STUDY OF OPTICAL PROPERTIES OF DENSE KRYPTON PLASMA

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Study of the thermophysical properties of dense plasma has been stimulated by the absence of a strict theory which would adequately describe the thermodynamic, transport, and optical properties of such a medium. A detailed analysis of presently available dense plasma models requires a comparison of their results to experiments performed with various chemical elements. Experimental data on thermodynamic properties and electrical conductivity of dense plasmas of a number of chemical elements shows a general tendency: The experimental enthaply and electrical conductivity of the plasma are lower than the corresponding theoretical values, the differences increasing with increase in charged particle concentration. With regard to optical properties the experimental situation is not well defined. For some elements experimental values have been found to be above theoretical ones, while for other elements the opposite is true. In connection with this further studies of the optical properties of dense plasma over a wide parameter range are necessary.

The present study will investigate the optical properties of dense krypton plasma. A three-chamber heated pneumatic shock tube (Fig. 1) was used to produce the dense plasma. The three-chamber tube 7 consists of a high pressure chamber (HPC), intermediate chamber (IC), and low pressure chamber (LPC). The gas to be studied, krypton, is pumped into the low pressure chamber, while the CI and HPC are filled with a driver gas, helium. The gas pressure in the intermediate chamber is chosen equal to the geometric mean of the pressures in the HPC and LPC. Use of the intermediate chamber makes it possible to increase the shock wave intensity by 20-30% over that of the two-tube variant of [1]. The entire tube is located within a heater 8 and heated to a specified temperature. Before the beginning of the experiment the LPC is evacuated to a pressure of ∿1 Pa and filled with krypton. The following quantities were recorded in the experiments: initial pressure and temperature of working gas (in all experiments the initial gas pressure was 12.6 kPa, with initial temperature of 873°K), incident and reflected shock wave velocities, plasma density behind incident and reflected waves. The plasma density was measured by x-ray diagnostic techniques [2]. Incident shock wave velocity was measured over two baselines using photomultipliers (PM) 1, 2 and 2, 3 and x-ray tube 9. The experimental parameters and conservation laws on the shock discontinuity were used to determine the plasma pressure and enthalpy behind the incident and reflected shock waves. A more detailed description of the experimental equipment is presented in [3]. The technique and accuracy of study of dense plasma thermodynamic parameters by the heated shock tube method were analyzed in detail in [2, 4].

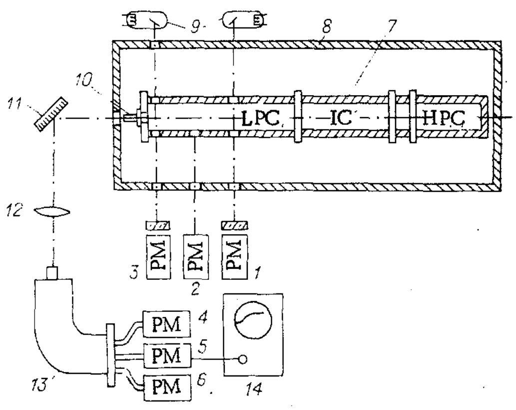

Fig. 1

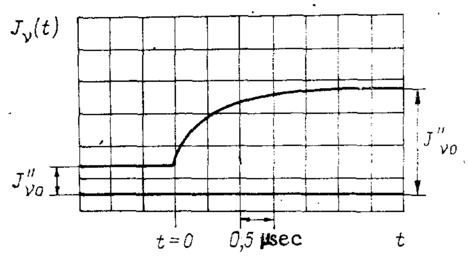

Fig. 2

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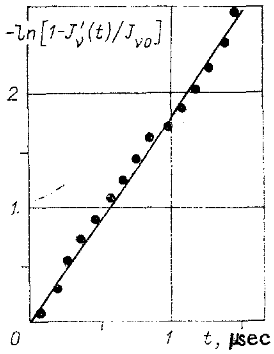

Fig. 3

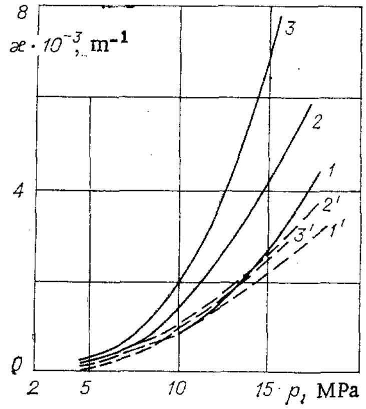

Fig. 4

In analyzing the experimental results it was established that the experimental krypton plasma thermodynamic parameters were described well by the theoretical approximation of Debye theory with a large canonical ensemble, so that approximation was used to calculate the thermodynamic composition of the plasma.

To determine the absorption coefficient of the dense krypton plasma the intensity of plasma radiation from the face of the shock tube was recorded. The radiation from the plasma normally incident on an artificial carborundum glass installed in the shock tube face was fed through collimator 10, rotation mirror 11, and lense 12 to the input slit of an ISP-51 spectrograph 13. The collimator was a blackened metal tube 0.1 m long with internal diameter of $0.5 \cdot 10^{-2}$ m. At the spectrograph focal plane there was a piece of fogged photographic film with slits 10^{-3} m wide engraved at locations corresponding to wavelengths of 458, 579, and 708 nm. Radiation was fed through a lightguide to photomultipliers 4, 5, 6, the signals from which were fed through cathode followers to S1-74 oscilloscopes 14.

Figure 2 shows an oscillogram of plasma radiation intensity. Before the shock wave arrives at the tube face radiation from the incident shock wave $J'_{\nu 0}$ is recorded, while after reflection from the tube face we have radiation from reflected and incident waves

$$J_\nu(t) = J''_{\nu 0}[1 - \exp(-\varkappa' U t)] + J'_{\nu 0} \exp(-\varkappa' U t),$$

where $J''_{\nu 0}$ is the intensity corresponding to black body radiation; U, reflected shock wave velocity; $\varkappa' = \varkappa\left[1 - \exp\left(-\frac{h\nu}{kT}\right)\right]$, plasma absorption coefficient with consideration of constrained radiation. Using the experimental value of reflected shock wave velocity U and the function $J_\nu(t)$, the dense plasma absorption coefficient behind the reflected wave can be determined.

A possible source of systematic error in determining the plasma absorption coefficient by the above method is the absorption of a portion of the radiation by the viewing window. A spectrographic study of the plasma radiation established the absence of absorption lines and bands corresponding to the evaporating part of the viewing window in the visible spectral range.

The intensity of the recorded radiation can also change due to clouding of the window surface in contact with the plasma. This phenomenon would lead to a change in the value of $\varkappa' U$ on the portion of the transfer characteristic form $J'_{\nu 0}$ to $J''_{\nu 0}$, and to decrease in the intensity of the recorded radiation after reaching a maximum value. Results of processing plasma radiation intensity versus time oscillograms are shown in Fig. 3, where $J'_\nu(t) = J_\nu(t) - J'_{\nu 0}$, $J_{\nu 0} = J''_{\nu 0} - J'_{\nu 0}$.

To an accuracy of ±10% the quantity $\varkappa' U$ remains constant over the entire range and the intensity of plasma radiation from the shock tube face reaches a constant level ($J''_{\nu 0}$ of Fig. 2).

The change (increase) in reflected shock wave velocity during its formation segment leads to an increase in charged particle concentration, and correspondingly to an increase in the plasma absorption coefficient, i.e., to a change in the value of the product $\varkappa' U$. This effect has not been observed in experiment (see Fig. 3), which indicates that the process of reflected shock wave formation occurs over a very brief time interval. Change in the intensity of radiation from the incident shock wave $J'_{\nu 0}$ over a portion of the transfer characteristic is related to a decrease in thickness of the plasma layer located between the reflected shock wave and the contact surface, and did not exceed 5% in all experiments. Due to absorp-

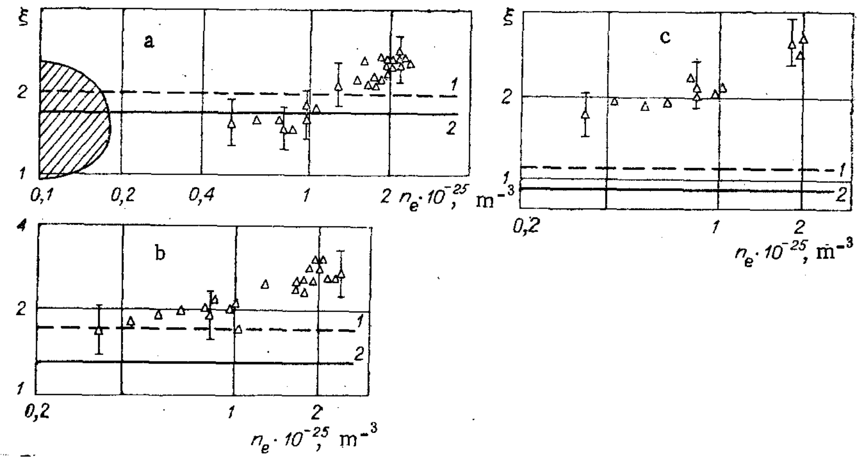

Fig. 5

tion of a portion of the radiation from the incident shock wave by the plasma layer behind the reflected wave the effect of this phenomenon on recorded radiation intensity will be still lower, ∿1-2%, and may be neglected.

The optical properties of the dense krypton plasma were studied in the parameter ranges: $n_e = (0.35\text{-}2.5)\cdot 10^{25}$ m^{-3}, $T = (1.4\text{-}1.95)\cdot 10^4$ °K, $\Gamma = e^2/(kTr_D) = 0.36\text{-}0.61$ (nonidealness parameter).

Figure 4 shows experimental and theoretical dependences of the dense krypton plasma absorption coefficient on pressure for various wavelengths: 1, 458; 2, 579; 3, 708 nm, experimental data of present study; 1', 458; 2', 579; 3', 709 nm, theoretical approximation [5]. Over the entire parameter range studied the experimental values of the plasma absorption coefficient for the 708-nm wavelength exceed the theoretical values. At 458 nm for pressures $p \leq 12$ MPa the experimental results are below the theoretical values, but exceed the latter at high pressures.

Figure 5a shows experimental data and theoretical expressions [5, 6] for the ξ-factor of the dense krypton plasma as a function of electron concentration at λ = 458 nm. The experimental values of the ξ-factor are presented in the form [7]

$$\xi = \varkappa \left[4.3 n_e^2 (kT)^{-1/2} \exp\left(-\frac{\Delta I}{kT} + \frac{h\nu}{kT}\right) \nu^{-3}\right]^{-1}$$

(ΔI is the reduction in ionization potential in Sach's expression); Δ are the data of the present study; 1, [5]; 2, [6]; the dashed region, studied in [8, 9]. Figure 5b shows the dependence of the krypton plasma ξ-factor on electron concentration for λ = 579 and 708 nm.

In all the figures there is some slight change in experimental values of the ξ-factor with increase in electron concentration; at λ = 458 nm at electron concentrations $n_e \leqslant 10^{25}$ m^{-3} the experimental results coincide within the limits of uncertainty with the theoretical approximation of [6]. At 708 nm over the entire parameter range the experimental results are significantly (by a factor of 3) higher than the theoretical values. Figure 6 shows ξ-factor values over the spectral interval studied for two values of the electron concentration: $n_e = 0.35\cdot 10^{25}$ and $2.5\cdot 10^{25}$ m^{-3} (points ▲ and Δ in Fig. 6). It is interesting that the experimental data of the present study coincide with the results of [10], which were obtained with a similar electron concentration of $n_e \simeq 10^{24}$ m^{-3}. The experimental results can be reconciled with the theoretical approximation of [5, 6] if we consider optical reduction of the atomic ionization potential, related to merging of a portion of the upper excited levels under the action of internal microfields within the plasma. At the limiting parameter values of the present study $n_e = 2.5\cdot 10^{25}$ m^{-3} and $T = 1.95\cdot 10^4$ °K, to reconcile the theoretical values with the experimental data at 458 and 579 nm the optical reduction in atomic ionization potential must be equal to $0.8\cdot 10^{-19}$ J, which is significantly less than the value given by Inglis and Teller [11] — $1.92\cdot 10^{-19}$ J. The significant excess of the experimental results above theory at λ = 708 nm (approximately 3 times) can be explained by the effect of a quasicontinuum near the atomic ionization boundary upon optical characteristics of the dense plasma. This occurs because of overlap of the wings of spectral lines from different series located close to one another in the red portion of the spectrum.

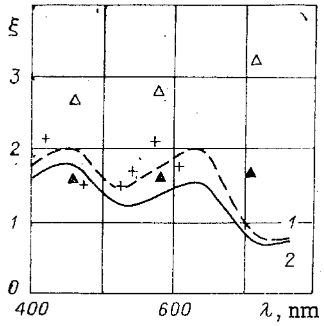

Fig. 6

In [12] the optical properties of a dense xenon plasma were studied. The character of the change in ξ-factor with increasing electron concentration was found to be complex. Over the entire parameter range studied the experimental results were described by the approximation of [5] to an accuracy of ±100%. Generalizing the experimental data on optical properties of krypton and xenon plasma, it can be proposed that the extrapolation approximations of [5, 6] describe the optical properties of dense inert gas plasmas to that accuracy.

LITERATURE CITED

1. B. Henshell, "Use of the multidiaphragm system in a shock tube," in: Shock Tubes [Russian translation], Inostr. Lit., Moscow (1962).
2. V. A. Sechenov and O. E. Shchekotov, "Impulsive shock tube roentgenography in cesium vapor using two x-ray tubes," Teplofiz. Vys. Temp., 10, No. 5 (1972).
3. V. A. Sechenov, "Experimental investigation of absorption coefficient of a dense xenon plasma," in: Proc. XV Int. I.C.P.I.G.: Contributed Papers, Vol. 1, Minsk (1981).
4. A. V. Bushman, B. N. Lomakin, et al., "Thermodynamics of nonideal cesium plasma," Zh. Eksp. Teor. Fiz., 69, No. 5 (11) (1975).
5. D. Schlueter, "Die Emissionkontinua thermischer Edelgasplasmen," Z. Phys., 210, No. 1 (1968).
6. D. Hofsaess, "Emission continua of rare gas plasmas," JQSRT, 19, No. 3 (1978).
7. G. É. Norman, "Continuous radiation (absorption) spectra of a nonideal plasma," Teplofiz. Vys. Temp., 17, No. 3 (1979).
8. D. Meiners and C. O. Weiss, "Continuous emission of argon, krypton, and xenon plasmas," JQSRT, 16, No. 3 (1976).
9. A. A. Bakeev, T. P. Naprozhnaya, et al., "Electrical and optical characteristics of a pulsed discharge in krypton," Teplofiz. Vys. Temp., 9, No. 4 (1971).
10. O. E. Berge, A. Boehm, and L. Rehder, "Spektroskopische Messungen am Membranstosswellenrohr, Teil. II, Absolutbeststimmung der ξ-Factoren neutraler Edelgasatome," Z. Naturforsch., 20a, No. 1. (1965).
11. D. R. Inglis and E. Teller, "Ionic depression of series limits in one-electron spectra," Astrophys. J., 90, No. 3 (1939).
12. V. A. Sechenov, "Study of optical properties of dense xenon plasma," Fiz. Plazmy, 7, No. 5 (1981).