BRIGHTNESS OF SHOCK WAVES IN ARGON IN THE VACUUM UV REGION

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A description is given of a method and results of investigation of the brightness of shock waves in argon of normal density in the spectral region 78 nm < λ < 99 nm. The experimental values of brightness temperatures are evidence that the radiation is "black" in the shock speed range investigated, from 4.9 to 9.2 km/sec. The absorption coefficients of the shock-compressed argon are evaluated.

The brightness of strong shock waves in inert gases was previously investigated experimentally in the visible and near UV spectral regions [1, 4]. The absence of experimental data on the spectral distribution of the radiation in the shortwave spectral region, which contains most of the radiative energy is associated with the difficulty of using the known methods for recording the vacuum UV [5] in the specific conditions of the short-duration experiment.

The present paper shows that it is possible to determine the brightness of an inert gas in the spectral region near the ionization potential (φ_0) from the experimentally measured intensity of volumetric photoionization of atoms of a gas mixture with known ionization potential ($\varphi_1 < \varphi_0$), added in a certain proportion (~0.1%) to the gas under investigation.

It has been observed that an electric current flows in the circuit of an electrical probe mounted in front of a shock wave, the probe taking the form of two plane electrodes supplied with a voltage from an external source. The current can only result from volume photoionization of the added atoms whose ionization potential is less than that of the basic gas, since radiation with quantum energy $h\nu > \varphi_0$, capable of ionization atoms of the basic gas, is absorbed in a thin layer immediately ahead of the shock [6]. If the flow densities are small enough the radiation can fall in the "saturation" regime, where all the charged particles formed from volumetric photoionization do not recombine, but reach the electrodes, and the current I is then a measure of the photoionization intensity q, i.e., the number of electron–ion pairs formed in unit volume and unit time is

$$q = \frac{I}{eSd}, \tag{1}$$

where e is the electron charge; S is the area of the probe electrodes; and d is the distance between the electrodes. The photoionization intensity is determined by the flux density of quanta N at the probe position (at distance z from the shock front):

$$q(z) = \varkappa_0 N(z) = \varkappa_0 N_0 \sin^2 \alpha \exp(-\varkappa_0 z), \tag{2}$$

where $\varkappa_0$ is the photoionization absorption coefficient of the impurity; N_0 is the flux density of quanta radiated from the shock front in the spectral range $\varphi_1 < h\nu < \varphi_0$; and α is a specific experimental geometrical angle, i.e., the angle seen by the radiating surface from the point z. From Eqs. (1) and (2) we obtain

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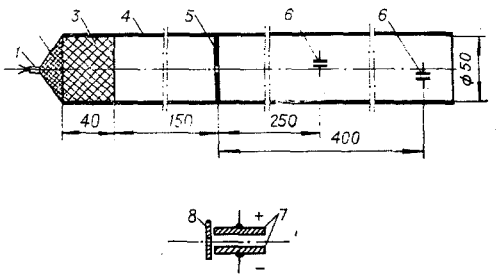

Fig. 1

$$N_0 = \frac{I \exp(\varkappa_0 z)}{eSd \sin^2 \alpha}. \quad (3)$$

The absorption coefficient $\varkappa_0$, which depends on the impurity concentration and is therefore unknown beforehand, is determined experimentally by means of two probes, mounted at different distances z_1 and z_2 from the shock front. From Eq. (3) we can derive a formula for computing $\varkappa_0$ in terms of the probe currents I_1 and I_2:

$$\varkappa_0 = \frac{1}{z_2 - z_1} \ln \frac{I_1 \sin^2 \alpha_2}{I_2 \sin^2 \alpha_1}.$$

Thus, the proposed method allows us to calculate the radiative flux N_0 in the spectral region given by the ionization potentials of the basic gas and the impurity, and then to determine the brightness temperature from N_0, i.e., the temperature of a perfect black body which radiates the same flux of quanta per unit area in the given spectral range as the test object.

In the experiments two electric probes 6 were used to record the radiation from shock waves obtained by discharging a plane detonation wave at the face of a cylindrical charge of explosive material 3, located in the tube 4 with argon of standard density (Fig. 1; 1) the electrical detonator, 2) the explosive lens). The probes were mounted at distances of 40 and 55 cm from the face of the charge near the tube axis. In order to reduce the radiative density incident on the probe, and also to record radiation only in the central part of the shock wave front, a diaphragm 5 with aperture diameter $d_1 = 1.5$ mm was placed between the probes and the explosive charge [the diaphragm diameter determines the angle in Eq. (2): in $\sin \alpha = d_1/l$, where l is the distance from the diaphragm to the probe]. Immediately ahead of the probe there was a slotted diaphragm 8 of transparent plastic, the slot width ($d_2 = 1$ mm) being chosen so that radiation would not strike the probe electrodes 7 and the recorded signal would not be distorted by the influence of the photoeffect from the electrode surface [with the diaphragm present one should replace d by d_2 in Eqs. (1) and (3)]. The area of the electrodes was $S = 1.0 \times 1.5$ cm^2, and the distance between them was $d = 2$ mm. The electrodes were given a voltage $U_0 = 500$–1000 V. The current in the probe circuit was recorded by a type OK-33 oscilloscope.

The shock speeds in the tube were measured by a photographic timing method in preliminary tests.

The tube was filled with "pure" argon from a bottle by flushing for 2-5 min immediately before a test. With this filling method a very small amount of atmospheric air remains in the tube (~0.1%), the main components of which (oxygen and nitrogen) constitute the impurity in the test gas. The remaining impurities can be neglected because of their considerably smaller concentration. The ionization potentials of argon, nitrogen, and oxygen are 15.7, 15.8, and 12.5 eV, respectively [5]. The nitrogen impurity, whose ionization potential is greater than that of argon, does not affect the probe measurement results, since the radiative spectrum of the shock wave is limited by the argon ionization potential. The ionization intensity measured by the probe is determined by radiation with quantum energy in the range from the ionization potential or argon to that of oxygen, which corresponds to the wavelength interval 78.0 nm < λ < 99.0 nm.

The probe parameters were chosen so that saturation current was obtained [7] at the given ionizing radiative flux. It is known that the voltage between the electrodes in this event must be large enough, on the one hand, so that the effects of the volume charge between the electrodes and of recombination of charged particles may be neglected, and must not be so large, on the other hand, that the motion of the charged particles in the electric field will generate secondary ionization of gas atoms by collisions.

The ion density due to volume photoionization was not greater than $n_{max} = q\tau$, where $\tau = d^2/k_+ U_0$ is the time of flight of an ion between the electrodes, and k_+ is the ion mobility. The effect of volume charges can be neglected if the associated change in electric field intensity $\Delta E \sim e n_{max} d/2\varepsilon_0$ (ε_0 is the electrostatic constant) is small compared with the initial intensity $E_0 = U_0/d$, i.e., if

$$q \ll \frac{\varepsilon_0 k_+ U_0^2}{ed}. \quad (4)$$

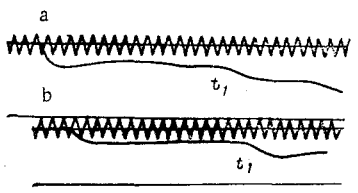

Fig. 2

With $U_0 = 10^3$ V, $d = 10^{-3}$ m and $k_+ = 3 \cdot 10^{-3}$ $m^2/V \cdot sec$ (estimated using the Langevin formula) we obtain the condition $q \ll 10^{17}$ $1/cm^3 \cdot sec$. From the solution in [7] of the steady motion of electrons and ions between plane electrodes it follows that the volume charge can be neglected in these experimental conditions, even for $q = 10^{17}$ $1/cm^3 \cdot sec$.

The rate constant for oxygen and recombination of argon of standard density is not larger than $k = 10^{-7}$ cm^3/sec [8]. The number of ions recombining per unit volume per unit time is not greater than kn^2_{max}. Substituting numerical values, we can check that when condition (4) is satisfied, the number of recombining ions is negligibly small compared with q.

An estimate of the collision ionization coefficient (the Townsend coefficient) shows that the secondary ionization is also negligible [7] in argon at atmospheric pressure and with $E_0 = U_0/d = 5 \cdot 10^3$ V/cm.

Typical current oscillograms in the probe circuit are shown in Fig. 2 (a is for probe 1; b is for probe 2; and the period of the reference sinusoid is 1 μsec). The current increases from zero to a maximum in the first 1.5-2.0 μsec and then remains roughly constant until time t_1. The timed photographic measurements showed that the shock speed in the tube remained practically constant for $t < t_1$, and time t_1 corresponds to the shock wave approaching the diaphragm.

Table 1 presents photoionization intensities q computed from the values of I_m, the gas absorption coefficients $\varkappa_0$ ahead of the shock, and the brightness temperatures T_{eff} in the spectral region investigated. In calculating brightness temperatures we used the tables of [9]. For comparison we also give computed values [3] of argon temperature behind the shock, corresponding to the shock speed as determined experimentally.

The voltage on the probe electrodes was varied in the experiments in the range $U_0 = 600$-1000 V. Variation of the electrode voltage did not affect the current growth time, nor the value of T_{eff}. This result indicates that the probe parameters chosen by estimation actually correspond to the current saturation regime, and that the steep fall at the leading edge of the current pulse is determined by increase in brightness when the detonation wave exits into the tube from the gas, and not by a temporary breakdown of the probe.

The brightness temperatures obtained from the probe measurements are close to the computed gas temperature and agree well with the results of brightness measurements in the near-UV and visible regions. This supports the conclusion that in the range of shock speeds investigated in argon one can regard the radiation to be black, not only in the spectral regions previously investigated, but also in the vacuum UV, 78 nm $< \lambda <$ 99 nm.

The absorption coefficient $\varkappa_0$, whose value was roughly the same ($\varkappa_0 \simeq 0.1$ cm^{-1}) in all the tests, is dictated by the impurity concentration: $n \simeq \varkappa_0/\sigma = 10^{15}$–$10^6$ cm^{-3}, where $\sigma = 10^{-17}$–10^{-16} cm^2 [5] is the oxygen absorption cross section in the spectral region 78 nm $< \lambda <$ 99 nm.

From the increase in shock-wave brightness in the first moments after the detonation sets out from the face of the explosive charge, estimates of the absorption coefficient $\varkappa_1$ of the radiating gas were made. The thickness of the gas layer compressed by the shock increases as $x = Dt/\delta$, where D is the shock speed; δ is the relative compression in the shock. The radiative density N must increase because of increase in the optical thickness of the radiating gas layer, according to the law [6]

TABLE 1

Test number	D, km/sec	$I_m \cdot 10^3$, A		$q \cdot 10^{-16}$, $cm^3 \cdot sec$		$\varkappa_0$, 1/cm	$T_{eff} \cdot 10^{-3}$, K	$T \cdot 10^{-3}$, K	$\varkappa_1$, 1/cm
		probe 1	probe 2	probe 1	probe 2				
1	4,9	0,750	0,133	3,10	0,551	0,047	15,8	17,0	8,0
2	4,9	0,135	0,024	0,56	0,010	0,066	16,0	17,0	
3	9,2	0,910	0,058	3,70	0,024	0,122	25,0	25,4	
4	9,2	0,740	0,043	3,10	0,018	0,130	25,0	25,4	
5	9,2	0,920	0,058	3,84	0,024	0,122	25,0	25,4	9,2
6	9,2	1,54	0,117	6,42	0,49	0,080	25,1	25,4	

$$N = N_m\left[1 - \exp\left(-\varkappa_1 \frac{D}{\delta} t\right)\right].$$

From the current oscillograms we constructed the relation

$$\lg \frac{I_m - I(t)}{I_m} = f(t),$$

and the mean values of $f(t)$ were determined from several oscillograms (between 4 and 10) for each time instant. The mean values are a good fit to a straight line, and from the slope we determine the absorption coefficient $\varkappa_1$ of the shock-compressed argon given in the table.

In conclusion, it should be noted that in processing the experimental data we did not account for effects such as line absorption by atoms of the basic gas, the dependence of ionization cross section of impurity atoms on wavelength in the spectral region investigated, nor edge effects at the probe electrodes. Estimates indicate that neglect of these effects should lead to low values of brightness temperatures. The fact that the brightness temperatures proved to be close to the highest possible values for equilibrium radiation of a perfect black body justifies the assumptions made and gives reason to hope that the present method can be used to investigate brightness not only of shock waves, but of other plasma objects, for example: a laser plasma or the plasma of a high-power gaseous discharge.

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