenerate plasma.[2] The investigated range of parameters was covered by experiments with different gases—air, neon, argon, and xenon. The maximal parameters were obtained in experiments with xenon, because of its relatively small ionization potential and high efficiency of xenon heating in the shock wave. The maximum values of Γ attained for each gas are determined by the energy capabilities of the active explosive charge and by the largest initial pressure P_0 ~20–30 atm that the glass walls of the shock-tube channel can withstand. The minimum values $P_0 = 0.25$ atm were chosen to facilitate stabilization of the instabilities of the contract surface[21] separating the detonation products from the plasma.

The experimental results are listed in Table I, where each point is the average of 5–10 independent reductions of the experimental current-voltage characteristics. The thermophysical properties of the shock-compressed plasma were calculated from the measured values of D within the framework of the Debye approximation in the grand canonical ensemble,[20] which agrees qualitatively with the experiments on cesium[22] and argon.[17] In the investigated range of parameters $P\sim 0.3$–20 kbar, $T\sim 10$–$30\cdot 10^3$ K, $n_e\sim 10^{18}$–$2\cdot 10^{21}$ cm^{-3} the plasma is not degenerate $(n_e\lambda_e^3\sim 10^{-3})$ and the interaction of the charged particles is decisive, whereas other forms of non-ideality, such as the ion-atom $(\gamma_{ia}=\alpha e^2 n_a^{1/3}/kT\sim 10^{-4})$, electron-atom $(\gamma_{ea}=\hbar^2 N/m_e kT\sqrt{\pi Q_{ea}}\sim 0.1)$, and atom-atom $(\gamma_{aa}=an/kT\sim 0.01)$, are less significant.2) In this case greatest interest attaches to the Coulomb component of the electric conductivity σ_C, which is due to scattering of the conduction electrons by the charges. The organization of the experiment ensured a sufficiently high degree ionization of the plasma. Thus, the measured electric conductivity was determined in practice by σ_C, thereby greatly simplifying the interpretation of the results, by decreasing the influence of the uncertainty in the thermodynamic composition of the plasma and of the inaccuracies in the transport scattering cross sections. The correction for the electron-atom collisions was introduced in an approximation additive in the collision frequency, and the applicability of this approximation was monitored against calculations by Frost's semiempirical method.[10] In view of the smallness of this

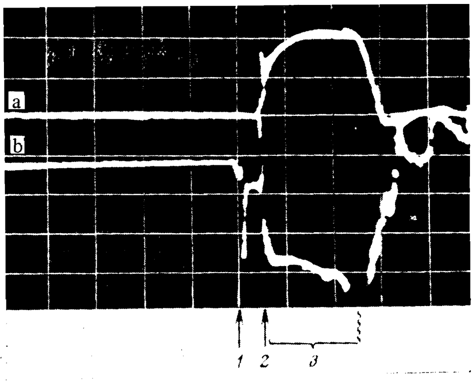

FIG. 3. Oscillograms of the current (a) and voltage (b). Sweep 2.5×10^{-6} sec/div. 1) Arrival of plasma at the potential electrodes, 2) shock-wave front, 3) region of shock-compressed plasma.

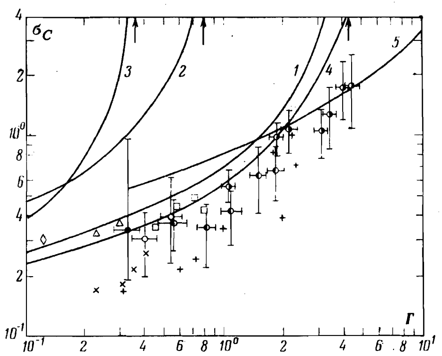

FIG. 4. Dependence of the Coulomb component of the electric conductivity of the plasma on the non-ideality parameter. Our data are represented by circles: ◐—argon, ◑—xenon, ○—neon ●—air. □—[16], ◇—[7], △—[8], ×—[15].

correction, we neglected in the estimates of the conductivity of the electron-atom subsystem the scattering by the excited atoms (in the Born approximation[23] this contribution is less than 3%), the quantum interference effects ($n_a \lambda_e Q \sim 10^{-2}$), the effect due to the non-paired character of the scattering, and the influence of the spatial correlations of the scattering centers with proper dimension R, $nR^3 \sim 10^{-2}$. The experimental data on the averaged transport scattering cross sections were taken from[5]. The value of σ_C for shock-compressed air was separated by using the data of[18] and is subject to considerable errors, in view of the low degree of ionization ($\sim 10^{-3}$).

The data for the electric conductivity are plotted in Fig. 4 in dimensionless coordinates, the abscissa representing the non-ideality parameter[3] Γ and the ordinates the dimensionless conductivity $\bar{\sigma} = 1.48\,\sigma_C/e^2\sqrt{2\pi(kT)^3 m_e}$. The figure shows also a comparison of our results (circles) with those obtained by others and with a number of theoretical models. Curve 1 corresponds to the Spitzer theory,[24] which is widely used in plasma calculations and is based on a numerical integration of the Fokker-Planck kinetic equation. By applying a diagram technique (with account taken of annular and ladder fragments) to the equations of motion for the time-dependent Green's functions, a kinetic equation was obtained in[25], in which account was taken of the interparticle interaction via a screened Coulomb potential; this equation is valid in first order in Γ (curve 2). The collective effects in the Coulomb interaction were taken into account in[26] on the basis of the Fokker-Planck equation for a single-particle function, where the collision integral contains all the moments of the distribution function (curve 3). It is characteristic that the use[25,26] of a finite number of Sonine polynomials in the Chapman-Enskog procedure for solving the corresponding kinetic equations leads in the actual calculations to deviations (noted by the arrows in Fig. 4) of the expressions for the electric conductivity at increased non-ideality parameters. In a dense plasma an important role can be played by ion-correlation effects that are peculiar to liquid metals and semiconductors and lead to simultaneous scattering of the conduction electrons by several charged centers. The ion correlations were taken into account in an approximation analogous to Ziman's theory,[27] using a Debye potential and a corresponding correlation function (grand canonical ensemble) (curve 4). The scattering of the charges was calculated in the Born approximation with a screened Debye potential; the electron-electron interaction was accounted for by Spitzer's method.[24]

From a comparison of the theory with experiment it follows that Spitzer's theory seems to describe satisfactorily the behavior of the electric conductivity up to $\Gamma \sim 0.1-0.6$. In the region $0.6 \lesssim \Gamma \lesssim 4.5$ the measured values of the electric conductivity are finite and lie below curve 1 (see in addition[13,15]), whereas the more rigorous theories (curves 2, 3)[25,26] predict an increase of the electric conductivity with increasing Coulomb interaction. This behavior of the electric conductivity in a strongly non-ideal plasma can have different causes. The decrease of the electric conductivity can be due[5] to an increase in the cross sections of the Coulomb collisions in comparison with the results of the theoretical estimates, which predict in the region $\Gamma \gtrsim 1$ anomalously small screening radii—in our conditions $r_D \sim 10^{-8}$ cm. It appears that the interaction becomes renormalized in a dense plasma and the correlation radius of the charges is of the order of the interparticle distance ($r_0 \sim n^{-1/3} \sim 10^{-7}$ cm), just as in the case of metals and semiconductors.[28] The corresponding model[28,29] used successfully to describe the scattering of conduction electrons by impurity ion centers of doped semiconductors is labeled 5 in Fig. 4. On the other hand, the spatial correlation of the charges, together with a certain decrease of σ_C in accordance with the model of curve 4[27] can lead to a qualitative decrease of the number of carriers in view of their partial localization in the dense plasma.[30] The effective electroconductivity of the plasma may also be underestimated because of a decrease of the external electric field acting on the charge, in view of the screening of the electrons in a dense plasma.[3] An estimate of the influence of the quantum effects in Coulomb interaction ($\lambda_e/r_D \sim 1$) in accordance with[31] also yields a negative correction to the electroconductivity of the plasma, the value of which, however, does not exceed 10% under our conditions. The non-Coulomb character of the electron scattering in the ion field at short impact parameters leads to a decrease of the theoretical values of σ_C. However, allowance for this circumstance by the quantum-defect method[32] yields in the investigated range a correction smaller than 5%. In view of the serious difficulties of rigorously calculating theoretically the transport phenomena in a dense plasma, the experimental data can be described at present apparently only within the framework of model approximations.

The authors are grateful to L. V. Al'tshuler for useful discussions and remarks.

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[1] This distance was varied in a special series of experiments.

[2] Here $\lambda_e = \sqrt{\hbar^2/2\pi m_e kT}$, α is the polarizability of the atom and a is the van der Waals constant.

[3] The uncertainty in Γ, due to errors in the registration of D

and to inaccuracies of the thermodynamic composition of the plasma, is marked by horizontal bars in Fig. 4.

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Shock-wave production of a non-ideal plasma

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Experiments on generation of a non-ideal argon or xenon plasma by intense shock waves are described, and results of investigation of the equation of state of the plasma are presented. The experiments are performed with explosive generators of rectangular shock waves in which condensed explosives are employed as the active elements. A thermodynamically complete equation of state of the imperfect plasma is determined by recording the kinematic parameters of the shock wave and the temperature. The equation is compared with theoretical models.

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1. INTRODUCTION

The thermodynamic properties of a dense low-temperature plasma with strong interparticle interaction is presently the object of intensive theoretical and experimental research.[1] This is due to the need for a physical analysis and hydrodynamic calculation of the phenomena caused by intense pulsed energy release in dense media, which are the basis for the development of various prospective designs and devices.[2] At the same time, a non-ideal plasma occupies an extensive region of the phase diagram of matter, in which strong electrostatic interaction is decisive and can lead to various and qualitatively new physical phenomena and effects.[1]

In view of the considerable mathematical difficulties, the possibilities of a pure theoretical study of strongly interacting disordered electron-ion systems are quite limited, and to describe them thermodynamically it is necessary for the time being to resort to model considerations. Heuristic models of this type[1] are in fact extrapolations of ideas about the role of quantum and collective effects in Coulomb interactions, originally developed for the weakly non-ideal region, and the results are therefore highly uncertain. Much more