# Emission from a recombining laser-produced beryllium plasma in the far expansion zone

V. V. Afrosimov, S. V. Bobashev, A. V. Golubev, D. M. Simanovskiĭ, and L. A. Shmaenok

*A. F. Ioffe Physicotechnical Institute, USSR Academy of Sciences*
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An experimental procedure was developed and an investigation was carried out of the UV emission of an expanding beryllium plasma produced by an Nd laser (50 J, 50 ns, $q \sim 10^{12}$–$10^{13}$ W·cm$^{-2}$). The plasma-emission spectra in the 20–80 nm range were recorded at distances $R \sim 5$ and 10 cm from the target. A large number of intense lines of the hydrogen- and helium-like beryllium ions $Be^{3+}$ and $Be^{2+}$ were investigated. The structure of the spectrum and the relative line intensities were found to be practically independent of $R$. The populations of $Be^{3+}$ excited states with principal quantum numbers $n = 3$ to 7 were determined from the relative intensities of the BeIV lines. An increase of the population with increasing $n$ was observed. The aggregate of the experimental data shows that in the far expansion zone ($R \gg 1$) cm only one intense process takes place in the plasma—three-particle recombination of ions with electrons. Measurements of the absolute line intensities yielded the recombination rate and made possible the use of the Gurevich-Pitaevskiĭ equation to estimate the plasma temperature, found to be $T_e \sim 0.1$ eV.

## INTRODUCTION

A laser plasma expanding in a vacuum after the heating radiation pulse ceases to act on a target has been the object of numerous experimental and theoretical investigations. These investigations were aimed mainly at solving two problems: optimizing the conditions for population inversion in a plasma,[1,2] and obtaining an intense beam of multiply charged ions for ionic inertial fusion.[3,4] Spectroscopic investigations and calculations (see Refs. 5–8) have shown that a plasma expanding to a size $R \gtrsim 1$ mm is in a recombination nonequilibrium. The temperature $T_e$ the density $N_e$, and the populations $N_i^{nl}$ of the ion excited states were determined experimentally in the expansion region all the way to $R \lesssim 1$ cm. Mass spectrometry methods were used in Refs. 3, 9, and 10 to measure the ion energy and charge spectra at very large distances from the target, $R \gtrsim 1$ m. Calculations exist[11–13] on the role of recombination processes in the formation of the ion charge spectra.

Until quite recently, however, the plasma parameters ($T_e$, $N_e$, $N_i^{nl}$) in the space $R \gtrsim 1$ cm were not directly investigated. From our point of view it is this—remote—laser-plasma expansion zone that is of interest to the physics of atomic collisions. Indeed, extension of the known data for the region $R \sim 1$–10 cm within the framework of present notions leads to estimates $T_e \lesssim 1$ eV and $N_e \approx N_i \sim 10^{11}$–$10^{14}$ cm$^{-3}$, and ions with charge $Z \gg 1$ constitute a noticeable fraction of the total number of particles. At this combination of plasma parameters, it becomes attractive to perform beam-plasma experiments for direct investigation of elementary interactions of electrons and photons with multiply charged ions. A reliable determination of the basic parameters and of the radiative characteristics of a laser plasma in the range considered by us is a necessary preliminary stage for collision experiments.

In addition, an experimental study of recombination processes in a space in which the plasma density changes by several orders (and for which there are no exact data on $T_e$) is important for the development of a laser-plasma source of multiply charged ions.

We have investigated the vacuum ultraviolet (VUV) radiation from a laser-produced beryllium plasma far from the target ($R \gg 1$ cm). In the course of these investigations we developed a procedure for VUVspectroscopy of a plasma in this heretofore univestigated spatial region. Preliminary results of our investigations were reported in Ref. 14.

## 1. EXPERIMENTAL SETUP AND PROCEDURE

Laser-plasma emission spectra in the VUV were investigated with the setup illustrated in Fig. 1. Radiation from a $Q$-switched neodymium laser was guided into vacuum chamber 1 and focused on a flat beryllium target 2. At a laser-emission energy $Q = 10$–50 J and a laser-pulse duration $\tau \approx 50$ ns the power flux density in the focal spot on the target was $q \sim 10^{12}$–$10^{13}$ W/cm$^2$. The pressure in chamber 1 did not exceed $2 \cdot 10^{-6}$ torr. The plasma-expansion geometry in the vacuum chamber was set by a system of collimators 3, which shaped the sharp boundaries of the plasma bunch and determined the expansion angle (45°) in the horizontal plane. The ion density in the plasma was measured with two movable collectors placed at various distances from the target. To prevent ion reflection from the chamber wall opposite to the target, a special plasma trap 5 was placed on this wall and consisted of a row of deep slit collectors.

Laser-plasma emission was observed from a region separated by a distance $R$ from the target. The value of $R$ could be varied from 5 to 20 cm by moving the target. The plasma radiation was recorded by spectral channels, one of which contained monochromator 6 and was the main one. The sec-

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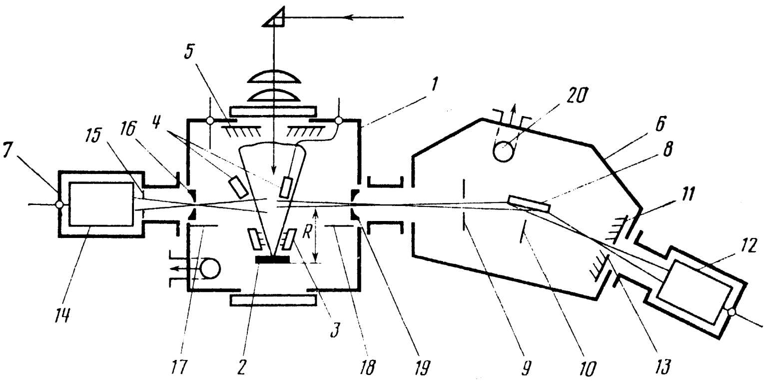


FIG. 1. Diagram of experimental setup: 1—laser-plasma chamber, 2—target unit, 3—plasma collimators, 4—ion collectors, 5—trap for ions, 6—monochromator, 7—monitor, 8—diffraction grating, 9—aperture diaphragm, 10—screen, 11—trap for radiation, 12, 14—photomultipliers, 13—exit slit, 15—diaphragm with filter, 16—entrance slit of monitor, 17, 18—screens protecting the entrance slits of the radiation-recording channels against scattered ions, 19—entrance slit of monochromator, 20—exhaust.

ond channel was a narrow-band detector and served as the monitor 7. The monochromator in the main recording channel was of the type with constant deflection angle.[15] It contained a spherical diffraction grating of 1 m radius and 600 lines/mm. The monochromator had a spectral resolution 0.3 nm and could record radiation of wavelength 10–90 nm. The error in the determination of the wavelengths of the spectral lines in the entire spectral range was not more than 0.2 nm. The diaphragms, screens, and traps (9, 10, 11) mounted in the monochromator reduced the scattered light to a minimum. The VUV radiation detector was a VEU-2A open secondary-electron multiplier (12) placed behind the exit slit 13 of the monochromator.

The monitor 7 was a combination of a VEU-2A multiplier 14 and a thin-film (0.3 $\mu$m) celluloid filter mounted on a diaphragm 15. This combination made it possible to record all the radiation in the range 4.4–10 nm. The geometry of light gathering in this channel was determined by the relative placement and by the dimensions of diaphragm 15 and the monitor exit slit 16. In both recording channels the radiation was incident from practically the same region of the plasma, the width of which in the direction of the expansion axis was $\Delta R \approx 2$ mm (Fig. 1).

The signals form the detectors of the two channels were recorded with broadband amplifiers and an S8-14 storage oscilloscope, ensuring an average time resolution 20 ns. To obtain satisfactory reproducibility of the recorded spectra, the output signal of the main channel was normalized to the monitor signal.

The laser-plasma emission spectra were recorded at distances $R_1 = 5$ cm, $R_2 = 10$ cm, and $R_3 = 30$ cm from the target, with a spatial resolution not worse than 4%. The emission spectra were investigated in detail for $R_1$ and $R_2$, and the brightest lines were reliably detected also at the distance $R_3$. It was observed that in the interval $R = 5$–$10$ cm the relative line intensity does not depend on $R$ (within a measurement accuracy $\sim 30\%$).

Figure 2 shows a plasma–emission spectrum typical of the $R = 5$–$10$ cm region in the wavelength range 25–80 nm in which the brightest recorded lines were located.

The spectrum in Fig. 2 contains singlet and triplet lines of the helium-like ions BeIII, corresponding to transitions between levels with $n = 2$–$7$ and $n = 2$. It contains also lines of helium-like BeIV, corresponding to the hydrogen series $n \to 2$ ($n = 3$–$7$) and $n \to 3$ ($n = 4$–$6$). To identify the spectrum reliably, many bright lines were recorded in the second and third spectral orders. The line intensities $J_{aa'}$ of the spectrum shown in Fig. 2 represent relative intensities with allowance for the relative sensitivity of the spectral channel.

The channel relative sensitivity was calibrated directly during the main experiment by the method of line pairs with common upper level.[16] Lines of the transitions ($n - n'$) and ($n - n''$) in BeIV were used, It was assumed that the level populations of the initial-state multiplet are proportional to

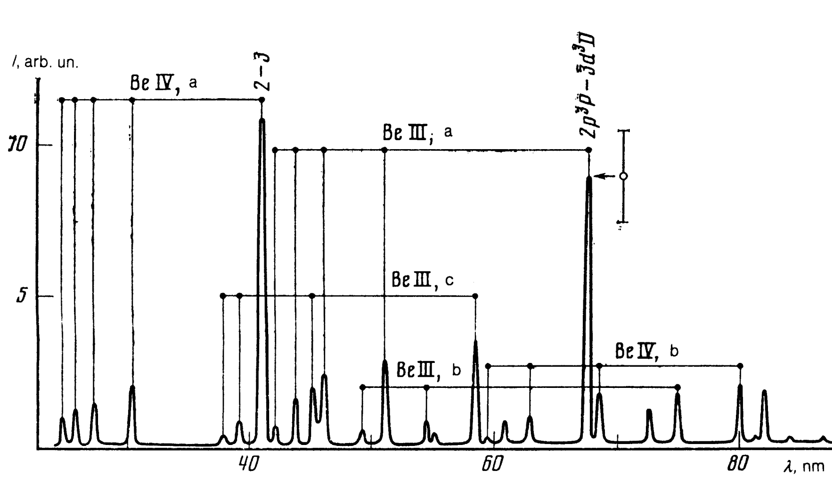


FIG. 2. Emission spectrum of laser plasma in far zone of the expansion. Series of spectral lines corresponding to transitions in $Be^{2+}$ and $Be^{3+}$ ions: BeIV: a—transitions $n \to 2$ ($n = 3$–$7$), b—$n \to 3$ ($n = 5$–$8$); BeIII: a—$nd\,^3D - 2p^3P$ ($n = 3$–$7$), b—$nd\,^1D - 2p^1P$ ($n = 3$–$5$); c—$np^3P \to 2s^3S$ ($n = 3$–$7$).

TABLE I. Relative line intensities.

| BeIV transition | $J_{aa'}$ arb. un. | $\lambda$, nm | BeIII transition | $J_{aa'}$ arb. un. | $\lambda$, nm |
|---|---|---|---|---|---|
| 2–3 | 100 | 41.0 | $2p^3P$–$3d^3D$ | 100 | 67.5 |
| 2–4 | 23 | 30.3 | $2p^3P$–$4d^3D$ | 32 | 50.9 |
| 2–5 | 14 | 27,1 | $2p^3P$–$5d^3D$ | 28 | 45.7 |
| 2–6 | 15 | 25.7 | $2p^3P$–$6d^3D$ | 18 | 43.4 |
| 2–7 | 11 | 24.8 | $2p^3P$–$7d^3D$ | 7 | 42.0 |
| 3–5 | 18 | 80.1 | $2s^3S$–$3p^3P$ | 39 | 58.2 |
| 3–6 | 16 | 68.3 | $2s^3S$–$4p^3P$ | 22 | 45.1 |
| 3–7 | 8 | 62.7 | $2s^3S$–$6p^3P$ | 11 | 38.8 |
| 3–8 | 3 | 59.6 | $2s^3S$–$7p^3P$ | 7 | 37.7 |
| | | | $2p^1P$–$3d^1D$ | 20 | 74.6 |
| | | | $2p^1P$–$4d^1D$ | 6 | 54.9 |
| | | | $2p^1P$–$5d^1D$ | 6 | 48.9 |
| | | | $2p^3P$–$3s^3S$ | 13 | 72.5 |

the statistical weights and that the plasma is optically thin for both lines.

Since the relative line intensities are independent of $R$, the spectrum in Fig. 2 and Table I give for the ions $Be^{3+}$ and $Be^{2+}$ the average values of $J_{aa'}$ in the interval 5–10 cm, normalized to the intensity of the brightest line of the corresponding ions. The phonon signal on the spectrogram of Fig. 2 is due mainly to scattered light. The background level was estimated for the monochromator tuned to the wavelength region $\lambda \leqslant 10$ nm, in which the reflection of the diffraction grating should be zero.

Figure 3 shows typical oscillograms of the recorded signals: a—of the laser pulse (1) and of the plasma emission in the spectral line (2), and b—of the ion collector. One can see on oscillogram 3b the photoeffect (1) induced by the emission of the plasma during the stage of its heating by the laser pulse, and the ion current (2) of the expanding plasma bunch.

The density of the plasma ions in the observation region was measured, with time resolution, by ion collectors whose design permitted reliable separation of the ion and electron components of the plasma. The ion density was determined from the relation $N_i = j/sv\bar{Z}e$, where $j$ is the recorded ion current, $s$ the area of the collector entrance diaphragm, $v$ the ion velocity determined in our experiment directly from the time of flight (Fig. 3b), and $\bar{Z}$ the average ion charge, assumed to equal 3. The choice of $\bar{Z} \approx 3$ was based on the data

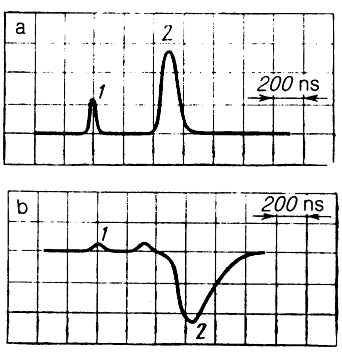


FIG. 3. Typical oscillograms of recorded signals ($Q = 15$ J, $\tau = 50$ ns): a) 1—laser-pulse signal from coaxial-photocell output, 2—signal from monochromator, $\lambda = 41$ nm ($R = 10$ cm); b) signal from ion collector located at a distance $R = 12.5$ cm: 1—signal from photoelectrons produced by plasma radiation during its heating, 2—ion signal.

of Refs. 17 and 18, where a mass-spectroscopic investigation was made of the ion composition of a laser plasma produced under conditions close to those considered here. Measurement with the collectors have shown that in the interval $R_1$–$R_3$ the peak values of the density $n_i$ varied in the range $10^{12}$–$10^{13}$ cm$^{-3}$.

It was established by a set of control experiments that the recorded radiation is produced only in the plasma and is not due to excitation processes occurring when the plasma ions are scattered from inner surfaces of the apparatus and to interactions between these ions and the residual gas. To this end, the chamber wall in the field of view of the monochromator was moved away another 10 cm from the entrance slit, and this slit was protected by a screen (17 and 18 in Fig. 1). The line intensities were measured at various pressures $p$ of the residual gas in the range $2\cdot 10^{-6} \leqslant p \leqslant 2\cdot 10^{-5}$ Torr. No effect on the spectrum characteristics were observed in this case. Moreover, no lines of excited atoms or of ions of the wallmaterial and of the residual gas were observed in the investigated spectrum.

## 2. POPULATION OF THE EXCITED STATES OF $Be^{3+}$ IONS. ABSOLUTE MEASUREMENTS OF LINE INTENSITIES

We calculated from the relative intensities $J_{aa'}$ the populations of the excited states of $Be^{3+}$ ions with principal quantum numbers $n = 3$ to 7. The populations were calculated using the known probabilities of radiative transitions in hydrogen-like ions. The relative populations $N_n/N_3$ for $Be^{3+}$ are listed in Table II, from which it can be seen that they differ greatly from the Boltzmann values at $T_e \sim 1$ eV.

To estimate the density of the excited ions in the observation region, we measured the absolute intensities of the brightest lines. The this end, an absolute calibration of the main spectral channel was carried out. The calibration procedure was based on experience gained in measurements of absolute values of VUV photon fluxes from a hot laser plasma.[19] The laser emission (20 J, 50 ns) was focused on a tungsten target placed in the monochromator field of view. It is known from Ref. 19 that the VUV emission spectrum of a laser-produced plasma on a tungsten target is continuous, and the photon flux $I_\nu$ per unit spectral interval is also known. In particular, $I_\nu = 10^{21}$ nm$^{-1}\cdot$sr$^{-1}\cdot$s$^{-1}$ at $\lambda = 60$ nm. From the known values of $I_\nu$ we estimated the absolute sensitivity of the spectral channel and calculated the abso-

TABLE II. Population ratio $N_n/N_3$ of excited states of hydrogen-like $Be^{3+}$ ions.

| $n$ | $N_n/N_3$ | |
|---|---|---|
| | experiment | calculation |
| 3 | 1.0 | 1.0 |
| 4 | 1.8 | 2.2 |
| 5 | 3.1 | 4.3 |
| 6 | 8.0 | 7.6 |
| 7 | 11.0 | 12.3 |

lute intensities $J_{aa'}$ ($\text{phot}\cdot\text{cm}^{-3}\cdot\text{s}^{-1}$) of certain lines of $Be^{2+}$ and $Be^{3+}$ as functions of $R$. The results of the estimates are listed in Table III, and the absolute values were determined by us accurate to a coefficient 5.

### 3. DISCUSSION OF RESULTS

In the analysis of the experimental data we paid primary attention to elementary atomic processes capable in principle of producing excited $Be^{2+}$ and $Be^{3+}$ ions, whose population distributions over the levels deviate greatly from the Boltzmann law, in a laser plasma at sufficiently large distances from the target. We considered three-particle recombination, photorecombination, and ion-ion collisions. The absence of contributions from the latter process in the far zone of the expansion becomes obvious from an estimate of the maximum energy $E_{ii}$ of interaction between two ions, one of which is emitted from the acceleration zone near the target ($r \lesssim 10\,\mu\text{m}$) at a time $\tau$ (the laser pulse duration) after the second, and overtakes the latter at a distance $r$. At typical experimental velocity $v$ and laser pulse duration $\tau$ ($v \sim 10^7$ cm/s, $R \sim 10$ cm, $\tau \sim 10^{-7}$ s), $E_{ii}$ does not exceed several electron volts, patently not enough for an inelastic interaction capable of exciting Be ions.

Turning now to recombination processes, we note first that according to Ref. 8 the rate of radiative recombination becomes much lower than the rate of three-particle recombination at $T_e < 10^{-14} z N_e$, meaning under our conditions $T_e \lesssim 0.5$ eV. It is also known that photorecombination proceeds predominantly in the ground state and its rate decreases steeply with increasing quantum number (Ref. 20), but does not correspond to the experimentally observed growth of the level populations with increase of $n$ (see Table II).

Three-particle recombination with participation of a $Be^{z+}$ ion and two electrons leads at $T_e \lesssim 1$ eV to population of excited states with large $n$, having an energy $E_n \sim T_e$. The lifetime of the ion excited state is determined by two processes, radiative decay and inelastic scattering of free electrons from the excited ions. These process have significantly different dependences on $n$, so that when the distribution of the recombination flux over levels with different $n$ are considered it is convenient to introduce a certain value of $ne$ such that at $n > n_0$ the dominant role in the decay of the highly excited states is played by collisions, but at $n < n_0$ by radiation. To estimate $n_0$ one uses usually[20] the equation

$$n_0 = z(10^{18}/N_e)^{1/7}(T_e/z^2R_y)^{1/14},$$

from which it follows that for $Be^{3+}$ ions ($z = Z+1 = 4$) we have $n_0 \approx 20$ in the considered plasma-expansion region ($T_e \lesssim 1$ eV, $N_e \sim 10^{13}$ cm$^{-3}$).

Assuming that the principal role in the formation of the observed plasma is played by three-particle recombination, we have calculated the populations of the excited states of the $Be^{3+}$ ions using the equation

$$N_n = \frac{I_r}{W_n} C(n_0, n), \tag{1}$$

in which $W_n$ is the probability of the radiative decay of a level with principal quantum number $n$, $C(n_0,n)$ is a cascade-matrix element equal to the summary relative probability of a radiative transition from the level $n_0$ to the level $n$ ($n_0 > n$),[20] $I_r = \alpha N_i N_e$ is the intensity of ternary recombination of an ion with charge $Z+1$ with formation of an ion having a charge $Z$, $N_i$ is the density of the ions of charge $Z+1$, and $N_e$ is the electron density. For highly excited states with $n > 10$ it is convenient to calculate $C(n_0,n)$ by using the analytic expression obtained in Ref. 21.

The calcualtion has shown that variation of $n_0$ in the range from $n_0 = 15$ to $n_0 \to \infty$ has practically no effect on the relative values of the populations. The calculated values of $N_n/N_3$ listed in Table II were obtained at $n_0 = \infty$. The good agreement between the calculated and measured $N_n/N_0$ confirms the assumed recombination origin of the recorded radiation.

In (1), $\alpha$ is the coefficient of three-particle recombination, for which Gurevich and Pitaevskiĭ[22] obtained the expression

$$\alpha = N_e \frac{4\pi(2\pi)^{1/2}}{9} \frac{e^{10} z^3 \Lambda}{m^{1/2} T_e^{9/2}}. \tag{2}$$

Although Eq. (2) was obtained assuming large $z$ ($z > 10$), the only substantial constraint in its use for $z < 10$, as indicated in Ref. 22, is the condition $T_e \ll \varepsilon_i$ where $\varepsilon_i$ is the ionization potential of the ion, equal to 218 eV in the investigated case (for $Be^{3+}$).

Our absolute measurements of the laser-plasma radiation intensity (Table III) permitted an estimate of the electron temperature $T_e$ in the emission observation region, owing to the favorable ratio of $T_e$ to the rate of the three-particle recombination. It was established that in the investigated expansion region $T_e$ decreases by an approximate factor 1.5 in the interval $R = 5$–$10$ cm, to a value $(0.1 \pm 0.05)$ eV. The slow decrease of $T_e$ at an appreciable increase of the laser plasma volume with increasing $R$ is due apparently to recombination heating of the electron gas. Estimates show that a beryllium plasma having this temperature and a density $N_e \sim 10^{13}$ cm$^{-3}$ is "weakly nonideal."[8]

TABLE III. Number of photons emitted by plasma vs distance $R$ to target.

| $R$, cm | $J$, cm$^{-3}$s$^{-1}$ | |
|---|---|---|
| | BeIV, 2—3 | BeIII, $2p^3P$—$3d^3D$ |
| 5 | $1.5\cdot10^{18}$ | $1.3\cdot10^{18}$ |
| 10 | $1.5\cdot10^{17}$ | $1.1\cdot10^{17}$ |
| 20 | $2.2\cdot10^{15}$ | $1.1\cdot10^{15}$ |

The aggregate of the experimental and calculated data considered above is evidence that only elementary collision process, three-particle recombination of ions with electrons, takes place in a laser plasma in the far expansion zone. This process determines completely the radiative characteristics of a laser plasma in the far expansion zone and the change of its charge composition.

## CONCLUSION

We have investigated experimentally a laser plasma in the far exansion zone, and found it to be characterized by a temperature $T_e \sim 0.1$ eV, an ion or electron density $N_i \sim N_e \sim 10^{13}$–$10^{14}$ cm$^{-3}$, and an appreciable average charge $Z \sim 3$. In this region, judging from all the above, only one elementary process takes place with noticeable probability, viz., three-particle recombination of electrons with ions.

A plasma in the far expansion zone can be regarded as a promising medium for the study of elementary atomic processes in which multiply charged ions participates, inasmuch as in this region the plasma has a noticeable density of such ions, and they can be reliably detect by spectroscopic means.

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