# *INVESTIGATION OF THE VACUUM ULTRAVIOLET RADIATION FROM A POWERFUL PULSED DISCHARGE*

V. D. PIS'MENNYĬ, I. M. PODGORNYĬ, and Sh. SUKEVER

Moscow State University

Submitted to JETP editor June 30, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 2008-2014 (December, 1962)

Results of an investigation of the radiation emitted by a powerful pulsed discharge in the range between 150 and 2200 Å are presented. It is shown that for a discharge current of 200 kA the ion temperature is 200 eV and the electron temperature is 20 eV. The cause of the difference between the electron and ion temperature is discussed.

DURING the ten years which have passed since the discovery of hard radiation from short-duration powerful pulsed discharges dozens of works have been published in which the properties of such a discharge are described. However, as far as we know, up to the present time no one has investigated the radiation from a powerful pulsed discharge in the vacuum ultraviolet region in conditions where the discharge duration is determined by inertial times. This region, at temperatures of a few tens of eV, is particularly rich in spectral lines. It is also attractive because it embraces a wide range of atomic energy-level differences. The latter fact, in conditions where the levels populations have a Boltzmann distribution, enables the electron temperature to be determined with great accuracy.

The results reported here have the important disadvantage that the spectrograph plate was exposed for the whole duration of the discharge. Nevertheless, bearing in mind the results of Luk'yanov and Sinitsyn[1], which showed that the highly ionized states of the atoms emit mainly for ~ 1 μsec, it is possible to compensate for this defect to a considerable extent and obtain new information about the state of the plasma at the time of maximum compression of the pinch.

## EXPERIMENTAL CONDITIONS

The experiments were carried out with a pulse generator described in earlier publications (see for example [2]). The capacity of the condenser bank of the generator is 36 μF and the circuit inductance is 500 cm.* For a voltage of 40 kV on the condensers the amplitude of the current is 200 kA. The electrode discharge took place in a discharge vessel consisting of a porcelain tube 170 mm in diameter and 1000 mm long. The vessel was fitted with two holes in the central region. One of them, 32 mm in diameter, served as an exit for radiation from the vessel. The other hole, 100 mm in diameter, on the opposite side, was used for pumping out the vessel. As can be seen from Fig. 1, the geometry of the vessel and the disposition of the apparatus have been chosen so that radiation from the walls of the discharge vessel cannot fall in the slit of the spectrograph. A tube 500 mm long was used to connect the spectrograph to the vessel. Because of this, only radiation from the discharge region shown shaded in the diagram was able to fall on to the spectrograph slit.

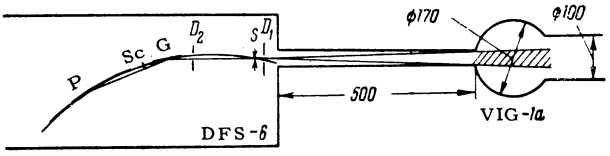


FIG. 1. Diagram showing the connection of the spectrograph to the discharge chamber. D – diaphragms, S – spectrograph slit, Sc – screen, G – grating, P – photographic plate.

A DFS-6 vacuum spectrograph was used with a curved diffraction grating having 600 lines per mm. In order to reduce the background caused by scattered light, a system of diaphragms was used. As a result of long, painstaking work, the background was reduced to a minimum and it was possible to obtain spectra of radiation from the plasma over the range 150—2000 Å. Sodium salycilate was used as a sensitizer. All photographs of the spectra were obtained on aerophotoplates with a sensitivity of 1400 GOST units. In converting from plate den-

*1 cm = 1.11 pF

sities to intensities the quantum yield of the sensitizer was assumed to be constant over the range of wavelengths studied[3].

The data presented below were obtained as a result of evaluating 21 plates exposed with spectrograph slit widths of 20, 40, and 80 $\mu$. The number of discharges required to obtain a line in the normal density region depends on the intensity of the line and on the slit width; in various experiments it varied from 50 to 800.

Spectra were taken for discharges in hydrogen and nitrogen. The hydrogen was purified by means of nickel filters. The main experimental data was obtained at an initial hydrogen pressure of $5 \times 10^{-2}$ mm Hg, which corresponded to the maximum yield of hard radiation of a potential of 40 kV. Before each discharge the vessel was pumped out to $(7-9) \times 10^{-7}$ mm Hg by an oil diffusion pump with nitrogen trap.

## RESULTS

Discharge spectrum. A typical spectrum is depicted in Fig. 2 and has been obtained with a spectrograph slit width of 40 $\mu$ and an exposure duration of 400 discharges. In the discharge spectrum in hydrogen, purified by passing through a nickel filter, 50 lines (see Table I) have been identified, of which only the single weak 1215.6 Å line belongs to hydrogen. In contrast to the spectra of hydrogen discharges stabilized by a magnetic field, in which bright carbon lines are observed, the spectrum shown in Fig. 2 is poor in carbon lines, and the strongest lines in it are the lines of the lithium-like ions of oxygen and nitrogen. This difference in the spectra is evidently due to the difference in wall materials. Previously[4-6] the discharge vessel was made of stainless steel.

The presence of bright carbon lines in the discharge spectrum of the ZETA device made possible the discovery of the 2278-Å CV line from the $2s^3S-2p^3P^0$ transition. The search for the analogous line OVII (1627.60 Å) in ZETA was unsuccessful. In the experimental conditions described here a weak line has been found at 1627.6 Å, which evidently corresponds to the OVII transition $2^3S_1-2^3P_2$. Among the lines corresponding to transitions with terms having a high excitation potential one should note the bright $2^2S-3^2P$ and $2^2P-3^2D$ OVI lines with excitation potentials of 82 and 83 eV, respectively, and also the $2^2S-4^2P$ and $2^2P-3^2D$ NV lines with excitation potentials 76 and 60 eV, respectively.

Along with oxygen and nitrogen, bright lines of silicon also appear in the spectrum. These belong to ions in lower states of ionization.

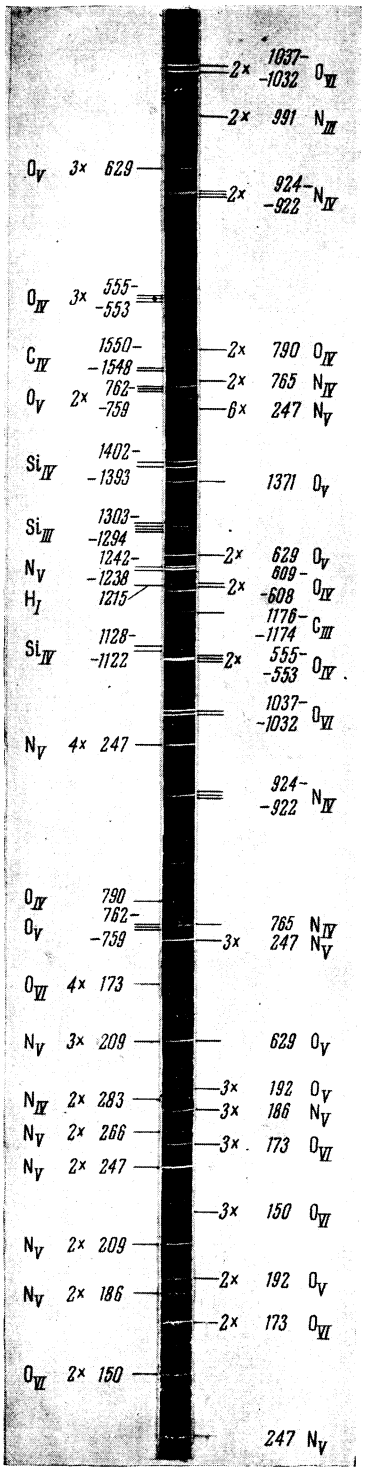


FIG. 2. Photograph of the spectrum of the pulsed discharge in hydrogen: C = 36 $\mu$F, V = 40 kV, p = $5 \times 10^{-2}$ mm Hg, width of spectrograph slit 40$\mu$, exposure 40 discharges.

Electron temperature. The electron temperature has been determined from the relative intensity of two spectral lines of atoms of the same element in identical ionization states. Such a method of determination enables one to exclude from consideration equations for the probability that one particular state of ionization or the other will exist in the given conditions. In evaluating the electron temperature it has been assumed that the popula-

## Table I

| Wavelength, Å | Line identification | | Intensity* | Ionization energy, eV | Excitation potential, eV |
|---|---|---|---|---|---|
| 1862.8<br>1854.7 | $Al_{III}$ | $3s\,^2S - 3p\,^2P$ | 11<br>12 | 18.6 | 6.7 |
| 1718.6 | $N_{IV}$ | $2p\,^1P - 2^2\,^1D$ | 22 | 47.2 | 23.3 |
| 1627.6 | $O_{VII}$ | $2s\,^3S - 2p\,^3P$ | 5 | 138.0 | 570 |
| 1550.8<br>1548.2 | $C_{IV}$ | $2s\,^2S - 2p\,^2P$ | 20<br>35 | 47.7 | 8.0 |
| 1402.7<br>1393.7 | $Si_{IV}$ | $3s\,^2S - 3p\,^2P$ | 30<br>56 | 33.5 | 8.8 |
| 1371.3 | $O_V$ | $2p\,^1P - 2p^2\,^1D$ | 45 | 77.1 | 28.6 |
| 1353.8—<br>—1346.9 | $Si_{II}$ | $3p^2\,^4P - 4s\,^4P$ | 5 | 8.1 | 14.6 |
| 1312.6 | $Si_{III}$ | $3p\,^1P - 4s\,^1S$ | 12 | 16.3 | 19.6 |
| 1303.3<br>1301.1<br>1298.9<br>1296.7<br>1294.5 | $Si_{III}$ | $3p\,^3P - 3p^2\,^3P$ | 19<br>13<br>21<br>13<br>16 | 16.3 | 16.0 |
| 1242.8<br>1238.8 | $N_V$ | $2s\,^2S - 2p\,^2P$ | 240 | 77.1 | 10.0 |
| 1215.7 | $H_I$ | $1s\,^2S - 2p\,^2P$ | 5 | | 10.1 |
| 1176.3—<br>—1174.9 | $C_{III}$ | $2p\,^3P - 2p^2\,^3P$ | 24 | 24.3 | 17.0 |
| 1128.3<br>1122.5 | $Si_{IV}$ | $3p\,^2P - 3d\,^2D$ | 19<br>21 | 33.5 | 19.8 |
| 1113.2—<br>—1108.3 | $Si_{III}$ | $3p\,^3P - 3d\,^3D$ | 15 | 16.3 | 17.6 |
| 1037.6<br>1031.9 | $O_{VI}$ | $2s\,^2S - 2p\,^2P$ | 90<br>180 | 113.4 | 12.0 |
| 997.4—<br>—993.5 | $Si_{III}$ | $3p\,^3P - 4s\,^3S$ | 5 | 16.3 | 18.9 |
| 991.6<br>989.8 | $N_{III}$ | $2p\,^2P - 2p^2\,^2D$ | 33<br>19 | 29.5 | 12.5 |
| 977.0 | $C_{III}$ | $2s^2\,^1S - 2p\,^1P$ | 5 | 24.3 | 12.6 |
| 955.3 | $N_{IV}$ | $2p\,^1P - 2p^2\,^1S$ | 22 | 47.2 | 29.0 |
| 924.3<br>923.7<br>923.2<br>922.5<br>922.0 | $N_{IV}$ | $2p\,^3P - 2p^2\,^3P$ | 35<br>—<br>35<br>26<br>38 | 47.2 | 21.7 |
| 818.1<br>815.0 | $Si_{IV}$ | $3p\,^2P - 4s^1\,S$ | 5 | 33.5 | 24.0 |
| 790.2<br>790.1<br>787.7 | $O_{IV}$ | $2p\,^2P - 2p^2\,^2D$ | —<br>25<br>15 | 54.7 | 15.7 |
| 779.8<br>779.9 | $O_{IV}$ | $2p^2\,^2D - 2p^3\,^2D$ | 9 | 54.7 | 31.5 |
| 774.5 | $O_V$ | $2p\,^1P - 2p^2\,^1S$ | 13 | 77.1 | 35.5 |
| 765.1 | $N_{IV}$ | $2s^2\,^1S - 2p\,^1P$ | 19 | 47.2 | 16.1 |
| 763.3<br>764.4 | $N_{III}$ | $2p\,^2P - 2p^2\,^2S$ | 5 | 29.5 | 16.2 |
| 762.0<br>761.1<br>760.4<br>760.3<br>759.4<br>758.7 | $O_V$ | $2p\,^3P - 2p^2\,^3P$ | 16<br>15<br>26<br>—<br>15<br>15 | 77.1 | 26.4 |
| 629.7 | $O_V$ | $2s^2\,^1S - 2p\,^1P$ | 90 | 77.1 | 19.6 |
| 625.8<br>625.1<br>624.6 | $O_{IV}$ | $2p^2\,^4P - 2p^2\,^4S$ | 14<br>18<br>— | 54.7 | 28.5 |
| 609.8<br>608.4 | $O_{IV}$ | $2p\,^2P - 2p^2\,^2S$ | 14<br>21 | 54.7 | 20.3 |
| 555.3<br>554.5<br>554.1<br>553.3 | $O_{IV}$ | $2p\,^2P - 2p^2\,^2P$ | 24<br>44<br>31<br>25 | 54.7 | 22.3 |
| 322.7—<br>—322.5 | $N_{IV}$ | $2p\,^3P - 3s\,^3S$ | 5 | 47.2 | 46.7 |
| 335.0 | $N_{IV}$ | $2p\,^1P - 3d\,^1D$ | 14 | 47.2 | 53.0 |
| 303.1—<br>—303.1 | $N_{IV}$ | $2p^2\,^3P - 3d\,^3D$ | 5 | 47.2 | 62.4 |
| 283.6—<br>—283.4 | $N_{IV}$ | $2p\,^3P - 3d\,^3D$ | 31 | 47.2 | 51.8 |
| 266.4<br>266.2 | $N_V$ | $2p\,^2P - 3s\,^2S$ | 29 | 77.1 | 56.3 |
| 247.7<br>247.6 | $N_V$ | $2p\,^2P - 3d\,^2D$ | 100 | 77.1 | 59.8 |
| 238.6<br>238.4 | $O_{IV}$ | $2p\,^2P - 3d\,^2D$ | 5 | 54.7 | 51.8 |
| 220.3 | $O_V$ | $2p\,^1P - 3d\,^1D$ | 5 | 77.1 | 75.6 |
| 215.3—<br>—215.0 | $O_V$ | $2p\,^3P - 3s\,^3S$ | 5 | 77.1 | 67.6 |
| 209.3<br>209.3 | $N_V$ | $2s\,^2S - 3p\,^2P$ | 44 | 77.1 | 59.0 |
| 203.9<br>203.8 | $O_V$ | $2p^2\,^3P - 3d\,^3D$ | 5 | 77.1 | 87.0 |
| 192.9—<br>—192.7 | $O_V$ | $2p\,^3P - 3d\,^3D$ | 23 | 77.1 | 74.2 |
| 186.1<br>186.1 | $N_V$ | $2p\,^2P - 4d\,^2D$ | 15 | 77.1 | 76.3 |
| 172.2 | $O_V$ | $2s^2\,^1S - 3p\,^1P$ | 5 | 77.1 | 71.7 |
| 173.1 | $O_{VI}$ | $2p\,^2P - 3d\,^2D$ | 22 | 113.4 | 83.3 |
| 162.6 | $N_V$ | $2s\,^2S - 4p\,^2P$ | 5 | 77.1 | 75.9 |
| 150.1<br>150.1 | $O_{VI}$ | $2s\,^2S - 3p\,^2P$ | 15 | 113.4 | 82.3 |

*In this column the height of the spectral line is given in relative units to an accuracy of 10-15%.

**Table II**

| Line | Transition | $A_i g_i$, sec$^{-1}$ | Excitation potential, eV | Intensity | $T_e$, eV |
|---|---|---|---|---|---|
| $O_V$ 759 | $2p\,^3P—2p^2\,^3P$ | $2.86\times10^9$ | 26.4 | 94 | 19 |
| $O_V$ 629 | $2s^2\,^1S—2p\,^1P$ | $12.3\times10^9$ | 19.6 | 572 | |
| $N_{IV}$ 955 | $2p\,^1P—2p^2\,^1S$ | $2.9\times10^9$ | 29 | 100 | 31 |
| $N_{IV}$ 924—922 | $2p\,^3P—2p^2\,^3P$ | $22\times10^9$ | 21.7 | 940 | |
| $N_V$ 186 | $2p\,^2P—4d\,^2D$ | $1.31\times10^{11}$ | 76.3 | 100 | 27 |
| $N_V$ 247 | $2p^2P—3d\,^2D$ | $4.23\times10^{11}$ | 59.8 | 590 | |
| $N_V$ 186 | $2p\,^2P—4d\,^2D$ | $1.31\times10^{11}$ | 76.3 | 100 | 13 |
| $N_V$ 209 | $2s\,S^2—3p\,^2P$ | $1.3\times10^{11}$ | 58 | 265 | |
| $Si_{IV}$ 1122 | $3p\,^2P—3d\,^2D$ | $8.68\times10^9$ | 19.8 | 140 | 4.5 |
| $Si_{IV}$ 1402 | $3s\,^2S—3p\,^2P$ | $1.75\times10^9$ | 8.8 | 305 | |

tion of the energy levels of the ions is determined by Boltzmann's equation, so that

$$T = \frac{\Delta E}{k}\left[\ln \frac{J_2 \nu_1 g_1^{(in)} A_1}{J_1 \nu_2 g_2^{(in)} A_2}\right]^{-1},$$

where $\Delta E$ is the difference in energy of the levels, $J_1$ and $J_2$ are the total line intensities, $g^{in}$ is the statistical weight of the initial state, A are the transition probabilities[7], $\nu$ are the line frequencies, and k is Boltzmann's constant.

A calculation recently carried out by V. I. Kogan (private communication) gives grounds for assuming the Boltzmann distribution. The results of the calculation indicate that under the conditions of the present work, the Boltzmann equilibrium is established for the first excited levels of $O_{VI}$ and $N_V$. The validity of this assumption is supported by the good agreement of the values of the electron temperature obtained from an analysis of the lines of nitrogen and oxygen for different states of ionization. The results of the measurements of the electron temperature of a discharge in hydrogen are presented in Table II.

From these data it follows that the electron temperature determined from oxygen and nitrogen is about 20—30 eV, which is several times greater than the value of the electron temperature determined using silicon. It is possible that such a discrepancy arises from the injection of heavy ions into the discharge during the later stages of compression. Unfortunately, detailed data on the time dependence of the intensities and on the spatial distribution of the emission centers are not available for the various lines, but the authors hope that in the near future they will be able to answer these questions. However, the results of the measurement of the electron temperature by means of the relative intensity of silicon lines must be treated with caution since, in contrast to oxygen and nitrogen, where the ratio of the intensities of multiplet lines differs by about 10% from the theoretical value, in the case of silicon the discrepancy generally exceeds 30%. The latter fact indicates that the silicon lines are strongly self-absorbed.

In order to estimate the electron temperature by an independent method, we used the results of calculations presented in [8] for the Elwert equilibrium of oxygen ions. For such an equilibrium to exist the ionization must be produced by electron collisions, and the reverse process must be brought about mainly by recombination with emission of a quantum as a result of double collisions. Physically this means that the recombination probability for three-body collisions is much smaller than the probability of radiative recombination resulting from double collisions. The relative values of these processes can be estimated from Elwert's[9] data, but in his work the probability of three-body recombination is greatly underestimated, since no account is taken of the capture of an electron at high levels and subsequent transition to the ground state. A method of calculation which takes into account the capture of electrons at high levels was proposed by O. B. Firsov. The results of such computations carried out for high temperatures are presented in the paper of Belyaev and Budker[10].

As a consequence of the work of the authors referred to [9,10] it follows that under the experimental conditions described in this report, three-body collisions can be neglected, and therefore an equilibrium of the type considered must set in if the duration of the compressed state is long enough for equilibrium to be reached. A density of $10^{17}$,[11] is insufficient for an Elwert equilibrium to set in [12] so that such an estimate is more likely to give a lower limit of the electron temperature. The intensity distribution of the lines of the various oxygen ions observed in our work corresponds to the

Table III

| Element | Wavelength, Å | $T_i$, $10^6$ °K | Element | Wavelength, Å | $T_i$, $10^6$ °K |
|---|---|---|---|---|---|
| $O_{VI}$ | 1032 | 2.5 | $N_V$ | 1242 | 2.4 |
| $O_V$ | 629 | 2.6 | $N_{IV}$ | 1718 | 2.7 |
| $O_V$ | 1371 | 2.3 | $N_{IV}$ | 922 | 2.3 |
| $O_{IV}$ | 554.5 | 2.8 | $N_{IV}$ | 765 | 2.6 |

electron temperature of 20—30 eV presented above.

As far as the lines of silicon are concerned, they belong to the ions $Si_{IV}$, $Si_{III}$, and $Si_{II}$, whereas the oxygen lines belong to the ions $O_{VI}$, $O_V$, and $O_{IV}$, which is further corroboration of the low value of the electron temperature of the silicon-enriched plasma.

The addition of 20% oxygen (by volume) to the hydrogen produces a sharp change in the character of the spectrum. The $O_{VI}$ and $O_V$ lines die away and the lines of $O_{III}$ appear. In this case the energy of compression of the plasma column is distributed among a large number of particles.

Ion temperature. The ion temperature of the plasma has been measured by line-broadening of the highly ionized states of oxygen and nitrogen. The line profiles were approximated by Voigt functions. Subsidiary experiments performed with a vacuum spark source showed that the apparatus broadening function was closely dispersive in form, as expected. The apparatus broadening function was subtracted from the experimentally obtained curve to determine the width of the true line. The ion temperature was determined by assuming that the line width resulted from Doppler broadening. The values of the ion temperature obtained do not depend on the charge on the ion (see Table III) and amount to $T_i \sim 2.5 \times 10^6$ °K, which is in satisfactory agreement with the results of other authors[11].

## DISCUSSION OF RESULTS

The data obtained in this work characterize the properties of a plasma column in the compressed state, since it is at this very instant that the lines of highly ionized ions appear. The value of the ion temperature agrees with a plasma-column compression speed $v_0 = 2 \times 10^7$ cm/sec, a value well known both from the inertial theory as well as from numerous experimental investigations.

At first glance it is difficult to understand the large difference between the electron and ion temperatures ($T_e = 20$ eV and $T_i = 250$ eV), since at densities $n_e = 10^{17}$ and compressed-state durations $\tau \sim 1\,\mu$sec the electron and ion temperatures should be equal. In actual fact such considerations are not valid, since they do not take account of the complete energy balance. The electrons not only draw energy from the hot ions, but they also lose it to excitation and ionization of the ions and atoms. At impurity concentrations of a few per cent these losses[8] become comparable with the rate of energy input from the ions. As a consequence, the inequality $\overline{T}_e < \overline{T}_i$ will always hold for the plasma of a powerful pulsed discharge at the instant of maximum compression.

The authors thank L. A. Artsimovich and V. I. Kogan for interesting discussions and Yu. K. Zemtsov and L. Cher for their participation in various stages of the work.

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Translated by F. L. Curzon
343