pendences of the density and of the velocity of the plasma.

Another factor very sensitive to the laser-plasma dynamics is the SMBS-induced exhaustion of the pump wave. This follows from the fact that small changes of the argument of the exponential in (4.3) affect strongly the character of the penetration of the pump wave into the plasma. According to the definition (3.7), this exponent is directly proportional to the intensity of the wave and to the plasma-inhomogeneity scale is inversely proportional to the plasma velocity. With increasing inhomogeneity scale we therefore have an increased scattering intensity, in qualitative agreement with the ideas concerning the influence of the contrast. Conversely, with increasing plasma expansion velocity, the scattering intensity decreases and it can be stated that the plasma motion suppresses the SMBS. This conclusion agrees with the results of a numerical solution of the gasdynamics equations.[18] The physical cause of the suppression of the SMBS is that the acoustic waves drift together with the plasma and pass more rapidly through the region of the resonant interaction in the inhomogeneous plasma, and consequently have a smaller growth.

It should be noted that our analysis is not quite consistent, since we did not take into account the fact that the plasma hydrodynamic characteristics (the density and the expansion velocity) are themselves dependent on the incident-wave intensity. A consistent allowance for this dependence is possible if the equations hydrodynamics and the equation for the pump waves are solved simultaneously.

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[1)] We note that the quantity M_c determines the plasma velocity at the point x_c, but not the velocity of the point x_c itself.

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Experimental investigation of the emission of a mercury plasma near the photorecombination thresholds at high pressure

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The spectra of the line and continuous emission of a mercury plasma were investigated in the frequency interval $(0.4–1.25)\times 10^{15}$ sec^{-1} at electron densities 5×10^{15} and 4×10^{17} cm^{-3}. At high charged-particle densities it was observed that the spectral lines vanish near the photorecombination thresholds, but the thresholds themselves are hardly displaced. In a less dense plasma, in the near-threshold regions of the spectrum, a coalescence of the spectral lines was observed in accordance with the Inglis-Teller model, leading to an apparent shift of the photorecombination thresholds towards lower frequencies.

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A well known density effect in a plasma is the coalescence of the higher terms of the spectral series near the photorecombination (photoionization) thresholds.[1,2] To describe the transition of the line spectrum into a continuum it is customary to use the assumption that the oscillator-strength density df/dE is not perturbed.[2,3] It was shown[4] that on going to a nonideal plasma a qualitatively new effect may appear,

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namely the vanishing of the spectral lines because the upper energy levels of the atoms are not realized in quasistatic microfields.

In this case, the assumption that the oscillator-strength density remains unperturbed is wrong. Owing to the short-range character of the real interaction potential in a dense plasma, the threshold value of the distribution df/dE vanishes, i.e., a dip can appear in the distribution df/dE near the threshold. Attention was called[5] to the statistical character of the action of the microfields on the atoms in a plasma. The final form of the distribution df/dE over the microfields determines the vanishing of the spectral lines in the near-threshold region without prior overlap, and the absence of a noticeable shift of the photorecombination thresholds.[4]

Although the effect of deviation from ideality on the emission of a plasma has been noted in a number of studies (see[4,6,7] and the references therein), these effects have not yet been sufficiently well studied. In the present paper we report an experimental study of the emission of a mercury plasma at substantially differing densities of the charge d particles. We study the character of the vanishing of the spectral lines near the photorecombination thresholds, and determine the intensity and the frequency distributions of the continuous radiation and the positions of the photorecombination thresholds. Preliminary results on the emission of a mercury plasma were reported in[7].

EXPERIMENTAL TECHNIQUE

The mercury plasma is a suitable investigation object, since the visible and near infrared regions of its emission spectrum, which can be conveniently recorded, contain several photorecombination thresholds due to transitions to the levels $7s\,^1S_0$, $7s\,^3S_1$, $6p\,^1P_1^0$, $6p\,^3P_2^0$, $6p\,^3P_1^0$, and $6p\,^3P_0^0$. The plasma sources were mercury-quartz lamps: a tubular high-pressure lamp of the PRK-4 type and a spherical ultrahigh pressure lamp of the DRSh-250 type. The lamps were connected to a dc source in series with a ballast resistor. The operating conditions of the lamps were chosen in accord with the current-voltage characteristics (see the table). The working pressures were calculated according to the known formulas[8] that relate the electric and geometric characteristics of the lamps.

The line and continuous radiation were recorded with a DFS-13 spectrograph (4 Å/mm) with photographic registration. In the absolute measurements of the intensity of the continuum and of the lines, the standard was the radiation of the anode crater of a weak-current carbon arc in air.[9] The lamps were mounted vertically and the image of the arc was rotated 90° to register on the photographic plates the distribution of the radiation across the arc column. The radial distributions of the line and continuous radiation were obtained by recalculation with the aid of the Abel integral equation. All the data presented here on the diagnostics and on the optical properties of the plasma pertain to the axis of the arc column.

PLASMA DIAGNOSTICS

Estimates show[10] that the plasma of the axial zone of the arc in a DRSh-250 lamp is in a state of local thermodynamic equilibrium, while the plasma in the PRK-4 lamp is close to this state. Calculation of the composition of the mercury lamp was carried out under the assumption of single ionization with allowance for the corrections for non-ideality.[11] The statistical weights and energies of the levels were taken from[12].

The parameters of the plasma in the PRK-4 lamp were measured by several methods. The temperature of the population was determined from the absolute intensity of the atomic lines of the mercury. Owing to self-reversal of the well known intense lines, such as HgI-5460.73 Å (transition $7s\,^3S_1$-$6p\,^3P_2^0$), we chose for the diagnostics the three lines HgI-2925.41 Å ($9s\,^3S_1$-$6p\,^3P_2^0$), HgI-2893.59 Å ($8s\,^3S_1$-$6p\,^3P_1^0$), and HgI-2752.78 Å ($8s\,^3S_1$-$6p\,^3P_0^0$), corresponding to transitions from higher levels. The oscillator strengths for these lines are respectively 0.014 and 0.013.[13] The wavelengths were taken from,[14] and the needed constants from[15]. We determined also the electron temperature from the relative intensity of the recombination continuum on the levels $7s\,^1S_0$ and $7s\,^2S_1$, which decreases exponentially in the frequency interval $(0.51-0.83)\times 10^{15}$ sec^{-1} and is free of other recombination thresholds. The results of the measurements of the temperature in the PRK-4 agree with one another (see the table).

At the obtained values of the temperature, the plasma composition has a strong temperature dependence, so that it is desirable to estimate directly the electron density. This can be done from the intensity of the continuum. We assume in first-order approximation that the end-point frequency is close to the photoionization frequency of the $6p\,^3P_1^0$ state. The mercury factor $\xi(\nu, T)$, which depends on the frequency ν and the temperature T, is given in[2]. The absolute intensity of the continuum was taken at the frequency 0.7×10^{15} sec^{-1}. The obtained concentrations and the equilibrium temperatures corresponding to them are listed in the table.

The diagnostics of the parameters of the dense plasma in the DRSh-250 lamp encounters substantial difficulties. The temperature determined by measuring the absolute intensities of the lines used above is apparently somewhat undervalued: 5600–6100 K. The electron temperature determined from the relative intensity of the exponentially decreasing recombination continuum in the frequency intervals $(0.39-0.60)\times 10^{15}$ sec^{-1} and $(0.6-0.86)\times 10^{15}$ sec^{-1} is noticeably higher (see the table).

TABLE I.

Type of lamp	PRK-4	DRSh-250
Current, A	3.0	4.5
Voltage, V	67	87
Pressure, atm abs.	0.66±0.1	39±6
T, K, absolute line intensity	6350±150	–
T, K, relative continuum intensity	6800±1000	9000±1500
n_e, cm^{-3} absolute continuum intensity	$(5.0\pm1.2)\cdot10^{15}$	$(4.0\pm0.8)\cdot10^{17}$
T, K, from plasma composition	6450	8400

Under conditions of high density of the charged particles, the Stark broadening of the indicated lines greatly exceeds the broadening due to the interaction with the neutral particles. An estimate of the electron density from the line half-width according to the data of[15] yields a value $(0.8-1.0)\times 10^{18}$ cm^{-3}, which is apparently somewhat overestimated because of the noticeable line shift, since use was made of registered line contours due to emission from inhomogeneous layers of the arc column. In this case the reduction of the line contour with the aid of the Abel integral equation is not justified because of the low accuracy of this operation.

The high-pressure parameters were also estimated from the absolute intensity of the continuum under the assumption that the theory of the continuous emission[2] is valid in this region of the state parameters (see the table). We note that the obtained values of the temperature and concentration of the electrons are needed only to estimate the parameter region to which the spectrum singularities discussed below pertain.

PROCEDURE FOR REDUCTION OF LINE SPECTRUM

In the analysis of the spectral interval in which the line spectrum gradually changes into a continuum, we traced individual spectral line for the purpose of ascertaining the character of the convergence of the lines and revealing the last line that can still be distinguished against the continuum. We calculated, with allowance for the refraction of the air, the wavelengths of the transitions from highly excited levels with principal quantum numbers $n \geq 10$, which are not listed in the tables.[14] The interpretation of the spectrum and the identification of the lines were carried out in accordance with the following attributes: comparison of the wavelength of the line with the calculated one, the monotonic decrease of the intensity of the lines of one series and of the interval between, and the shape and broadening of the lines, the character of which was the same for lines of the same series and differed strongly for lines of different series. Using these criteria, we succeeded to trace, at low electron density, the lines in the series up to a principal quantum number $n = 12$ to 13 and verified the absence of higher terms of the series.

We reduced and analyzed the series of lines corresponding to transitions from the levels $ns\,^1S_0$, $nd\,^1D_2$, $ns\,^3S_1$, $nd\,^3D_1$, $nd\,^3D_2$, $nd\,^3D_3$ to the levels $6p\,^1P_1^0$ and $6p\,^3P_2^0$–five series in accordance for the selection rules for each level. The lines of the sharp series are distinctly separated against the background of the continuum and can be traced to large values of the principal quantum number. The intense and broad lines of the diffuse series, in view of the proximity of the level energies, coalesce into one broad lines, which is traced on the microphotographs to lower values of the principal quantum number. (The series of the lines from the d levels of the series will be hereafter designated in the form ndD-$6p\,^1P_1^0$ and ndD-$6p\,^3P_2^0$.)

The line spectra were obtained with a normal width of the spectrograph slit, photometrized, reduced, and plotted against the background of the continuous emission of the plasma. Narrow spectral lines are marked on the figure by vertical segments, and broad ones are approximated by triangles that reflect qualitatively the real line width. The height of a line on the figure corresponds to the intensity of the line at the maximum, and the error in the determination of the intensity ranges from 100 or 150% for the first term of the spectral series to 30–40% for the higher terms. To avoid difficulties with the analysis of the transition of the lines into the continuum near the considered photorecombination thresholds, the figure does not show line series corresponding to transitions to levels $6p\,^3P_1^0$ and $6p\,^3P_0^0$. In the wavelength region 3400–4000 Å we observed several low-intensity impurity lines that pertain apparently to metallic impurities, such as iron or chromium, that are present in the mercury.

DISCUSSION OF RESULTS

The figure shows the measured values of the coefficient of continuous radiation in the frequency interval $(0.39-1.26)\times 10^{15}$ sec^{-1} and the atomic lines of several spectral series that converge to the two photorecombination thresholds of the states $6p\,^1P_1^0$ and $6p\,^3P_2^0$.

1. *Continuous emission.* The frequency distribution of the continuum of the mercury plasma at a pressure close to atmospheric (PRK-4) has in the investigated region two clearly pronounced recombination thresholds (see spectra a in the figure). Besides those indicated above, a common recombination threshold is observed on the levels $7s\,^1S_0$ and $7s\,^3S_1$. The positions of the thresholds are shifted noticeably towards the red. That the continuum is of recombination origin is indicated also by the exponential section of the decrease of the intensity in the frequency interval $(0.51-0.83)\times 10^{15}$ sec^{-1}. The horizontal dashed line in Fig. (a) shows the value of the continuum-radiation coefficient obtained from the Biberman-Norman integral formula[2] with $\xi(\nu, T) = 1$ on the basis of temperature measurements, under the assumption that the end-point frequency ν_g lies in the ultraviolet region of the spectrum. Such an approximate estimate agrees on the whole with experiment and shows that for a more accurate description of the continuum, with an accuracy that approaches that of the experimental data (20 – 30%), it is necessary to take into account the photoionization cross sections of individual states, as well as the bremsstrahlung of the electrons in the fields of the neutral particles.

The intensity of the continuum at high pressure (DRSh-250) is higher by almost four order of magnitude (see spectra b in the figure). The lack of accurate independent measurements of the plasma parameters does not permit a comparison of the absolute intensity of the continuum with the calculations. We note that the steeper decrease of the continuum intensity at frequencies $\nu > 0.95\cdot 10^{15}$ sec^{-1} and the practical absence of radiation in the region of the threshold at the level $6p\,^3P_2^0$ are due to reabsorption of the radiation in the far red wing of the resonance line HgI-2536.52 Å.

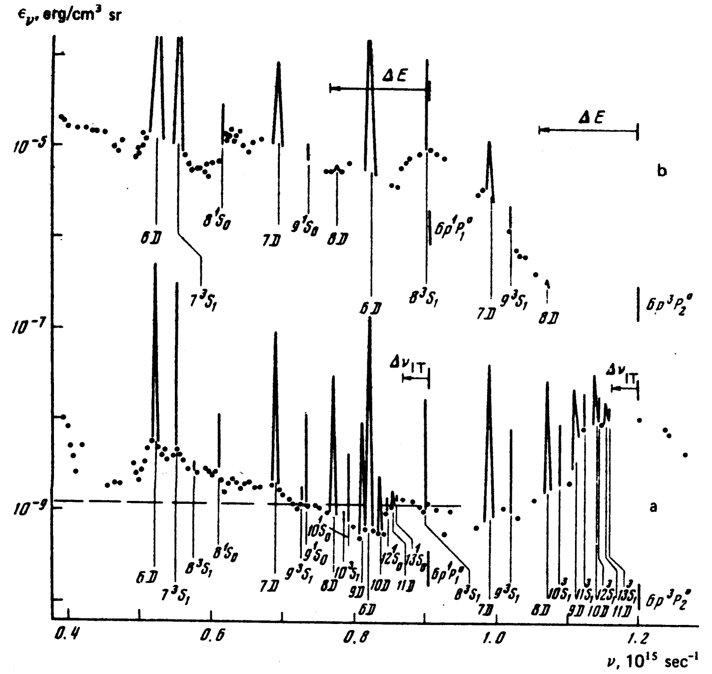

FIG. 1. Spectra of the line and continuous (points) emission of a mercury plasma: $a - n_e = 5 \cdot 10$ cm^{-3}, $T = 6400$ K; $6 - n_e = 4 \cdot 10^{17}$ cm^{-3}, $T = 8400$ K. Under each spectral line is marked the simplified designation of the upper state of the given transition. The unperturbed positions of the photorecombination spectra are indicated. $\Delta\nu_{IT}$ is the shift of the thresholds according to the Inglis-Teller formula, ΔE is the estimated size of the unrealized discrete states.[4] Dashed line—calculated intensity of the continuum according to [2].

2. *Near-threshold region of the spectrum.* We consider the singularities of the transition of the line radiation into the continuum near the photorecombination thresholds in the cases of low and high charged-particle densities.

a) $n_e \approx 5 \cdot 10^{15}$ cm^{-3} (n_e is the electron density). The figure shows the intensities of the spectral lines (a) that form the series ndD-$6p\,^1P_1^0$, nsS-$6p\,^1P_1^0$, as well as ndD-$6p\,^3P_2^0$ and $ns\,^3S_1$-$6p\,^3P_2^0$. It is seen that the spectral lines of the different series merge together as the unperturbed position of the thresholds of photorecombination to the levels $6p\,^1P_1^0$ and $6p\,^3P_2^0$ are approached, and this leads to an apparent red shift of the threshold. The positions of the last observable lines are separated from the unperturbed positions of the thresholds by an amount close to the value given by the Inglis-Teller formula ($\Delta\nu_{IT} \approx 0.16$ eV). These lines are due to transitions from the levels $13s\,^1S_0$ and $11dD$ to the level $6p\,^1P_1^0$ and respectively from the levels $13s\,^3S_1$ and $11dD$ to the level $6p\,^3P_2^0$. The overlap of the wings of the spectral lines, whose half-widths are less than the distance between them, leads to a smooth course of the continuum in this region. On the whole, the picture of the transition from the line spectrum to the continuous one agrees with that assumed in the theory of the optical spectra of a tenuous plasma and confirms the assumption that the density of the oscillator strengths df/dE is unperturbed in the near-threshold region.[2-4]

b) $n_e \approx 4 \cdot 10^{17}$ cm^{-3}. In this case one observes near the photorecombination thresholds qualitatively new singularities. As seen from the figure, near the threshold the photorecombination into the state $6p\,^1P_1^0$, the higher terms of the spectral series ndD-$6p\,^1P_1^0$ and nsS-$6p\,^1P_1^0$ vanish without overlapping. The last lines that are observable in the series yield transitions to the state $6p\,^1P_1^0$ from the levels $8dD$ and $9s\,^1S_0$. The Stark half-widths of these lines are smaller by more than one order than the distance to the neighboring lines of the same series. The smooth maximum of the intensity of the continuum, which corresponds to recombination to the $6p\,^1P_1^0$ level, occupies a position close to the unperturbed threshold frequency. The near-threshold region of the spectrum is thus "rid" of the higher terms of the spectral series, and the shift of the photorecombination threshold is in fact nonexistent. As a result, a dip is produced in the radiation intensity at the photorecombination boundary.

The near-threshold region of the spectrum, which corresponds to photorecombination into the $6p\,^2P_2^0$ state and which has been investigated in less detail because of the reabsorption of the resonance line, agrees with the above-described picture of line vanishing without overlap. The spectral-line series that converge to the thresholds of photorecombination into the states $7s\,^1S_0$ and $7s\,^3S_1$ at $\nu < 0.5 \times 10^{15}$ sec^{-1} have not been considered in the present study, but the frequency region $(0.52-0.61) \times 10^{15}$ sec^{-1} is free of lines that pertain to these thresholds, and the burst of intensity of the continuum at the frequency $\nu = 0.62 \times 10^{15}$ sec^{-1} corresponds to the unperturbed position of these thresholds.

c) The obtained experimental results agree with the developed theoretical concepts[4] concerning the effect of non-ideality on the emission of a plasma near photorecombination thresholds. Let us estimate the size ΔE, of the near-threshold energy region in which the distribution df/dE can differ from the unperturbed one. We use for this purpose the classical expression for the lowering of the potential barrier $\Delta E(F) = 2e(eF)^{1/2}$ (e is the electron charge and F is the microfield intensity). We change over to the relative value of the microfield $\epsilon = F/F_0$, where $F_0 = 2.6031 e n_i^{2/3}$ (n_i is the ion density, $n_i = n_e$) and average $\Delta E(\epsilon)$ over the distribution $P(\epsilon)$ of the ionic microfields in the plasma. As a result we get

$$\Delta E = 2e(eF_0)^{1/2}\int_0^\infty \varepsilon^{1/2}P(\varepsilon)\,d\varepsilon = Ce^2(2n_i)^{1/3}, \quad (1)$$

where C is a numerical coefficient of the order of unity. The average value of the region of nonrealized discrete energy levels, referred to the temperature T, $\Delta E/kT = C\gamma$, turns out to be proportional to the non-ideality parameter $\gamma = e^2(2n_i)^{1/3}/kT$ (k is Botzmann's constant). The value of the coefficient is $C \approx 3-4$ and is determined by the distribution of the microfield in the plasma.[16,17] The value of C depends little on the non-ideality parameter and at $\gamma < 1$ it decreases somewhat in the indicated limits with increasing γ. We note that (1) was obtained by extrapolating the expression for $\Delta E(F)$ to the region of high densities of the charged particles and is approximate.

The averaged size of the region of the non-realized levels is in the case of a dense plasma, as follows from (1), approximately 0.6 eV. In fact, the deviation of the distribution df/dE from the unperturbed one and consequently the weakening of the spectral lines can take place also in a somewhat larger frequency region because of the statistical character of the action of the microfields on the plasma atoms. This is in fact the cause of the relatively smooth character of the spectrum near the threshold of photorecombination to the $6p\,^1P_1^0$ level. The attenuation of the intensity of the spectral lines was observed in experiments on the diagnostics of a dense plasma. The temperature corresponding to the intensity of these lines turned out to be much lower than the values obtained by other methods.

In the case of a less dense plasma the size ΔE of the region is small (it does not exceed 0.1 eV) and can be neglected in first-order approximation. The value of ΔE is marked on the figure (b). It is seen that an estimate with the aid of (1) agrees well enough with the value of the near-threshold region in which there are practically no longer any higher terms of the spectral series.

The foregoing singularities in the near-threshold regions of the spectrum should apparently manifest themselves also in a plasma of other chemical elements at $n_i \gtrsim (0.5-1)\times 10^{18}$ cm^{-3}. The spectra of a dense argon plasma[18] were interpreted in analogous fashion in [4]1).

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1)The experimental investigations of the influence of the non-ideality of a plasma on its optical properties were initiated in [7]. The measurement results[7,18] contain important information on both the integrated spectra and the positions of the photorecombination thresholds. The effect of non-ideality on the integrated spectra[4,6] are not discussed in the present paper.

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