SOVIET PHYSICS JETP VOLUME 29, NUMBER 2 AUGUST, 1969

IONIZATION OF A MEDIUM BY ULTRAVIOLET RADIATION EMITTED BY A SUBSTANCE HEATED IN THE FOCUS OF A LASER

T. U. ARIFOV, G. A. ASKAR'YAN, and N. M. TARASOVA

P. N. Lebedev Physics Institute, U.S.S.R. Academy of Sciences

Submitted September 9, 1968

Zh. Eksp. Teor. Fiz. 56, 516–521 (February, 1969)

Experiments on the ionizing effect of ultraviolet radiation, produced by focusing a laser beam on a target, are described. It is shown that, even at moderate laser powers, ultraviolet radiation is very likely to ionize gas atoms and molecules, particularly near the hot spot. This presents new opportunities for obtaining a highly ionized plasma by directing a laser beam on a speck, target, or a portion of a gas. Microwave diagnostics, probes, and phosphors were used to study ultraviolet radiation and its ionizing effect. Experiments on focusing ultraviolet radiation by metal polished mirrors are described. It is shown that the latter are applicable not only to the problem of obtaining a plasma using a laser but to photodissociation, excitation of atoms, obtaining polarized electrons from polarized atoms, and to experiments on the effects of concentrated ultraviolet radiation on matter and biological specimens.

1. INTRODUCTION

THE development of powerful lasers has provided means for rapid heating of a small amount of matter to high temperatures, exceeding millions of degrees. The spectral composition of the radiation of matter heated in this way has been investigated[1–4] and it has been found that the spectrum includes hard vacuum ultraviolet and x-ray wavelengths, confirming that high temperatures are reached by laser heating even at moderate output powers of several megawatts or more. The spectra of multiply ionized atoms have also been recorded[5,6] and the degree of ionization has indicated that high temperatures have been reached during heating. However, in these investigations the emission spectra are given in relative units; because of the difficulties encountered in making absolute measurements in this part of the spectrum, the absolute yield and ionizing effect of such radiation have not been investigated, although these factors are important in practical applications of laser-excited radiators as ionizing agents, in estimating the role of radiation in the laser heating of matter, etc. These problems are discussed in the present paper, which describes detailed experimental investigations of the ionization of gases by the ultraviolet radiation generated by matter heating at the focus of a laser (the preliminary results were published in a short note[7]). The results are also given of experiments on the focusing of the ionizing radiation, the control of this radiation, and the filtering of secondary ionizing agents.

Since the photoionization cross section is $\sigma_{ph} \sim 10^{-17}$–$10^{-18}$ cm^2, we can expect a strong ionizing effect, with the probability of the ionization of an atom close to unity, at intensities $N_q \approx 1/\sigma_{ph} \approx 10^{-17}$–$10^{-18}$ quanta/cm^2, which corresponds to a vacuum ultraviolet radiation density of the order of a fraction of 1 J/cm^2. We shall show later that this can be achieved using even moderate laser powers and that much higher (record) ultraviolet energy and power densities can be reached near the focal hot spot. In view of the brief duration of the de-excitation process ($t \sim 3 \times 10^{-8}$–10^{-7} sec), the ultraviolet power density may reach 1 GW/cm^2 or higher values. Such levels of the ionizing effect of the hard ultraviolet radiation on dense media have not yet been investigated and they may be of interest in relation to a number of problems in experimental and applied physics, biology, etc.

2. DESCRIPTION OF APPARATUS AND MEASUREMENT METHOD

A ruby laser, Q-switched by the rotation of a prism, was used in the pulse heating of matter. The energy of the laser radiation was ≈ 1.5 J for a pulse duration (at its half-width) of ≈ 30 nsec. A laser beam was focused on a target placed in a chamber in which the gas pressure could be varied from 10^{-6} to 1 Torr.

The ionizing effect of the radiation from the target was investigated by observing the formation of a plasma, due to the photoionization of the gas, and the photoemission from special probes.

The plasma formed in the gas was detected by means of microwave radiation of $\lambda \approx 1$ cm wavelength. A transmitting antenna produced a directional flux of radio waves, parallel to the target plane, but at some distance from it (cf. Fig. 1). We used also an auxiliary metal grid, placed at a distance of 3 cm from the target, which screened the part of the chamber containing the target from the microwave radiation. This enabled us to compare more exactly the beginning of absorption of the microwave beam with the moment of appearance of the plasma in front of the grid. In some experiments we also used metal mirrors, which focused the ultraviolet radiation, and electrodes to which a potential was applied in order to remove the electron flux from the target and to carry out control tests.

The plasma produced by the photoionization was formed in the region where the measurements were carried out well before the plasma from the target reached that region. In some of the experiments with mirrors, the plasma from the target did not reach at all the region where the measurements were carried out in the gas. The contribution of fast photoelectrons and thermionic emission electrons to the ionization of the gas was found by preventing these electrons from reaching the ionization region by means of electric and magnetic fields. The ultraviolet radiation was recorded by means of probes and using sodium salicylate, a phosphor usually employed to detect the vacuum ultraviolet.

3. EXPERIMENTS AND RESULTS

A. In the first series of experiments, we recorded the ionization of the gas in front of the target on which a laser beam was focused (Fig. 1a). The focal length of the lens was 14 cm. The radio-frequency beam, used for the plasma diagnostics, passed at a distance of 4 cm from the target and was separated from it by a metal grid, located at a distance of 3 cm from the target. In high vacuum, the microwave beam recorded only the arrival of the plasma resulting from the direct effect of the laser radiation on the target (Fig. 2a). When a gas was admitted into the chamber, a "foreplasma" was generated by the action of the ionizing radiation which arrived earlier than the front of the plasma produced at the target itself (Fig. 2b). When the gas pressure was increased, the degree of absorption of the microwave beam by the foreplasma increased and, at a pressure p_{cr}, it became comparable with the strong absorption by the main plasma from the target. This indicated that the concentration of the foreplasma approached a critical value $(n_e)_{cr} \approx \pi / r_0 \lambda^2 \approx 10^{13}/\lambda^2 \approx 10^{13}$ electrons/cm^3 for the radio-frequency radiation employed ($\lambda \approx 1$ cm). Comparison with the concentration of molecules, $n_a \approx 3.5 \times 10^{16}$ p (Torr), made it possible to estimate the ionization probability

$$W_i(R) \approx (n_e)_{cr} / (n_a)_{cr} \approx 3 \cdot 10^{-4} / p_{cr}\,(\text{torr}).$$

The order of magnitude was $p_{cr} \approx 10^{-2}$–10^{-1} Torr, which yielded an ionization probability $W_i \sim 10^{-2}$ at a distance $R \approx 4$ cm from the focus. This value agreed quite well in order of magnitude with theoretical estimates made on the assumption that a considerable part of the energy (~ 0.1) of the laser radiation was transformed into the vacuum ultraviolet. Since, at a given laser energy, the ionization probability was $W_i \propto 1/R^2$, where R is the distance from the hot spot, complete photoionization should be expected at distances $R_1 \sim \sqrt{R^2 W_i(R)} \approx 1$ cm or less.

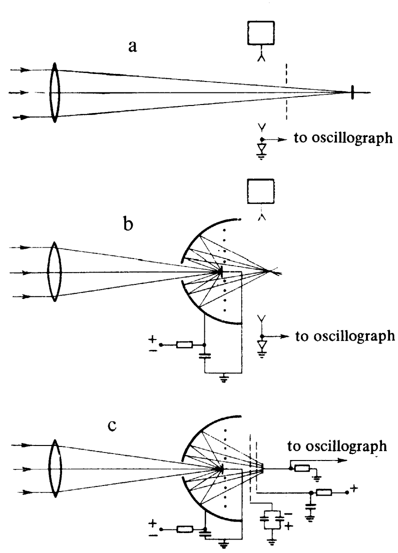

FIG. 1. Schematic diagrams of experimental layout.

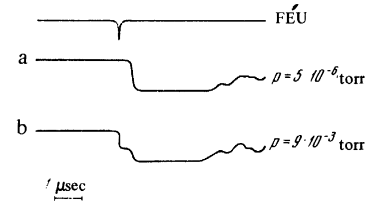

FIG. 2. Microwave absorption signals in the first series of experiments (Fig. 1a) at various pressures of air in the chamber. The top oscillogram represents the laser pulse.

We investigated aluminum, titanium, molybdenum, and lead targets with the chamber filled with air or hydrogen. Figures 2a and 2b give the results for a titanium target and air in the chamber. In this case, $p_{cr} \approx 2 \times 10^{-2}$ Torr and $W_i \sim 1.5 \times 10^{-2}$. The table gives the values of the critical pressures, from which it follows that the lead target produces the strongest ionizing effect and the ratio of the photoionization cross sections is

$$\frac{\sigma_{ph}(\text{air})}{\sigma_{ph}(\text{hydrogen})} \approx \frac{p_{cr}\,(\text{hydrogen})}{p_{cr}\,(\text{air})} \sim 10$$

for a titanium target and

$$\frac{\sigma_f\,(\text{air})}{\sigma_f(\text{hydrogen})} \approx 5$$

for a lead target, which is of the same order of magnitude as the ratio of the tabulated photoionization cross sections of molecules of the components of air and molecules of hydrogen.

We carried out control experiments to determine the possible role of fast electrons from the hot spot of the target in the formation of the foreplasma. The application of a transverse magnetic field $H_0 \approx 200$ Oe did not weaken the formation of the foreplasma. This indicated that the contribution of such electrons to the formation of the foreplasma was small. The rapid formation of the foreplasma (in a time ≤ 0.1 μsec) at a fairly large distance from the target (4 cm) indicated that this plasma was not due to the direct effect of the laser beam on the target, since the transit time from the target (even for substances with atomic weights close to the atomic weight of air) to the investigated region was several times longer than the time necessary for the formation

Values of critical pressures in the first series of experiments (Fig. 1a).

Target material	Critical pressure for hydrogen, torr	Critical pressure for air, torr
Pb	$9\cdot10^{-3}$	$4.5\cdot10^{-2}$
Mo	$1.9\cdot10^{-2}$	$2\cdot10^{-1}$
Ti	$2.2\cdot10^{-2}$	$1.9\cdot10^{-1}$
Al	10^{-1}	$5\cdot10^{-1}$

of the foreplasma. The more rapid formation of the foreplasma in the case of the heating of a heavy target also confirmed this conclusion. The simple experimental arrangement employed was not suitable for those cases when it was undesirable that the plasma should enter the working region. Therefore, we used also a different experimental layout.

B. In the second series of experiments, we used a system with metal mirrors which focused the ultraviolet radiation (cf. Fig. 1b). At one of the foci of a polished ellipsoidal copper mirror, we placed a target on which we focused, through a small aperture in the mirror, a laser beam, using a lens of 8 cm focal length. The other focus of this mirror was in the region through which the microwave beam passed (in the case when microwave diagnostics was used) and where an auxiliary probe was placed in order to measure the photoelectron current. The distance between the focuses $2x = 2\sqrt{a^2 - b^2}$ was 2 cm for a mirror with a semimajor axis $a \approx 2.8$ cm and a semiminor axis $b \approx 2.6$ cm. The mirror was polished in order to improve its reflectivity. It had been expected that, in the vacuum ultraviolet region, the reflection coefficients would not exceed 10% but in fact the focusing effect of the mirror compensated the poor reflection and it proved possible to obtain a high density of the ultraviolet radiation near the second focus of the mirror. Both the mirror and the target could be insulated from the chamber and potentials could be applied to them in order to carry out control experiments.

In such a system we found that the microwave radiation was strongly absorbed at gas pressures p_{cr} only several times larger than the critical values in the first series of experiments, in which the photoionization was due to the direct and not reflected ultraviolet radiation. This indicated that the total number of reflected ultraviolet quanta was approximately an order of magnitude smaller than the initial number of quanta in the first series of experiments, which was in agreement with the expected order of magnitude of the reflection coefficient of the mirrors. Exact comparison was made difficult by the fact that in the second series of experiments the focal length of the lens was shorter than that in the first series, which could have reduced the size of the hot spot (this size was proportional to the focal length of the lens) and increased the temperature to which the target was heated. The nature of the signal indicating the absorption of the microwave by the foreplasma was in this case very similar to the shape of the signal in the first series of experiments, but the signal from the target plasma was extremely small and shifted in time.

To check the contribution of the photoelectrons knocked out from the mirrors to the process of the ionization of the gas, a large positive potential (~ 400 V) was applied to the mirror, but this had practically no effect on the microwave absorption signal at the investigated pressures. A negative potential also did not affect the ionization of the gas. To check the reflecting role of the mirror, it was covered by an absorbing layer (soot or black paper). In this case, the signal due to the absorption by the foreplasma disappeared, which indicated that it was associated with the reflected photon flux. Figure 3 shows the absorption signals for an uncovered and covered mirror.

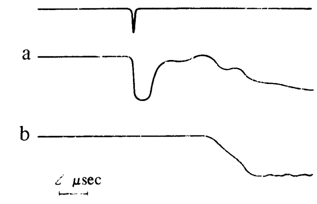

FIG. 3. Microwave absorption signals in the second series of experiments (Fig. 1b) at a pressure of 0.1 torr in the chamber: a) polished copper reflector; b) reflector covered with an absorbing layer. The top oscillogram represents the laser pulse.

To investigate the process of interest to us, we also used a special probe placed behind the target (cf. Fig. 1c). The photoemission from a probe electrode was measured and thus the contribution of electrons arriving from outside was estimated. A positive potential, which could be up to 100 V, was applied to the nearer grid, placed at a distance of 3 mm from the probe electrode. The probe electrode was grounded through a resistance of $R \approx 1.3 \times 10^{-2}\,\Omega$ and the magnitude and sign of the voltage on the electrode could be used to determine the sign and magnitude of the current to the electrode.

If α is the quantum yield of the photoemission effect ($\alpha \approx 0.1$ for copper in the ionizing range of the ultraviolet spectrum of interest to us), the maximum current to the electrode should be $I \propto \alpha e N_q/\tau$, where N_q is the total number of quanta incident on the target during a laser pulse of duration τ. This maximum value of the current J_m was used to estimate N_q, which was found to be of comparable order of magnitude with the number of quanta obtained in experiments on the ionizing effect on gas atoms.

The current from the probe disappeared when a transparent cellophane film, $\approx 20\,\mu$ thick, was placed in front of the probe. This confirmed that the observed signal was due to the hard ultraviolet radiation (known as the vacuum ultraviolet) and not by the focused reflected laser radiation or the soft ultraviolet radiation. The strong ionization of the gases confirmed this conclusion.

C. We also carried out direct measurements of the ultraviolet pulse using a phosphor, in front of which we placed various filters. The phosphor was sodium salicylate, which had been precipitated by evaporating an alcohol solution of this phosphor on a glass plate. The phosphor was placed in such a way that the photomultiplier received the largest possible fraction of the radiation from the phosphor and the smallest possible fraction of the light from the target (this was achieved by means of filters and lenses, which focused the light from the phosphor on the photomultiplier, and a blackened tube, which absorbed all stray light). The plate carrying the phosphor was placed on one side of the target so that it made a small angle with its axis and this also made it easier to separate the light from the target from the luminescence of the phosphor. We recorded a luminescence pulse of ~ 100–200 nsec duration when the chamber was evacuated ($\sim 10^{-3}$ Torr). The duration of this pulse was longer than the intrinsic afterglow of the phosphor. The admission of gas into the chamber, so that the pressure rose to ~ 1 Torr, reduced the signal by a factor of 1.3 and a thin quartz plate in front of the phosphor reduced the signal by a factor of 1.5 (the quartz plate transmitted 50% of the radiation with $\lambda > 2000$ Å). These experiments showed that an appreciable fraction of the radiation causing luminescence was within the vacuum ultraviolet range. A thin (~ 0.1 cm) glass plate, placed in front of the phosphor, reduced the signal by a factor of 6.

We also recorded an increase of the yield of the vacuum ultraviolet and its ionizing effect when the laser radiation power was increased. The dependence was fairly strong (nearly proportional), which supported the desirability of using high-power lasers.

4. CONCLUSIONS AND PROSPECTS

The experiments described demonstrate that the heating of matter at the focus of a laser can produce a strongly ionizing ultraviolet radiation pulse. Such a pulse can be used for the following purposes: the ionization of portions of a gas; the ionization of atomic beams to produce a plasma; the filling of traps; the photogeneration of polarized electrons from polarized atoms. The presence of ionizing radiation should reduce strongly the number of neutral atoms in the plasma produced by the laser and thus a highly ionized plasma should be obtained when a laser beam is focused on matter (a speck, a target, or a portion of gas). It has been demonstrated that mirror systems can be used to focus hard ultraviolet radiation. Ultraviolet radiation flashes can be used not only for the ionization of atoms and molecules but also for the photoexcitation and photodissociation of molecules. In particular, excited atoms produced by these processes can be employed in the generation of stimulated radiation in the ultraviolet range. The ultraviolet radiation of a plasma, observed when a laser beam is incident on a target, may be the cause of the strong photoemission current from the target and nearby conductors. This effect is similar to the effect of current generation in high-temperature radiation pulses near the earth's surface.

[1] A. W. Ehler and G. L. Weissler, Appl. Phys. Lett. **8**, 89 (1966).

[2] A. W. Ehler, J. Appl. Phys. **37**, 4962 (1966).

[3] P. Langer, G. Tonton, F. Floux, and A. Ducauze, IEEE J. Quantum Electronics **QE-2**, 499 (1966).

[4] B. C. Fawcett, A. H. Gabriel, F. E. Irons, N. J. Peacock, and P. A. H. Saunders, Proc. Phys. Soc. (London) **88**, 1051 (1966).

[5] D. D. Burgess, B. C. Fawcett, and N. J. Peacock, Proc. Phys. Soc. (London) **92**, 805 (1967).

[6] N. G. Basov, V. A. Boĭko, Yu. N. Voĭnov, É. Ya. Kononov, S. L. Mandel'shtam, and G. V. Sklizkov, ZhETF Pis. Red. **5**, 177; **6**, 849 (1967) [JETP Lett. **5**, 141; **6**, 291 (1967)].

[7] T. U. Arifov, G. A. Askar'yan, and N. M. Tarasova, ZhETF Pis. Red. **8**, 128, 387 (1968) [JETP Lett. **8**, 77, 239 (1968)].

Translated by A. Tybulewicz
65