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Radiation emitted by a shock-compressed high-pressure argon plasma

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Results are presented of measurements of the coefficient of optical absorption of a non-ideal argon plasma produced by powerful ionizing shock waves. The experiments were performed with explosive generators of rectangular shock waves, using condensed explosives. The obtained radiation of the shock-compressed plasma turned out to be much less than theoretical. The "transparentization" of the plasma is explained by using a bounded-atom model that takes into account the deformation of the electron energy spectrum.

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1. INTRODUCTION

The solution of many present-day problems of radiation gasdynamics and plasma physics, such as laser irradiation,[1] hypersonic aerodynamics,[2] explosive light sources,[3] gas-phase nuclear reactors,[4] and others call for detailed information on the optical properties of a high-density plasma in which the effects of interaction between particles play an essential role. An investigation of the radiation of such a plasma is also of definite fundamental interest, since it makes it possible to trace the influence of deviation from ideal conditions on the dynamics and on the energy spectrum of a dense disordered plasma.

The theoretical premises developed to date[5] pertain to a tenuous plasma, where the elementary processes can be easily separated, and the influence of deviations from ideal conditions reduces to a broadening of the spectral lines and to shifts of the photorecombination thresholds. The region of increased densities has become the object of investigations only most recently (see Refs. 6–8), and the degree to which it has so far been investigated is patently insufficient. The data available at present correspond to non-ideality parameters $\Gamma = e^3(8\pi n_e)^{1/2}/(kT)^{3/2} \leq 0.2-0.3$, $n_e \leq 10^{18}$ cm^{-3} and are to a great degree contradictory, but indicate nevertheless that the continuum radiation exceeds the calculated value when the plasma is increased. At the same time, the plasms screening[9] and the strongly fluctuating microfields[10] can noticably distort the near-threshold region of the spectrum, by decreasing the intensity of the recombination radiation of the dense plasma.[7,8,11]

In this paper we measure the optical properties of a strongly non-ideal ($\Gamma \sim 1.6$) plasma obtained by compression and irreversible heating of a high-pressure gas in the front of a high-power ionizing shock wave (SW). The use of dynamic methods has made it possible to obtain a plasma with extremely high parameters in volumes that are homogeneous and of controllable dimensions. In addition, in view of the small dimensions of the zone of relaxation processes and of the small thickness of the viscous shock discontinuity, the optical radiation is capable of emerging unobstructed from the plasma volume and carries therefore information on the equilibrium properties of the shock-compressed plasma. The absence of complex molecular and ion-molecular formations, the fact that the electron energy spectrum in the elementary radiative processes has been investigated in detail, as well as the high molecular weight, have all dictated the choice of argon as the object of the investigation. In addition, extensive information on the gas dynamic, thermodynamic,[12,13] and electrophysical[14] properties of a dense argon plasma has by now been obtained, so that the state of the plasma can be assessed with great certainty and the interpretation of the optical measurements is greatly facilitated.

The use of explosive dynamic methods has made it possible to trace the influence of the non-ideality on the absorption coefficient of the plasma in a broad and continuously varying range from the previously investigated states with $n_e \leq 10^{18}$ cm^{-3} and $\Gamma \leq 0.3$ to the extremely high $n_e \sim 2\times10^{20}$ cm^{-3} and $\Gamma \sim 1.6$ ($P \sim 5000$ atm), where the effect of "transperentization" of the plasma manifests itself. This effect is interpreted in the present paper from the point of view of distortion of the energy spectrum of the strongly compressed atoms by the strong interparticle interaction.

For a qualitative description of this effect, we use the model of a "bounded" atom, based on a quantum-mechanical calculation of the wave functions of bound electrons in a self-consistent field, with a boundary condition that imitates the action exerted on the atom by the plasma environment.

2. EXPERIMENTAL TECHNIQUE

The absorption coefficient $\varkappa_\nu$ was measured by recording the increase with time of the intensity of the optical radiation emerging from a flat plasma layer contained between the SW front and the contact surface.[15] Since the photon relaxation time is short compared with the characteristic gasdynamic time, the spectral intensity of the radiation $I_\nu(t)$ of such a layer takes in the quasistationary approximation the form[16]

$$I_\nu(t)=I_{\nu p}(1-\exp\{-\varkappa_\nu'(D-U)t\}), \qquad (1)$$

where $I_{\nu p}=I_\nu(\infty)$ is the Planck radiation intensity, $\varkappa_\nu' =\varkappa_\nu(1-e^{-h\nu/kT})$ is the absorption coefficient corrected for the stimulated emission, and D and U are the velocities of the front and rear boundaries of the radiating layer and are known from gasdynamic measurements.

The experimental setup is illustrated in Fig. 1. To produce powerful SW in compressed argon we used linear explosive generators of square waves of varying amplitude and duration, with an action based on accelerating metallic strikers to several kilometers per second by the detonation products of powerful condensed explosives (see Ref. 17 for details). The collision between the accelerated striker and the condensed target (lead, Plexiglas, aluminum) produces in the latter a shock wave with a pressure of several hundred kilobars. Emergence of this shock wave to the free surface leads to an isentropic expansion of the target; the latter, acting as a piston and moving with velocity U, generates in the investigated gas an ionizing shock wave that compresses and heats the gas. During the stationary stage of the process, the shock wave front and the contact surface move with constant velocities D and U, so that the layer of the shock-compressed plasma expands with time linearly $[\delta\sim(D-U)t]$ and radiates in accordance with Eq. (1).

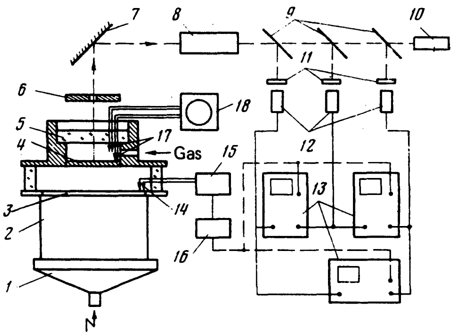

FIG 1. Experimental setup: 1—detonation lens, 2—explosive charge, 3—striker, 4—target, 5—transparent partition, 6—diaphragm, 7—mirror, 8—optical system, 9—semitransparent mirrors, 10—adjusting laser, 11—interference light filters, 12—photomultipliers, 13—recording oscillographs, 14—electric contacts that start the oscillographs, 15—pulse-shaping circuit, 16—delay line, 17—electric contacts for the measurement of the shock wave velocity, 18—OK-15 oscilloscope.

The main requirement that must be satisfied by this procedure, which is based on inertial containment of a high-pressure plasma, is to ensure conditions of homogeneity and stationarity of the flow in the registration zone, so that the measurement results can be interpreted by the simple relation (1) rather than by the complicated differential equation of radiation transport in the general form. To monitor the quasistationarity of the flow we perform gasdynamic calculations of the propagation of the shock waves and of the distorting relaxation waves emitted by various elements of the experimental setup.[18] The correctness of these calculations was checked in a special set of experiments by electric-contact and optical registration of the plasma motion at various distances from the target. We note that it is precisely the influence of the rear relaxation wave which limits the possibilities of this procedure on the low-density side, when the radiation range becomes comparable with the dimension of the quasistationary section of the flow.[1)] To eliminate the distorting influence of the side waves produced when the experimental assembly is scattered, the strikers, screens, and targets were made in the form of thin disks, and the registered radiation emerged through a diaphragm from a narrow (~2 mm) axial flow zone. The last circumstance decreased the effects of the curvature of the shock wave front.

The use of a specially shaped detonation lens and of an active explosive charge of sufficient dimensions, and the use of sufficiently high-grade material for the other elements of the generator made it possible to produce propelling devices having dynamic parameters reproducible within 2% and with a deviation of the shock-wave motion from synchronism not more than 10^{-7} sec in a target of 2 cm diameter. The intensity and the duration of the shock waves excited in the gas were measured by varying the brisance of the explosive and the thicknesses of the propelled plates.

The light from the plasma was directed to FÉU-30 multipliers with the aid of mirrors and an optical system, and the signals were recorded with high-speed oscilloscopes. The measurement system was triggered through delay lines by electric-contact sensors mounted on the screen and operating at the instant of the arrival of the shock waves.

The kinematic plasma parameters needed to determine the absorption coefficients were determined by optical and electric-contact base methods.[12] To this end, contacts were installed in the experimental assemblies and registered the time at which the shock wave traversed a specified distance. In addition, to register the velocities D and U and to monitor the reproducibility of the shock wave parameters, a transparent (Plexiglas, glass) partition was placed at a certain distance from the target. The emergence (1 in Fig. 2) of the shock wave from the target into the argon led to a smooth increase (2) of the optical radiation up to a saturation level in accordance with formula (1). The brightness burst 3 marks the time of arrival of the shock-wave front at the transparent partition, and consequently its

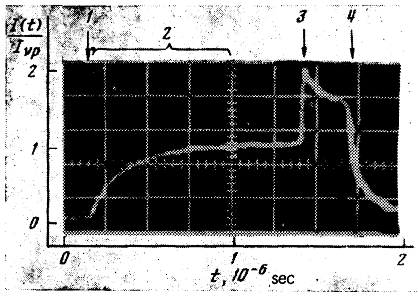

FIG 2. Oscillogram of experiments: 1—emergence of shock wave into the gas, 2—section where the radiation grows to saturation, 3—collision of shock wave front with transparent partition, 4—start of destruction of partition by the target material.

velocity D. The subsequent cutoff of the radiation (4) is due to destruction of the partition by the expanding massive target moving with velocity U.

We note that such an experimental procedure yields a rather diverse physical information. The increase of the intensity during the initial section of the flow determines the light-absorption coefficient, while the level of the radiation in the saturation stage I_{vp} determines the brightness temperature of the plasma.[3,12] Registration of the shock-wave reflection from the partition makes it possible to measure D and U; when account is taken of the mass, momentum, and energy conservation laws on the shock-front, this is equivalent to direct measurement of the pressure, density, and internal energy. The data obtained in this manner agree and supplement the results of special thermodynamic measurements.[12,13]

3. MEASUREMENT RESULTS AND THEIR DISCUSSION

To reveal the effects of the compression and to facilitate the interpretation of the results, the gasdynamic characteristics of the employed shock-wave generators were chosen such as to ensure approximate constancy of the temperature of the shock-compressed plasma, $T \sim 2 \times 10^4$ K. The frequency of the registered radiation, separated with an interference light filter, was $(5.17 \pm 0.05) \times 10^{14}$ sec^{-1}. To estimate the influence of the light flux reflected from the contact surface, a number of methodological experiments were performed, in which the reflecting properties of the piston were varied in wide range by varying the quality of its finish and by using different coatings. It turned out that under our conditions the reflection of the light from the piston can introduce an error not larger than 20% in the absorption coefficient.

The experimental values of the absorption coefficients, together with the parameters of the shock-compressed plasma, are listed in the table and are shown in Fig. 3, where each point was obtained by averaging 5–10 experiments with two or three independent oscillograms taken in each. The 1–2% accuracy in the measurement of D and U corresponds to errors on the order of 4 and 10% in the calculation of P and ρ from the conservation laws. Under the conditions of the dynamic experiment, the

TABLE 1. Experimental results.

$P\cdot10^{-3}$, bar	$T\cdot10^{-3}$, K	$n_a\cdot10^{-20}$, cm^{-3}	$n_e\cdot10^{-20}$, cm^{-3}	$\varkappa$, cm^{-1}	$P\cdot10^{-3}$, bar	$T\cdot10^{-3}$, K	$n_a\cdot10^{-20}$, cm^{-3}	$n_e\cdot10^{-20}$, cm^{-3}	$\varkappa$, cm^{-1}
0.13	18	0.19	0.13	10	1.8	20.5	4.0	0.74	56
0.27	19	0.50	0.22	22	2.8	20.6	6.2	1.0	73
0.40	19.4	0.81	0.28	27	3.7	20.5	7.8	1.2	100
0.64	19.7	1.4	0.38	31	5.1	20.4	10	1.5	150
1.2	20.3	2.7	0.57	45					

error in the measurement of the brightness temperature is 5–10%.[3,12] To estimate n_e and Γ we used the bounded-atom model proposed below, which describes the thermodynamic[12,13] and indirectly the electrophysical[14] in a non-ideal plasma. The error of such an estimate of n_e amounts to 20–30%. The error in the measurement of the absorption coefficients is determined mainly by the possibilities of amplitude and time resolution of the signals and is estimated at 30–40%. This conclusion is confirmed independently by a comparison (see Fig. 3) of our measurements with estimates based on Refs. 3 and 20.

The range of shock-wave velocities was chosen such as to ensure sufficiently high degrees of ionization of the plasma and to realize experimental conditions that are nearly optimal with respect to the Coulomb interaction.[17] At the same time, the shock wave amplitudes reached in the experiments are not high enough to heat noticably the gas in front of the shock wave by ultraviolet radiation, which would lead to screening of the radiation from the shock-compressed plasma. According to the measurements of Ref. 3, this effect manifests itself in atmospheric-pressure argon at $D \gtrsim 14$ km/sec and decreases with increasing initial gas pressure. The fact that the sidewalls of the high-pressure chamber are far from the measurement zone excludes also the influence of radiative bending of the shock-wave front.[3,21] The low plasma densities that are attainable with this procedure are determined by the condition that the ranges of the optical radiation be close to the dimen-

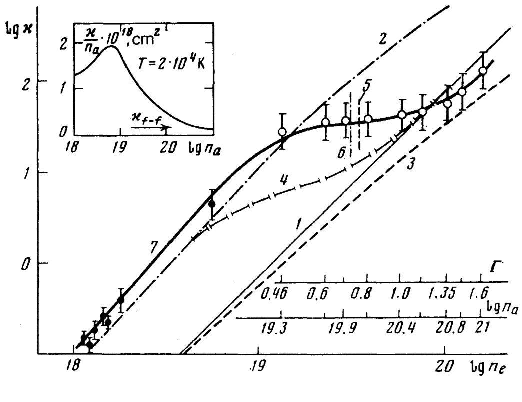

FIG 3. Results of measurements: ○—our points referred to a temperature 2×10^4 K, ●—results by others[6,7] referred to $T = 2.4\times10^4$ K, 1—free-free transitions ($\varkappa_{f-f}$), 2—calculation in accordance with Ref. 23 with allowance for $\varkappa_{f-f}$, 3—$\varkappa_{f-f}$ with screening taken into account, 4—our result, 5, 6—estimate of $\varkappa$ from results of Refs. 3 and 20; curve 7 connects together the experimental points obtained by various workers, referred to a frequency $\nu = 5.17\times10^{14}$ sec^{-1} and to a temperature $T = 2\times10^4$ K.

sions of the region of quasi-stationary flow of the shock-compressed plasma, corresponding to arrival of distorting relaxation waves. The minimum plasma density is limited by the smallness of the radiation range and consequently by the time resolution of the measurement apparatus.

The experimental data obtained with all these limitations taken into account are shown in Fig. 3 and cover continuously a wide range of parameters, from the region investigated earlier[5,6] to states of high density ($n_a \sim 1.4 \times 10^{21}$ cm^{-3}, $n_e \sim 1.8 \times 10^{20}$ cm^{-3}) with strong ($\Gamma \sim 1.6$) Coulomb interaction. Curves 1 and 2 of Fig. 3 correspond to the traditional methods of calculating the optical properties of a low-temperature plasma.[5] Absorption in free-free transitions of electrons in the fields of the ions is described by the Kramers formula with the Gaunt factor from Ref. 22 (curve 1). The calculation of the scattering of the electron by the screened Coulomb potential leads to a decrease of the absorption coefficient (curve 3). To obtain the total absorption coefficient (curve 2) it is necessary, in addition to the free-free transitions, to have a mechanism that photoionizes the bound electrons. At the chosen registration frequency ($h\nu = 2.14$ eV), the main contribution to the absorption is made by photoionization from the states $3p^5 3d$, for which the corresponding cross sections were calculated in Ref. 23 by the quantum-defect method. It is seen from Fig. 3 that the experimental data in the region of low densities agree with the earlier numerous measurements[8] and confirm the tendency that the registered radiation exceeds the calculated values. With further increase of plasma compression, the specific absorption coefficient per atom $\varkappa/n_a$ (see the inset of Fig. 3) decreases monotonically and turns out to be smaller by one order of magnitude that the results of the traditional plasma calculation, and close to the values determined by free-free transitions.

The transparentization effect registered in the experiments is probably the consequence of the deformation of the electron energy spectrum of the atoms when they are compressed by the surrounding particles. Regardless of the actual models used for the description (fluctuating microfields,[10] screening by charges,[9,24] etc.), the interparticle interaction makes the intra-atomic potential short-range and leads to a finite number of discrete energy levels and to a successive transition of the highly excited states into the continuum with increasing density. This vanishing of the part of the excited energy levels excludes naturally the mechanism of photoionization absorption from these states, and consequently leads to the observed decrease of the absorption coefficient per atom (see inset of Fig. 3).

For a qualitative description of the second effect, we consider a simplified model[2)] in which the action of the neighboring particles on the atom reduces to compression of the atom and is simulated by a potential of the form

$$V(r)=\begin{cases} Ze^2/r, & r<r_0, \\ \infty, & r>r_0. \end{cases} \qquad (2)$$

In this potential the system of intra-atomic electrons was calculated by the Hartree-Fock method[26] with cor-

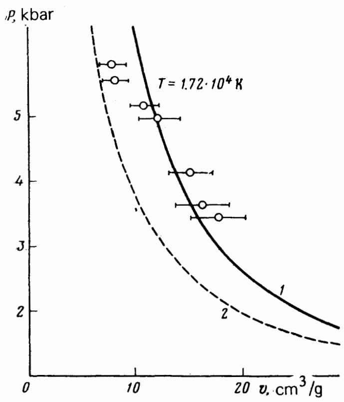

FIG 4. Comparison of the bounded-atom model with the thermodynamic measurements: ○—results of Ref. 13 referred to the isotherm $T = 1.72 \times 10^4$ K; 1—calculation by the bounded-atom model, 2—calculation by the Debye–Huckel model.[30]

rections[27] for the electron correlations. This made it possible to obtain the electron wave functions and the energy spectrum of the atom as functions of the parameter r_0 that characterizes the degree of compression of the plasma. The interaction of the atoms with one another was described by the hard-sphere model, for which computer calculations were used.[28] The condition that the free energy be a minimum with respect to r_0 determines the equilibrium value of the limiting radius r_0 as a function of the state parameters; this makes the model self-contained and suitable for the calculation of the thermodynamic and optical properties of a strongly compressed plasma. In the latter case, the photoionization absorption was calculated by resorting to the cross sections taken from Ref. 23, with photoionization limits shifted in accordance with the deformed energy spectrum.

It is seen (Fig. 3) that this model accounts for the experimentally recorded transparentization of the plasma upon compression. It is important that it provides also a quantitative description of the thermodynamic data obtained[13] under the same conditions, indicating that the compressibility of the plasma is lower than the theoretical predictions that ignore the deformation of the discrete spectrum. We emphasize that the possibility of a comprehensive description of the physical characteristics of the plasma is an additional advantage of the proposed approach over the model of nonrealization of levels in fluctuating microfields,[7,8] which pertains only to optical properties.

It is clear that the employed boundary condition (2) of the "hard wall" type is quite crude. This is attested simultaneously by the optical and thermodynamic data (Figs. 3 and 4), a detailed description of which calls apparently for the use of the model of "soft" spheres.[29]

The authors thank A. N. Dremin for support and useful discussions.

[1)]In the investigation of a less dense plasma under damping conditions, this method must be modified.[19]
[2)]Under the experimental conditions ($\Gamma \gtrsim 1$) the intensity of the

plasma microfield is ~10^7 V/cm, i.e., it is comparable with the intensity of the intra-atomic field, thus excluding the possibility of using perturbation theory[25] to calculate the shift of the energy levels.

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Envelope solitons of relativistic strong electromagnetic waves

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We investigate envelope solitons of circularly polarized electromagnetic waves in a cold plasma, due to the joint action of relativistic and striction nonlinearities. It is shown that in the approximation in which the plasma perturbations are quasineutral there exist only soliton small-amplitude solutions in which the oscillatory velocity of the electron is much lower than the velocity of light. Numerical integration with a computer yielded solitons with relativistic amplitudes, for which the plasma charge separation is substantial. These solitons differ in shape from ordinary small-amplitude solitons and have a discrete velocity spectrum. It is demonstrated that the concentration has a limit above which the plasma has no solitons with a specified carrier frequency.

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Recent progress in the development of high-power generators for various frequency ranges make it possible to speak of interaction between electromagnetic radiation and a plasma under conditions when the particle oscillation velocities can be comparable with the speed of light. In this case the relativistic nonlinearity is no longer quadratic and can be rigorously accounted for in only a few particular cases. For circularly polarized radiation, the relativistic nonlinearity was first taken into account rigorously by Akhiezer and Polovin[1] for a wave with constant amplitude.[1)] Gorshkov *et al.*[4] investigated stationary envelope waves of circularly

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