SPECTRAL DISTRIBUTION OF THE RADIATION OF SHOCK WAVES IN NOBLE GASES

E. G. POPOV and M. A. TSIKULIN

Institute of Earth Physics, USSR Academy of Sciences

Submitted March 13, 1969

Zh. Eksp. Teor. Fiz. 57, 389—394 (August, 1969)

Time-resolved ultraviolet and visible radiation spectra of shock waves in neon, argon, krypton, and xenon are obtained. The spectral brightness temperature of the shock wave front is measured. The shock waves are excited by detonation of an explosive.

BY using explosives it is possible to obtain strong shock waves in sufficiently dense gases, which are high-temperature surface emitters. The recently measured[1,2] brightness temperatures 70 000—90 000°K of such shock waves makes them some of the most brightest light sources. While the production of such waves involves complicated methods, shock waves with temperatures up to 30 000—40 000°K can be easily excited by emergence of the detonation of a strong explosive to a surface bordering on a gas. It is precisely the simplicity of such a method which caused frequent investigations[2-7] and applications[8-12] of such waves as light sources. In this connection, the use of heavy inert gases is of particular interest. The absence of energy loss to dissociation and the large atomic weight of these gases contributes to the attainment of high temperatures in the shock wave. On the other hand, owing to the high first ionization potential, the gas ahead of the front is transparent in a wide spectral range, and this leads, in connection with the high temperatures behind the front, to the emission of quite respectable energy fluxes by the wave[11].

The emitting properties of shock waves were investigated in great detail in experiments with Ar[2-7,13]. In spite of interest in shock waves in Xe and Kr (in which the temperatures produced by emergence of the detonation are higher than in other gases), measurements of their brightness are reported only in[1,2,13]. Worthy of attention are shock waves in Ne, the emission spectrum of which includes quanta with energies up to 21 eV; no such experiments with this gas have been described in the literature.

In the cited investigations, they used light filters to separate individual sections of the visible spectrum (the measurements in[2,4,5] cover the region of quartz ultraviolet radiation). The results obtained with their help do not provide a complete picture of the composition of the radiation, and were supplemented in[5,6] by spectral investigations in the visible part of the spectrum. These qualitative investigations are limited to an attempt to estimate the color temperature from the spectrophotochronograms. Improvement of the procedure[14] makes it possible to use the spectrophotochronograms both for a qualitative and for a quantitative investigation of the spectral brightness of the shock waves in the visible and ultraviolet regions of the spectrum.

The spectral investigations of the ultraviolet and visible radiation of shock waves in Xe, Kr, Ar, and Ne, described in this article, supplement the previously obtained results and continue our earlier work[14], where shock waves in air were studied.

PROCEDURE FOR MEASUREMENTS AND OBTAINING WAVES

The time-resolved radiation spectra of the shock waves were registered with a spectrophotochronograph FP-111[15]. A diffraction grating with 200 lines/mm and a spectral-time slit of 0.1 mm diameter ensured a time resolution of 10^{-7} sec and spectral resolution of 0.4 nm. High-contrast film and high-contrast development increased the measurement accuracy and made it possible to register reliably lines whose brightness differs by 1% and more from the adjacent continuum. The spectral brightness temperature was determined from a photometric comparison of the spectrophotochronograms of the shock wave and of a standard brightness source. The latter was an ÉV-39 pulsed source with a brightness temperature 41 000°K in the spectral interval 200—600 nm[16]. Density marks were printed simultaneously with the photography of the standard. To this end, a step-wedge with known spectral field transmission was placed on the focal arc of the SP-111 instrument in front of the exposed photographic film.

As a check on the measurements, the employed brightness standard was a stable shock wave in air with temperature 24 000 ± 1000°K. Experiment and theory[2,14,17] show that such a wave produces absolute black-body radiation in a broad spectral interval, 186—4000 nm. The possibilities of a shock wave in air as a brightness standard are illustrated by Fig. 1. Directly prior to the explosion experiment (or the photography of the ÉV-39 source), with the mirror of the SP-111 instrument rotating, we printed the spectrum of the mercury lamp[1)]. This spectrum was subsequently used to correlate the spectrophotochronograms and to identify the lines.

The accuracy with which the spectral brightness was measured was not worse than ±12% in the wavelength region λ = 550—300 nm and ±15% for λ = 300—200 nm. The corresponding error in the measurement of the temperature is shown in Fig. 5 (see below). The accuracy with which the brightness of shock waves in different gases were compared with one another was higher

[1)]The linearity of the dispersion of the SP-111 instrument makes it possible to simplify the experiment by dispensing with the need of imprinting a more detailed spectrum.

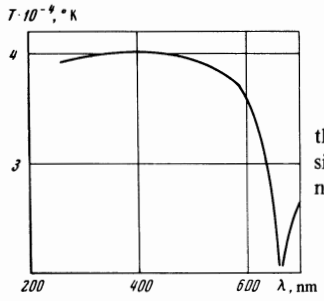

FIG. 1. Brightness temperature of the ÉV-39 source, measured using a single shock wave in air as the brightness standard.

(±5%), since the error introduced by the standard is eliminated in this case.

The shock waves were excited upon emergence of a plane detonation wave from the explosive TG4060 (40% TNT, 60% hexogen) to the interface with the investigated gas. The details of the procedure of obtaining shock waves and the arrangements of the instruments in the experiments are illustrated in Fig. 2. The Xe, Kr, or Ne are admitted into previously evacuated (10^{-3} mm Hg) cells and the pressure is allowed to rise to atmospheric. The Ar cell is filled by first blowing the gas through the cell for a long time (about 5 minutes) until the explosion occurs. The impurity content in the investigated gases does not exceed 0.01%, with the exception of kR, which contains 1% Xe.

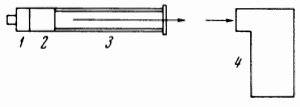

FIG. 2. Experimental setup: 1 – lens, 2 – TG40/60 charge of 50 mm diameter and 60 mm length, 3 – glass cell 200 mm long with quartz window, 4 – spectrophotocronograph.

DISCUSSION OF RESULTS

The time-resolved emission spectra of the shock waves (Fig. 3) are continuous; weak absorption lines[2)] are superimposed on the continuous background of the emission of the waves in Ar, Kr, and Xe[2)]. The intensity difference between the lines and the adjacent continuum does not exceed 5%. The observed lines are listed in the table. The continuum and the lines appear simultaneously, with the exception of lines 1, 2, and 3, which are produced (probably as the result of photoexcitation of the impurities ahead of the front) about 1 μsec following the start of the glow of the heated Ar.

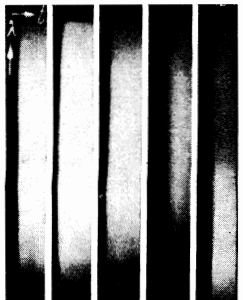

FIG. 3. Spectrophotochronograms of the radiation of shock waves, λ = 230–430 nm: 1 – Xe, 2 – Kr, 3 – Ar, 4 – Ne, 5 – Ar, λ = 460–660 nm.

[2)]The lines recorded on the spectrophotochronograms were so weak that they could hardly be reproduced in the prints.

Argon						Krypton			Xenon		
Line no.	λ, Å	Identification	Line no.	λ, Å	Identification	Line no.	λ, Å	Identification	Line no.	λ, Å	Identification
1	6562.85	H	8	4300.10	Ar	1	4418.77	Kr	1	4193.15	Xe^+
	6562.73	»		4272.17	»		4417.24	Kr^+	2	4180.10	»
2	6407	—		4277.55	Ar^+		4416.88	Kr	3	3967.54	Xe
3	6186	—		4266.29	Ar		4386.54	Kr^+	4	3948.16	»
4	5606.73	Ar	9	4259.36	»	2	4389.72	»	5	3083.54	Xe^{++}
5	5572.55	»		4266.53	Ar^+		4385.27	»		3082.62	Xe^+
	5559.62	»	10	4251.19	Ar	3	4369.69	»	6	3073.49	Xe^{++}
	5558.70	»	11	4200.68	»	4	4351.36	Kr	7	3054.49	»
6	4510.74	»		4198.32	»		4351.02	Kr^+			
	4522.32	»	12	4191.03	»	5	4317.81	»			
7	4323	—		4190.71	»	6	4268.81	»			
			13	4158.59	»		4268.57	»			
			14	3545.84	Ar^+	7	4259.44	»			
				3545.58	»						

The spectrophotochronograms of the shock wave in Ne revealed no lines. The absence of lines was observed also earlier in the emission spectrum of shock waves in air[14].

The brightness of the front increases sharply after the emergence of the detonation, and then decreases. The drop of the brightness agrees with the attenuation of the shock waves as recorded by the SFR slit camera in preliminary experiments. The front velocity measured in these experiments was at first equal to 9.4 km/sec for Ar and 8.3 km/sec for Xe. The velocity in Kr (8.7 km/sec) and in Ne (10 km/sec) was obtained by extrapolation[3)] (Fig. 4). The spectral brightness temperature corresponding to the maximum of the brightness is shown in Fig. 5, which also shows the temperature of the shock-heated gas calculated from the wave velocities; the calculation takes into account the multiple ionization, the Coulomb interaction (after Debye-Huckel), and the electron-excitation energy.

In the section λ = 300–600 nm (Fig. 5), the shock wave in Ar produces black-body radiation; the growth of the brightness on the spectrophotochronograms lasts approximately 10^{-7} sec. For λ < 300 nm, the delay of the maximum of the brightness exceeds the time resolution and reaches 2×10^{-6} sec at λ = 230 nm. During that time, the attenuation of the wave comes into play, and this explains the decrease of the brightness temperature at λ < 300 nm. The cause of the delay might be the growth of the thickness of the initially optically-thin layer of the shock-compressed gas. The theory predicts[17,18] an increase in the transparency of the heated gas with decreasing wavelength λ of the radiation. This increase becomes very strongly manifest at $\lambda < \lambda_1$, when all the excited levels are involved in the absorption. For argon, λ_1 = 290 nm (the absorption of Ar^+ at

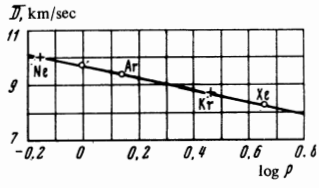

FIG. 4. Dependence of the velocity of the shock wave excited by the detonation of TG40/60 on the density of the gas ρ, referred to the density of air.

[3)]The solution of the problem involving the spreading of the detonation products in the gas involves the density and the effective adiabatic exponent of the gas, and the latter is approximately the same for different gases at high temperatures. Therefore the velocity of the shock wave depends essentially only on the density. Using the coordinate axes chosen in Fig. 4, this dependence is approximated by a straight line.

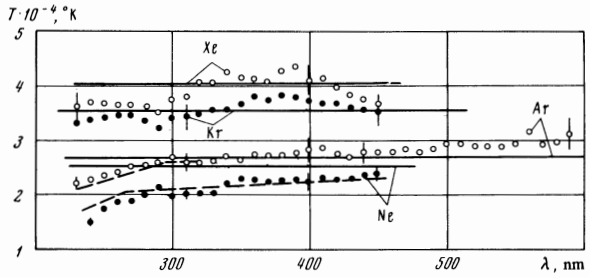

FIG. 5. Spectral brightness temperature of shock waves: ○, ● – experiment, straight lines and dashed lines – calculated temperatures of the gas in the wave for the initial front velocity and for the velocity at the instant of the brightness maximum.

$T < 30\,000°K$ and $\lambda > 200$ nm can be neglected); the delay of the maximum of brightness in the experiments begins to increase noticeably precisely starting with this value of λ. The brightness temperature becomes constant over the spectrum after 2×10^{-6} sec, when the wave is already optically dense (if $\lambda > 230$ nm). Replacement of the TG40/60 by hexogen compressed to a density of 1.74 g/cm^3, in several experiments with Ar, increased the brightness temperature by 200°K.

The measurements of the spectral brightness describe most fully the radiative properties of the shock waves, and make it possible to compare the results obtained in this manner with various measurements performed by others. The color temperature of the shock wave was estimated in[3] at 29 000 ± 1000°K from the relative intensity of the visible radiation produced when the detonation emerged from Tg40/60 in Ar. The spectral dependence of Fig. 5 yields the same color temperature. A color temperature of 20 000°K was obtained in[4] from the relative intensity of the ultraviolet (λ = 230–330 nm) and visible radiation of the wave. Calculation based on the spectral dependence of Fig. 5, yields a color temperature of 19 000°K in the visible and ultraviolet regions.

The flux of radiant energy from the shock wave in Ar, integrated over the cross section λ = 200–600 nm in Ar, was measured in[5]. The measured front velocity changed from 9.3 to 5 km/sec as a function of the distance to the charge. The density of the radiant flux amounted to 5×10^5–10^5 W/cm^2 for such a wave. The extrapolation of the plot on Fig. 5 to λ = 200 nm and subsequent calculation of the flux density yield 5×10^5 W/cm^2–the agreement with[5] is complete.

The brightness temperature in the sections with λ_{eff} = 545 nm and λ_{eff} = 405 nm and $\Delta\lambda$ = 20 nm, according to the data of[6], is equal to 21 000–26 000°K for a shock wave excited in Ar by detonation of TG40/60. The reason for the discrepancies in these measurements might have been the incomplete resolution of the brightness peak in[6]. The scatter of the brightness temperature and the form of the signal on the oscillograms, given in[6], confirm our assumption.

The results obtained here agree with the measurements of the brightness temperature of the shock waves in[2], and with the results given in[7]. The delay of the brightness peak in[3,6] is larger by one order of magnitude than in the present investigation, and the subsequent decrease of brightness in the course of time is attributed in[5,6] to the attenuation of the waves. We do not agree with the interpretation given in[3], where the decrease of the brightness is related to the radiant heating of the Ar ahead of the front and to the screening of the radiation of the front by the heated gas[4]. The estimates given below show that the radiant heating of argon ahead of the front is hardly sufficient for only weak screening in the lines. A decrease in the front brightness during the course of time, not connected with wave damping, was observed in[2] at high velocities (higher than 13 km/sec in Ar). The presence of lines in the emission spectrum of a shock wave in Ar was noted in[3-6].

The growth of the brightness in the experiments with Ne lasts from 2 μsec at λ = 450 nm to 4 μsec at λ = 260 nm, and is strongly drawn out when $\lambda < 260$ nm = λ_1. The influence of the attenuation on the spectral dependence of the brightness temperature is stronger than in the case of Ar. From the increase of the brightness it is possible to estimate, as is done in[13,3], the absorption coefficient κ of the heated gas. We present several such estimates: $\kappa = 1$ cm^{-1} (2 cm^{-1}) for Ne, λ = 450 nm, T = 22 000°K; $\kappa > 10$ cm^{-1} (15–100 cm^{-1}) for Ar, λ = 300–600 nm, T = 27 000°K; $\kappa = 1$ cm^{-1} (1 cm^{-1}) for Ar, λ = 230 nm, T = 27 000°K; here κ corresponds to the density ahead of the front, and the parentheses contain the calculated values in accordance with[18]).

Shock waves in Xe and Kr are characterized by a maximum in the spectral dependence of the brightness temperature. The attenuation does not influence the form of the dependence, since the brightness increases rapidly–within 0.1–0.6 μsec. The occurrence of the maximum can be connected with the high temperature in the wave, which in accordance with[17] leads to an intense radiant heat exchange on the front. The gas ahead of the front is heated by the photoionizing radiation of the wave, which in turn increases the temperature of the gas behind the front (something not taken into account by the calculation on Fig. 5). The corresponding increase of the brightness temperature is masked by the absorption of the radiation by the heated gas ahead of the front, which is stronger in the visible part of the spectrum. The transparency, to ultraviolet radiation, of the narrow layer behind the front in which the temperature increase is attained, leads to a decrease of the brightness temperature in the other end of the spectral section.

Screening by the heated gas ahead of the front can also explain another feature of the radiation of the shock waves in Ar, Kr, and Xe–the absorption lines in the spectrum. The corresponding estimates yield for the Ar temperature ahead of the front in the experiments not more than 1500°K. At such a temperature Ar is still perfectly transparent. It is shown in[19] that there is no thermodynamic equilibrium in the gas ahead of the front, and that the effective temperature, describing the ionization and the electron excitation, turns out to be

[4]The first recordings made with the SFR instrument did not register (as in [3]), the attenuation of the wave in Ar near the charge. A cause of misunderstandings was the bending of the front at the walls of the cell, as described in [2]. When this bending was eliminated by moving the walls away from the charge, it was possible to observe the attenuation of the wave.

higher than in the case of thermodynamic equilibrium. Allowance for this fact yields an effective temperature of approximately 10 000°K for Ar, Kr, and Xe, and makes screening in the lines possible. However, the heating of the gas ahead of the front in the experiments is patently insufficient to produce ion lines in the spectrum. As shown in[14], the radiation of the shock-heated gas can screen the relaxation layer on the front, in which the gas ionization develops. The correspondence between the ion concentrations in this layer and the observed lines, as well as estimate of the optical thickness of the layer, suggest that the singularities in the shock-wave radiation are connected with screening of this kind.

[1] A. E. Voĭtenko, I. Sh. Model', and I. S. Samodelov, Dokl. Akad. Nauk SSSR 169, 547 (1966) [Sov. Phys.-Dokl. 11, 596 (1967)].

[2] Yu. G. Zatsepin, E. G. Popov, and M. A. Tsikulin, Zh. Eksp. Teor. Fiz. 54, 112 (1968) [Sov. Phys.-JETP 27, 63 (1968)].

[3] J. Roth, J. Appl. Phys. 35, 1429 (1964).

[4] R. L. Conger, L. T. Long, J. A. Parks, and J. H. Johnson, Appl. Optics 4, 273 (1965).

[5] N. C. Anderholm, Bull. Amer. Phys. Soc. 11, 452 (1967).

[6] W. H. Taylor and J. W. Kane, Appl. Optics 6, 1493 (1967).

[7] D. Lochte-Holtgreven, Repts. Progr. Phys. 21, 312 (1958).

[8] C. A. Winning and H. E. Edgerton, J. Soc. Motion Picture Engers 59, 178 (1952).

[9] L. Deffet and R. Vandenbeghe, Applications diverses des eclairs pyrotechniques. Proc. 6th Inter. Congr. High-speed Photogr. The Hague, 1962, Haarlem, 484–491, 659–660, 755 (1963).

[10] L. K. Wanlass, Shock Wave Gas Ionization Pumped Laser Device, Patent No. 3, 235, 816; cl. 331–945, USA (1964).

[11] I. F. Zharikov, I. V. Nemchinov, and M. A. Tsikulin, Prikl. Mekh. i tekhn. fiz. 1, 31 (1967).

[12] A. N. Dremin and D. S. Savrov, Dokl. Akad. Nauk SSSR 179, 624 (1968).

[13] I. Sh. Modle', Zh. Eksp. Teor. Fiz. 32, 714 (1957) [Sov. Phys.-JETP 5, 589 (1957)].

[14] E. G. Popov and M. A. Tsikulin, ibid. 56, 522 (1969) [29, 286 (1969)].

[15] S. G. Grenishin, A. S. Dubovik, R. A. Esin, G. P. Ilyushin, P. V. Kevlishvili, A. I. Churbakov, and Yu. P. Shchepetkin, Zh. nauch. i prikl. fotogr. i kinematogr. (J. of Scient. and Applied Photography and Cinematography) 12, 344 (1967).

[16] M. A. Demidov, N. N. Ogurtsova, I. V. Podmoshenskiĭ, and V. M. Shelemina, Zh. Prikl. spektroskop. 9, No. 3 (1969).

[17] Ya. B. Zel'dovich and Yu. P. Raĭzer, Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavlenii (Physics of Shock Waves and of High-temperature Hydrodynamic Phenomena), Nauka, 1966.

[18] L. M. Biberman, G. É. Norman, and K. N. Ul'yanov, Optika i spektroskopiya 10, 565 (1961).

[19] E. G. Popov, ZhETF Pis. Red. 9, 176 (1969) [JETP Lett. 9, 102 (1969)].

Translated by J. G. Adashko
44