center of mass system). In the experiment this portion amounts to 15–20%. However, the results at our disposal do not yet allow us to decide to what extent such a discrepancy should be attributed to the doubtfulness of the simplest statistical model and to what extent it should be attributed to intranuclear or extranuclear cascade processes.

CONCLUSIONS

1. In the present work the range spectrum for the return component of $\pi^{\pm}$-mesons generated in lead nuclei has been determined and compared with the range spectrum in the direct current. The return meson flux was found to amount to 24 ± 7% of the direct meson flux.
2. It has been established that the number of π^{+}-mesons with a range of the order of 20 g/cm^2 depends weakly on the energy of the generating particles, decreasing somewhat with increase in this energy.
3. It has been shown that for measured energies of the generating particles (not higher than 5 Bev) the number of slow mesons formed also depends weakly on the atomic number of the nucleus.

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Measurement of High Temperatures in Strong Shock Waves in Gases

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A photographic method for the measurement of high temperatures and the absorption coefficient of radiation by the gases in a plane shock wave is described. Results of the measurement of the temperature and absorption coefficient of a plane shock wave in air are presented for wave velocities between 6.4 and 8 km/sec. In strong shock waves in heavy inert gases the experimentally measured temperatures are much lower than the calculated values. It is suggested that this phenomenon is due to screening of the shock wave front by a layer of gas heated by radiation from the shock front.

INTRODUCTION

DURING THE PAST FEW YEARS, methods have been developed to obtain powerful shock waves using explosives. Calculated temperatures up to 70000 °K at pressures of the order of 10^4 kg/cm^2 may be obtained in the wave front by propagating such shock waves is argon ($p_0 = 1$ kg/cm^2, $T_0 = 273$ °K). In spite of the difficulties associated with explosion experiments, the investigation of of strong shock waves is of great interest for the study of the properties of gases at such high temperatures and pressures.

At the present time, many perfected techniques and instruments are available in experimental gas dynamics for the investigation of rapidly-occurring processes. However, comparatively little attention has been paid to the development of methods of temperature measurement. Most of the work devoted to the luminosity of gases in a shock wave has been limited to the investigation of the character of the radiation and to very approximate temperature estimates.

Optical methods based on the temperature dependence of the radiation from a body are most convenient for the measurement of the temperature of a gas under the conditions of a compression shock. It should be noted, first of all, that the luminous spectrum of a gas compressed by a strong shock wave is continuous. Therefore, methods which are widely used for measuring the temperatures of transparent flames (using the radiation of spectral lines) are not suitable for the determination of the temperature of a gas in a strong shock wave. These methods may be applied only with weak shock waves in which the compressed gas layer is still semitransparent in the spectral region in which measurements are being made, and at relatively low temperatures limited by the standard light source. Color and brightness methods are the most widely used for the measurement of the temperature of bodies with continuous radiation spectra. The color method has been used to measure the temperatures of explosion products[1], of adiabatically compressed gases[2] and of technical flames[3]. However, the accuracy of this method, while satisfactory at temperatures on the order of 5000 °K, is insufficient at 10000 °K and above, because the relative distribution of energy in the visible region of the spectrum becomes only slightly sensitive to temperature changes. It was concluded from a comparison of the various known methods of optical pyrometry that the brightness method was the most suitable for the determination of the temperature of the gas in a shock wave, this method providing the greatest accuracy at high temperatures. Since the measurements are carried out over a narrow region of the spectrum, there is no necessity for an accurate determination of the sensitivity of the radiation receiver over a broad region of the spectrum, which is one of the basic difficulties in the comparison of the intensities of radiation of different wavelengths. The method does not require the use of complex spectral apparatus, and may be put into practice with the usual instruments widely used in the study of rapid processes.

PHOTOGRAPHIC METHOD OF HIGH TEMPERATURE MEASUREMENT

The photographic method of high temperature measurement is based on the determination of the ratio of brightnesses in a narrow spectral interval by the corresponding blackening of a photographic film.* compared with a standard with a known brightness temperature. The unknown temperature is found from the equation

$$(e^{C_2 / \lambda T} - 1) / (e^{C_2 / \lambda T_0} - 1) = \tau a \qquad (1)$$

where T_p is the brightness temperature of the standard, T is the temperature of the body under study, λ is the effective wavelength of the spectral interval used, τ is the ratio of the brightness of the standard to the brightness of the body being investigated a is the absorptivity of the body, C_2 = 1.438 cm-deg.

A luminous body whose brightness temperature can be measured in an independent way (temperature tube for calibration of optical pyrometers, the crater of a voltage arc, or any stable source of "black" or "grey" radiation of high brightness) may be used as a standard. For increased accuracy it is advisable to use a source whose temperature is near that being measured. In most of our experiments the sun was chosen as a standard.

The basic instrument for the measurement of the high temperatures arising during the shock compression of gases is the high-speed two-objective photochronograph with a rotating mirror developed by the author in 1948. The optics of the instrument are shown in Fig. 1. The image of the phenomenon being studied is focussed in the plane of slit D by objective O_1 (f = 75 cm, 1 : 6.3). The part of the image cut out by the slit is projected by objective O_2 (f = 7.5 cm, 1 : 2) on the photographic film P after reflection from rotating mirror M. A red lightfilter F which combined with the photographic film form a simple monochromatization system is placed in front of objective O_2. Film blackening is kept withing the limits of the rectilinear part of the characteristic curve of the film by a suitable diaphragm over the first objective. When the mirror rotates, the image of the illuminated slit moves across the film with the velocity $v = 4\pi Rn$, which for a given R is determined by the angular velocity of the mirror n. The maximum velocity with the image moved across the film (sweep velocity) was 2.4 km/sec. Control of the slit width and the sweep velocity varied the exposure time between 10^{-15} and 10^{-7} sec. The process being studied was synchronized

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*The photographic pyrometer for the measurement of nonstationary temperatures in the range 1000 – 1400 °K proposed by Male[4] in 1951 was based on the same principle.

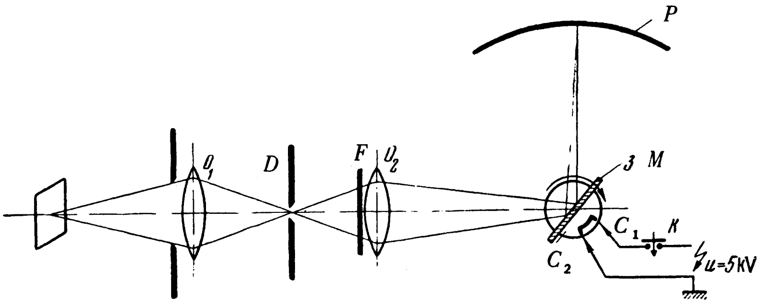

FIG. 1. Optical schematic of the photochronograph with a red filter for recording high temperatures in rapidly occurring processes.

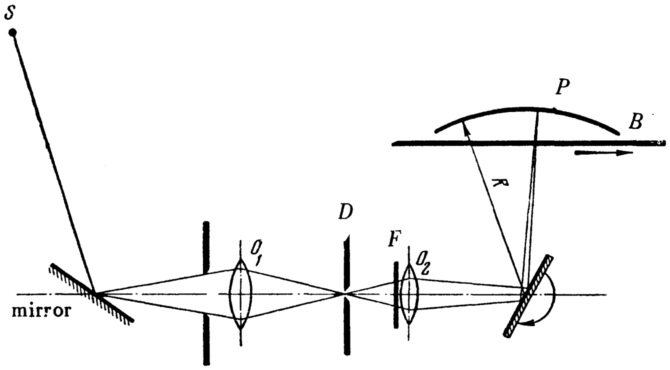

FIG. 2. Schematic of the photochronographic recording of solar film density.

with the mirror position by the rotating spark switch C, rigidly attached to the axis of the mirror, and by the two regulating contacts C_1 and C_2 included in the circuit of the electrodetonator. The circuit is completed by closing push-button K.

Photography of the standard S (the sun) was carried out on the same apparatus, equiped with a special shutter (Fig. 2). Blind B has a rectangular slot 5 mm wide. Initially (extreme left position) the film is covered by the blind. When triggered a spring mechanism moves the blind from left to right with a velocity of 2 m/sec. The angular velocity of the mirror is chosen such that the velocity of the image of the slit over the film is $\sim$ 0.5 km/sec. With this relation between the sweep velocity and the blind velocity, a new part of the film is illuminated during each revolution of the mirror. By obtaining on one film two series of images taken with different exposures H_1 and H_2, we may determine the tangent of the slope angle of the characteristic curve γ, which is necessary for the calculation of brightness ratios from density differences:

$$\gamma = (d_1 - d_2) / \log (H_1/H_2).$$

At the instant of photographing, the brightness temperature of the sun was measured by an optical pyrometer with a vanishing filament and an additional neutral filter.

The films of each series of experiments and the photographs of the sun were developed together. The results were thus protected from the influence of the photographic solutions. The photochronograms were prepared with a Zeiss nonrecording photoelectric microphotometer.

In photography it is usually assumed that the exposure within the limits of the image (neglecting atmospheric absorption) is independent of the distance to the object of the photograph and is determined only by the transmission of the optical system. This assumption is valid if the distance L between the object of the photograph and the instrument is considerably greater than the focal length f of the optical system. When L is comparable with f, it is necessary to take into account the difference in effective transmission which is determined by the ratio

$$k = \left(\frac{L_1 - f}{L_1}\right)^2 \bigg/ \left(\frac{L_2 - f}{L_2}\right)^2 .$$

In our work in which the shock wave is photographed at a distance of 10–20 m, and the standard (the sun) is practically at infinity, this condition must be taken into account.

It is well known that the photographic effect is a function of two independent variables; the illumination E and the exposure time t. However, the investigations of Kartuzhanskii and Meikliar[5] have shown that for exposure times less than 10^{-5} sec the reciprocity law holds – the blackening of the photographic emulsion is determined by the product of the illumination and the exposure time. This simplifies considerably the use of photographic recording for short-duration processes because deviations from the reciprocity law need not be investigated. To guarantee these conditions in all our experiments, the time during which light acted on the photographic film did not exceed 10^{-5} sec.

The wavelength λ of the part of the spectrum in which measurements of brightness ratios are made enters into Eq. 1, used for the determination of the temperature T. We singled out a narrow region of the spectrum by using the combination of a red glass light filter with a lower transmission limit $\lambda_1 = 0.57\,\mu$ and photographic film with an upper sensitivity limit $\lambda_2 = 0.66\,\mu$. The sensitivity of the photographic film v_λ and the transmissivity of the red filter τ_λ are plotted against wavelength in Fig. 3. The portion of the figure with double crosshatching represents the working spectral interval, extending over $\sim 0.09\,\mu$. In this case the effective wavelength for

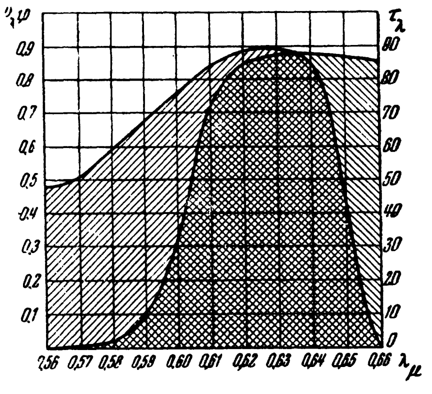

FIG. 3. Sensitivity of the photographic film and transmissivity of the red filter as a function of the wavelength λ; v_λ is the sensitivity of the film in relative units and τ_λ is the percentage transmissivity of the red filter.

the determination of the temperature T from the known temperature T_0 may be calculated from the ratio of the respective light fluxes F and F_0 passing through the red filter and received by the light-sensitive emulsion.

$$\frac{F}{F_0} = \int_0^\infty v_\lambda \tau_\lambda b_{\lambda, T}\, d\lambda \bigg/ \int_0^\infty v_\lambda \tau_\lambda b_{\lambda, T_0}\, d\lambda$$

$$\approx \sum_{\lambda_1}^{\lambda_2} v_\lambda \tau_\lambda b_{\lambda, T}\, \Delta\lambda \bigg/ \sum_{\lambda_1}^{\lambda_2} v_\lambda \tau_\lambda b_{\lambda, T_0}\, \Delta\lambda,$$

where $b_{\lambda,T}$ and b_{λ,T_0} are the spectral brightnesses at the temperatures T^0 and T_P respectively, calculated by Planck's formula

$$b_{\lambda, T} = C_1 \lambda^{-5} (e^{C_2/\lambda T} - 1)^{-1},$$

$$C_1 = 3{,}71 \cdot 10^{-5} \text{ erg-cm}^2/\text{sec}.$$

Knowing the ratio F/F_0, we find the value of the effective wavelength λ satisfying the equation

$$F/F_0 = (e^{C_2/\lambda T_0} - 1) / (e^{C_2/\lambda T} - 1).$$

In the high temperature region ($T > 8000\,°\mathrm{K}$) the effective wavelength λ changes only slightly with changes of the measured temperature, and a single value may be used for calculations. For the filter and photographic film described by Fig. 3, the effective wavelength was $0.625\,\mu$ at measured temperatures on the order of $10000\,°\mathrm{K}$ and at a standard brightness temperature $T_0 = 5500\,°\mathrm{K}$.

APPLICATION OF THE PHOTOGRAPHIC METHOD TO THE MEASUREMENT OF THE AIR TEMPERATURE IN A PLANE SHOCK WAVE

Three series of experiments were carried out, differing from one another by the velocity of the shock wave. The experimental setup is shown in Fig. 4. In one series of experiments a plane shock wave in air was created directly by the explosion products of a cylindrical charge of explosive 120 mm in diameter (Fig. 4a). In the other series (Fig. 4b) the shock wave velocity was decreased by placing an aluminum of organic-glass plate 2 mm thick in front of the charge. The axis of the charge was always situated parallel to the axis of rotation of the photochronograph mirror. A plane fixed mirror was placed in front of the charge at an angle of 45° with respect to its axis. With this arrangement the instrument records simultaneously the variations of wave front brightness and the velocity of propagation of the shock wave. A photochronogram of an experiment of this type is shown in Fig. 5. The sun

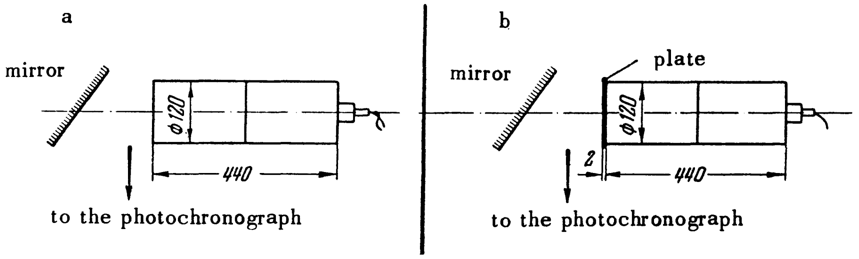

FIG. 4. Experimental setup for the simultaneous measurement of the temperature and propagation velocity of a shock wave in air. a — shock wave in air created directly by explosion products; b — shock wave created by a plate of organic glass or aluminum, accelerated by explosion products.

was photographed on the same apparatus using two different exposure times. The photographic conditions (diaphragm, slit width, sweep velocity) were selected such that the film density lay within the limits of the rectilinear part of the characteristic curve of the film. A fixed mirror whose reflection coefficient was practically equal to the reflection coefficient of the mirror in the actual experiment was used to aim the sun onto the entrance objective. By appropriate choice of the charge dimensions, the shock wave parameters were constant during the 10–12 microseconds following the instant at which the detonation wave left the end of the charge.

The film density in region 1 (Fig. 5) was used to determine the air temperature behind the shock wave front. The absorptivity of the shock wave front was calculated from the increase of the intensity of the luminosity using the method described below. The temperature in the shock wave was also determined from the film density of photographs taken in a direction perpendicular to the axis of the charge (region 2 in Fig. 5). In this case the absorptivity was taken to be unity in accordance with the measurements presented below.*

The results obtained from the photographs in the three series of experiments are presented in Tables 1, 2, and 3. Both values of temperature are given in the tables: T_p calculated from photometric data in region 1, and T_l calculated in region 2. The mean values of the temperatures from all three series of experiments are plotted graphically in Fig. 6. The solid points refer to measurements of T_p made in a direction parallel to the propagation of the shock wave front, and the circles refer to T_l measured laterally. Also shown on the figure is the temperature dependence of the shock wave velocity, calculated by Davies[6]. The dissociation of oxygen and nitrogen molecules and the formation of nitric oxide at high temperatures is taken into account in the calculations. Since at present the dissociation energy of nitrogen remains a subject of discussion, calculations were carried out for two probable values of the dissociation energy. The upper branch of the curve was calculated with an assumed dissociation energy $D_{N_2} = 9.76$ ev, and the lower curve results from the value $D_{N_2} = 7.38$ ev. The experimental results are in satisfactory agreement with the theoretical calculations. One might suppose that the data obtained, might decide between the two

TABLE I. Air temperature in a plane shock wave. Experimental setup as in Fig 4a ($V = 8.5$ km/sec).

V, km/sec.	T_p °K	T_l °K
7.93	11900	10640
8.12	12050	10870
8.22	9650	9120
8.10	10900	9800
8.18	11430	12050
8.24	9550	9750
8.13	10260	9850
8.03	10600	10320
8.03	10100	9800
7.93	11850	10300
7.95	10420	10200
7.91	11100	10640
7.92	12320	10300
8.10	10260	9650
Arithmetic mean 8.05	10900	10235

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*Temperature measurements using the photometric data in region 1 are more reliable. With photography in a direction perpendicular to the propagation of the wave front, the radiation passes through a region of lateral discharge, which may lead to error in the determination of temperature.

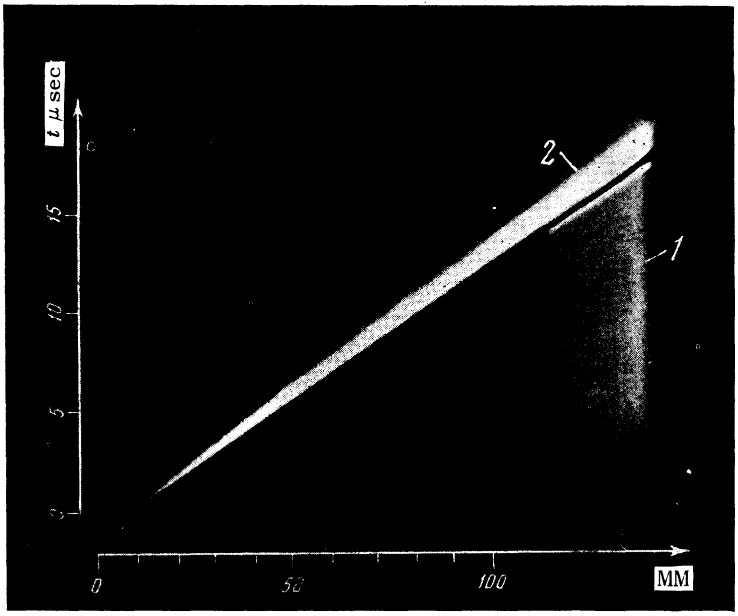

FIG. 5. Photochronogram of the experiment described in Fig. 4.

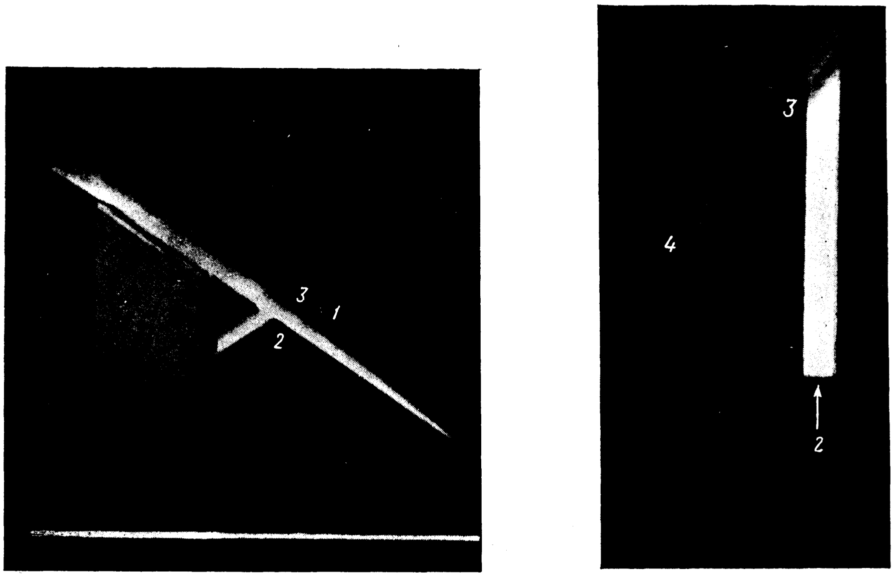

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FIG. 8. a — Photochronogram of the experiment described by Fig. 7a; b — photochronogram of the experiment described by Fig. 7b.

TABLE II. Air temperatures in a plane shock wave. Experimental setup as in Fig. 4b; plate material–organic glass ($V=7.1$ km/sec).

V, km/sec	T_p °K*	T_l °K
7.08	9500	8650
7.05	8780	8450
7.12	10100	9000
7.15	8700	8150
Arithmetic mean 7.1	9270	8560

*Values of the absorptivity of air for the calculation of T_p in this series of experiments was determined by interpolation between the absorption coefficients obtained for shock wave velocities of $V=6.4$ and 8.05 km/sec. A direct determination of the absorption coefficient by the increase of brightness of the shock wave front was not possible because the film density was too slight.

conflicting values of the dissociation energy of the nitrogen molecule. Unfortunately, the measuring accuracy achieved thus far and the insufficient number of experiments does not allow us at present to solve this problem uniquely.*

An analysis of the possible sources of error in the photographic method of measurement of high temperatures indicates that the accuracy of the method is ±6% at 7500°K, ±13% at 25000°K, and ±16% at 50000°K. The experimental error depends to a considerable extent on the magnitude of the temperature being measured, the ratio of the measured temperature and the standard temperature, and also on the effective wavelength of the spectral interval being used. Temperature measurements in the short-wave part of the spectrum provide greater accuracy than in the red end. However, the use of the red region of the spectrum has substantial advantages (smaller absorption of radiation in the atmosphere and optical parts, and simplicity of the monochronizing arrangement). The experimental error may be reduced somewhat by a more accurate determination of the standard temperature and of the angular velocity of the mirror of the photochronograph, and by making more precise the effective wavelength and the characteristic curve of the photographic film. According to our estimates, it is possible to decrease the probable error in the temperature measurement by a factor of 1.5–2.

MEASUREMENT OF THE ABSORPTION COEFFICIENT AND THE ABSORPTIVITY

To determine the true temperature of a body according to Eq. (1), it is necessary to know its absorptivity a. In many cases the determination of the absorption coefficient of radiation by gases at high temperatures is also of considerable interest.

TABLE III. Air temperatures in a plane shock wave. Experimental setup as in Fig. 4b; plate material–aluminum ($V=6.4$ km/sec).

V km/sec	T_p °K	T_l °K
6.22	7310	8530
6.46	7600	8300
6.51	8180	9670
6.51	7200	7500
6.32	7220	7850
6.40	7350	8480
Arithmetic mean 6.4	7480	8390

Experiments to determine the absorptivity were set up according to the scheme shown in Fig. 7. Here, the front of the plane shock wave created by the explosion of a cylindrical charge of explosive is

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*After the completion of these experiments an article by Christian et al[7] appeared, in which measurements of the mass and wave velocities of shock waves in nitrogen were used to determine the dissociation energy of nitrogen. According to these experiments, the higher value of $D_{N_2} = 9.76$ ev is correct.

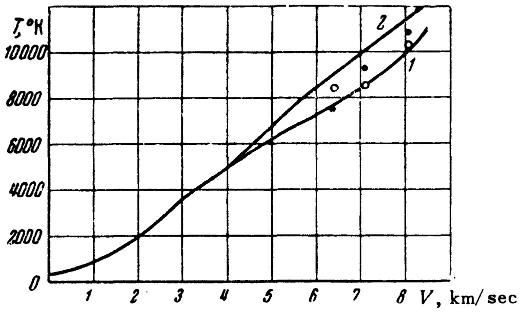

FIG. 6. Theoretical dependence of temperature on the propagation velocity of a plane shock wave in air, and experimentally measured temperatures. Solid circles represent measurements in the direction of propagation of the shock wave front (T_p); open circles represent lateral measurements (T_s). $1 - D_{N_2} = 7.38$ ev; $2 - D_{N_2} = 9.76$ ev.

illuminated by an auxiliary source of light in the direction of the arrow. In the first experiments (Fig. 7a) the auxiliary source of light was a shock wave in air from the same kind of charge, located behind the shock wave being studied. The principal and the illuminating charges were triggered simultaneously. On the photochronogram of this kind of experiment (Fig. 8a) the density of portions 1 and 2 corresponds to the brightness of a shock wave in air from the principal and auxiliary charges, and portion 3 corresponds to the brightness of the shock wave the auxiliary charge photographed through the shock wave being investigated.

If the absorptivity of the layer of gas under study differs from unity, an increase of brightness would be observed in region 3. In these first experiments it was noted that the absorptivity of the air in a shock wave ($V = 6.4$ to 8 km/sec) was equal to unity within the limits of photometric error, with the direction of photography perpendicular to the direction of propagation of the wave front.

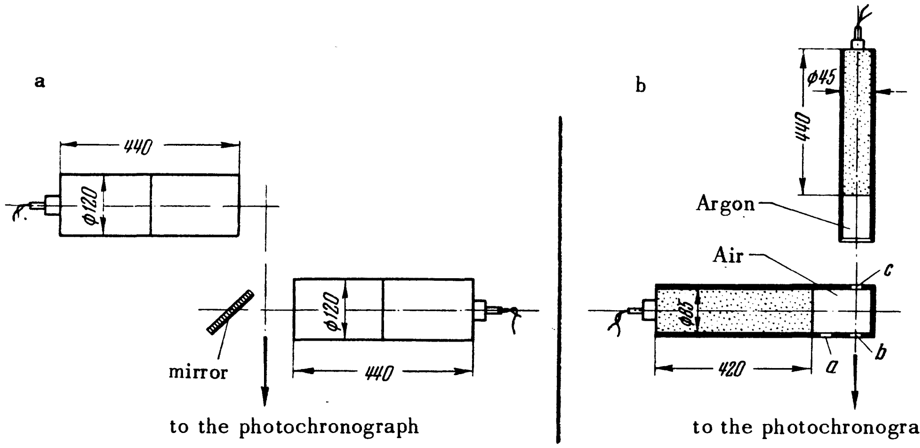

FIG. 7. Experimental setup for the measurement of the opacity of air in a plane shock wave.

In order to obtain more precise results, additional experiments were performed in which the luminosity of a shock wave front in argon was used to "illuminate" the shock wave in air (Fig. 7b). A plane wave in air was created by a cylindrical charge of explosive enclosed in a duraluminum container in whose walls three apertures (a, b, c) were made. Apertures b and c are located at the bottom of the container, opposite one another. An additional charge was placed perpendicular to the axis of the principal charge. The additional charge was determinated by a container with a transparent organic glass bottom. This container was filled with argon at atmospheric pressure. The axis of the additional charge coincided with the centers of windows b and c. Both charges were triggered simultaneously. On the photochronogram of this kind of experiment (Fig. 8b) we see first the brighter luminosity of the shock wave front in argon (the sweep direction is indicated by arrow 2), then the luminosity of the shock wave in air through window a (region 4), and finally, the luminosity or argon observed through the shock wave in air (region 3). Since the brightness of the shock wave in argon is greater than the brightness of the wave in air, this variant of the method substantially increases its sensitivity. It is clear from the photographs presented that the layer of air under investigation, compressed by the shock wave, is not transparent. Photometric results which give the same value of film density in regions 3 and 4 confirm this conclusion.

The large value of the absorption coefficient in the shock wave leads to complete opacity of the gas layer, even when it is very thin. Therefore, the determination of the absorption coefficient by the methods described is quite difficult. It is possible only when the width of the wave front is very small (a fraction of a centimeter). However, this requirement is not realizable in practice because of the extremely rapid discharge during the explosion of charges of small diameter.

The absorption coefficient and the absorptivity of gases under shock compression were determined by us using the following method, based on an examination of the variation of brightness of the shock wave front in the direction which it is propagating (Fig. 9). Let us assume that the parameters characterizing the shock wave (velocity, temperature, etc.) remain constant.* As the shock wave propagates, the thickness of the compressed gas layer continuously. The transmissivity of layer 1, "assembled" by the shock wave during the time $t_1 - t_0$, is given by the relation $g_1 = (b_{0,1} - b_1)/b_0$; similarly, for layer 2, $g_2 = (b_{0,1,2} - b_2)/b_{0,1}$. Here, B_0 is the brightness of the wave front at the instant t_0, b_1 and b_2 are the brightnesses of layers 1 and 2 respectively, $b_{0,1}$ is the brightness of the wave front at the instant t_1, and $b_{0,1,2}$ is the brightness of the wave front at the instant t_2. If the intervals $t_1 - t_0$ and $t_2 - t_1$ are equal, then $b_1 = b_2$, and

$$g_1 = g_2 = (b_{0,1,2} - b_{0,1})/(b_{0,1} - b_0) = g' \qquad (2)$$

Thus, the transmissivity g' of a gas layer of thickness l', "assembled" by the shock wave during the time $\Delta t = (t_1 - t_0) = (t_2 - t_1)$, may be found from three successive measurements of the brightness of the wave front, if the interval between measurements is Δt. For a homogeneous layer of gas the transmissivity if $g' = e^{-\varkappa l'}$, from which the coefficient of absorption $\varkappa$ may be determined if the thickness of the absorbing layer l' is known.

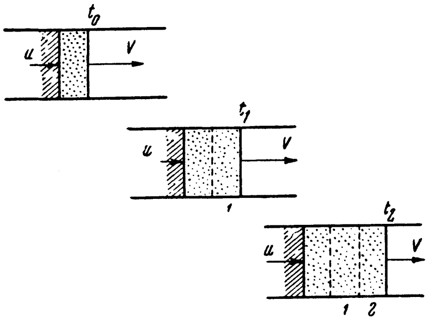

FIG. 9. Propagation of a plane shock wave in a gas.

For a layer of of arbitrary thickness l, the transmissivity $g = g'^{l/l'} = g'^{t/\Delta t}$ (since $l \sim t$). The last formula makes it possible for us to calculate the transmissivity of the gas layer "assembled" by the shock wave during the time t (considered from the instant the shock wave starts to propagate) and consequently, its absorptivity $a = 1 - g'^{l/l'} = 1 - g'^{t/\Delta t}$, which is necessary for the determination of the temperature using Eq. 1.

Measurements of the absorptivity and the absorption coefficient in a shock wave by the method suggested above are easily accomplished using the apparatus as used to determine gas temperatures, without any auxiliary sources of light. The method is applicable only to plane shock waves where conditions may be chosen such that the gas-dynamic parameters remain constant.

In Fig. 10, the solid curve shows the increase of intensity of the luminosity of the shock wave front ($V = 8.05$ km/sec) observed in the direction in which it is propagating. This curve is the mean result of 13 experiments. Photometry was done at intervals of 0.5 mm of film in the sweep direction. This corresponds to a shock wave front movement of 2.8 mm ($\sim 0.35\,\mu$ sec).

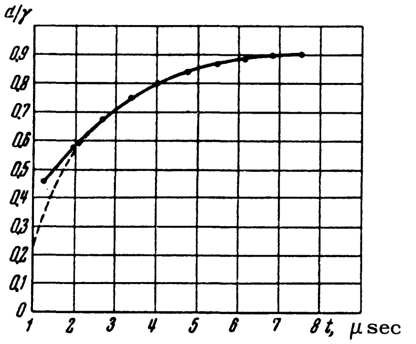

FIG. 10. Increase of the intensity of the luminosity of a plane shock wave front in air at $T = 10900\,^{\circ}$K; solid line–results of film photometry (mean of 13 experiments); dotted line–calculated curve corresponding to the value $\varkappa = 3.7$ cm^{-1}.

The transmissivity of the layer "collected" by the shock wave during $\Delta t = 1\,\mu$ sec is determined by Eq. 2:

$$g_{\Delta t} = e^{-\varkappa \Delta t} = \frac{(b_{t+\Delta t} / b_t) - 1}{1 - (b_{t-\Delta t} / b_t)},$$

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*This condition may be guaranteed during the initial stages of propagation of the shock wave by suitable choice of the size of the explosive charge.

where the values of $b_{t+\Delta t}/b_t$ and $b_{t-\Delta t}/b_t$ are calculated from the corresponding density differences

$$\log(b_{t+\Delta t}/b_t) = (d_{t+\Delta t} - d_t)/\gamma,$$

$$\log(b_{t-\Delta t}/b_t) = (d_{t-\Delta t} - d_t)/\gamma.$$

To increase the accuracy, it is necessary to determine $g_{\Delta t}$ at various parts of the curve and to take the mean of these values. The initial portion, which is outside the limits of the region of proportional blackening, must be excluded from consideration.

The calculated variation of intensity based on values of the absorption coefficient obtained in this way is shown by the dotted line in Fig. 10 (the calculated curve was made to fit the experimental curve at one point). Except for the initial portion, the calculated and the experimental curves are in almost complete agreement. Using this method, we determined the absorption coefficient for radiation ($\lambda = 0.625\,\mu$) with shock wave velocities in air $V = 6.4$ km/sec ($T = 7480\,°$K) and $V = 8.05$ km/sec ($T = 10900\,°$K). The initial air pressure in both cases was one atmosphere. Values of the absorption coefficient $\varkappa/\text{cm}^{-1}$ obtained experimentally, and also calculated with the known Kramers formula, taking account of the formation of nitrogen oxides, are presented in Table 4. The shock wave compression ρ/ρ_0 was assumed to be 10. The deviation of our results from the values calculated by Kramers' formula may by partially explained by the insufficient accuracy of the temperature determination,. Thus, if the absorption coefficient measured at $V = 6.4$ km/sec is referred to the temperature $T = 9200\,°$K (this results from calculations based on $D_{N_2} = 9.76$ ev), the deviation is substantially decreased ($\varkappa_{\text{theor.}} = 0.55$ cm^{-1}). It should also be kept in mind that the application of Kramers' formula to non-hydrogenlike atoms or ions may lead to significant errors[8,9].

TABLE IV. Values of the absorption coefficient of air in a shock wave for $\lambda = 0.625\,\mu$.

V, km/sec	T °K	$\varkappa$ cm^{-2}	
		experimental*	theoretical
8.05	10900	$3.7_{(13)}$	0.6
6.4	7480	$1.66_{(6)}$	0.083

*The subscripts following the experimental values of the absorption coefficient indicate the number of experiments.

TEMPERATURE MEASUREMENTS IN HEAVY INERT GASES IN STRONG SHOCK WAVES

From a theoretical consideration of the processes involved in a shock compression, it follows that the highest temperatures may be obtained by propagating a shock wave in heavy monatomic gases[10]. Using the method described above, experiments were carried out to verify the calculated temperatures of inert gases in shock waves. Shock wave temperatures were measured in argon, krypton, and xenon. For the determination of temperature, the absorptivity of the shock wave front was assumed to be unity.*

The results of calculations of the temperature in a shock wave front as a function of its propagation velocity, taking account of energy loss in ionization and thermal radiation, are presented in Fig. 11. Also shown in the figure are experimentally measured temperatures in the shock wave front. Comparing the experimental points with the calculations, it is clear that all the measured values lie below those calculated. This discrepancy can not be explained by errors in the method used to measure temperature. The experimental error in the temperature interval under consideration did not exceed ±20%, while the experimental value of temperature is lower than the theoretical value by a factor of 3 in krypton and by a factor of 3.5 in xenon. It should be noted that the experimentally observed temperatures, the theoretical calculations nothwithstanding, decrease in the order argon–krypton–xenon.

The most probable explanation of this interesting fact was proposed by Zel'dovich[11]. It is based on the assumption that a layer of gas in contact with the shock wave front is opaque owing to heating by radiation emanating from the wave front. A considerable part of the radiated energy at high temperatures is absorbed in the atmosphere directly in front of the shock wave front. If it is assumed that under these conditions the absorption of radiation

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*A sufficient basis for this assumption is the extremely sharp increase in the intensity of the luminosity during the initial period of propagation of the shock wave, attesting to a large value of the absorption coefficient.

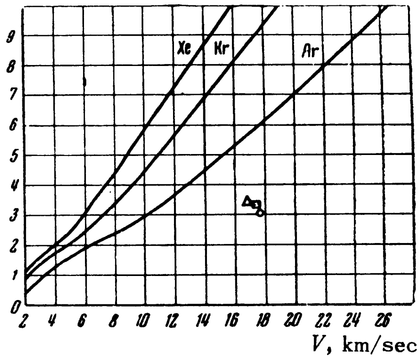

FIG. 11. Temperature of heavy inert gases in the front of a strong shock wave. Experimental values: O — argon, □ — krypton, Δ — xenon.

may be explained on the basis of photoexcitation and photoionization of the gas, then at comparatively low temperatures behind the wave front (up to ~ 10000°K), when the heat flux is small and the principal part of the radiation is produced in the region of the visible spectrum, there is practically no absorption. At higher temperatures where the principal part of the total radiation is produced in the region of characteristic absorption of the gases, the absorption of radiation must lead to heating of the gas in front of the shock wave front.

The radiation energy produced in the region of wavelengths from $\lambda = 0$ to $\lambda = \lambda_1$, may be calculated by Planck's formula

$$S = \frac{\int_0^{\lambda_1} C_1 \lambda^{-5} (e^{C_2/\lambda T} - 1)^{-1} d\lambda}{\int_0^{\infty} C_1 \lambda^{-5} (e^{C_2/\lambda T} - 1)^{-1} d\lambda}.$$

The calculated fractions of the total black-body radiation energy, produced in the wavelength region between $\lambda = 0$ and $\lambda = 0.11\,\mu$ (corresponding approximately to the limit of opacity for argon, krypton, and xenon under normal conditions), are presented in Fig. 12.

Let us now estimate the heating of the gas in in front of the shock wave front by radiation emanating from the wave front. As an example we consider a stationary wave in xenon with $V = 17.5$ km/sec in a system of coordinates moving with the wave front. Gas flows into the wave with velocity V, and radiation E leaves the surface of the wave front (Fig. 13). The velocity $V = 17.5$ km/sec in xenon corresponds to a temperature behind the wave front $T = 106000\,^\circ$K (see Fig. 11) and the flux of radiant energy is $E = \sigma T^4 = 7.15 \times 10^{15}$ erg/sec-cm^2. Hence, the energy absorbed by the gas in front of the shock wave front is, according to Fig. 12, $E' = ES = 6.72 \times 10^{15}$ erg/sec-cm^2. This energy is distributed among $N = nV = 4.72 \times 10^{25}$ atoms ($n = 2.7 \times 10^{19}$ is the number of atoms per cm^3 of gas at standard conditions). The energy per atom is

$$E'/N = 1.43 \times 10^{-10} \text{ erg}.$$

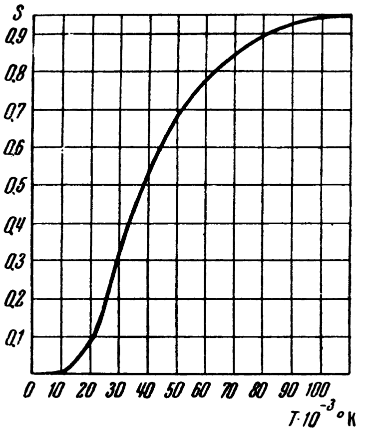

FIG. 12. Ratio of the energy radiated by a black body in the spectral interval $\lambda = 0$ to $\lambda = 0.11\,\mu$ to the total energy radiated, as a function of temperature.

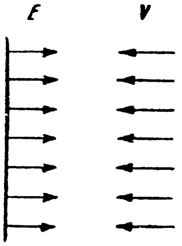

FIG. 13. Schematic for the calculation of the heating of the gas in front of the shock wave front by radiation emanating from the front.

Let us assume that the mean value of the heat capacity during the rise of gas temperature is $C = \epsilon/T'$, where ϵ is the energy falling on one gas atom, calculated by taking account of ionization and by assuming that the heating occurs at constant volume up to the temperature $T' = E'/Nc$. By the method of successive approximations, we find for the temperature of the incoming flow, $T = 63000\,^\circ$K. Such heating of the gas by radiation from the shock wave must lead to a rounding out of the temperature jump at the wave front. The temperature distribution in this case will be approximately as shown in Fig. 14. With the increase of the temperature of the gas in front of the shock wave front, the absorption coefficient increases and an optical thickness on the order of several units is realized under these conditions when the thickness of the layer is a

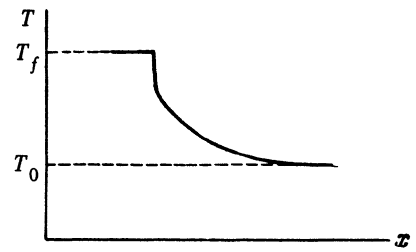

FIG. 14. Temperature distribution in the gas in front of the shock wave front.

fraction of a centimeter. Optical methods of temperature measurement are not applicable in this case because they give only the value of some effective temperature of the opaque gas layer that screens the shock wave front located behind it.

Similar effects of the "saturation" of the brightness temperature have been repeatedly observed by many investigators. In Glaser's experiments[12] on the measurement of the temperatures of condenser spark discharges in argon at high initial pressure, an increase of the specific power from 0.21×10^{15} to 0.42×10^{15} erg/sec-cm^3 led to a marked temperature rise from 20000 to 40000°K. However, a further increase in specific power to 1×10^{15} erg/sec-cm^3 did not increase the measured temperature. A similar "saturation" of the measured temperature was definitely established in experiments by Azarkh, Voinov, and the author on condenser spark discharges in argon with an initial pressure of 20 kg/cm^2. Here, a change of the energy of the discharge circuit from 0.75×10^9 to 1.5×10^9 ergs led to an increase of the measured temperature from 32000 to 37000°K. Increasing the energy of the circuit still further to 2.4×10^9 ergs left the maximum value of the temperature practically unchanged at 37000°K. Vul'fson, Libin, and Charnaia[13] also observed the existence of a limiting brightness during pulsed discharges in inert gases.

The above limitation on the possibilities of optical pyrometry depends on external conditions (density, pressure) as well as on the individual properties of the substance (excitation and ionization potentials), and the limits of applicability of optical methods must be established in each specific case, based on the concrete experimental conditions and accuracy requirements.

CONCLUSIONS

1. The photographic method of measurement of high temperatures in strong shock waves uses a comparison of the density of the photographic image of the shock wave front with the density of the image of a temperature standard, over a narrow interval of wavelengths. The method permits simultaneous measurement of temperature and shock wave velocity. Methods were developed to use the photochronograms for the determination of the coefficient of absorption of radiation in the front of a plane shock wave.

2. The temperatures measured in plane shock waves in air were 7480°K for a shock wave velocity of $V = 6.4$ km/sec, 9270°K for $V = 7.1$ km/sec, and 10900°K for $V = 8.05$ km/sec. The temperature measurements were accurate to within ±10%. The experimental results were in satisfactory agreement with theoretical calculations. The coefficient of absorption of radiation ($\lambda = 0.625\mu$) in the front of a plane shock wave in air was 1.66 cm^{-1} at $T = 7480$°K, and was 3.7 cm^{-1} at $T = 10900$°K.

3. The temperatures definitely established in the front of strong shock waves in heavy inert gases were several times lower than calculated. An analysis of the possible causes of the observed discrepancy indicated that at very high temperatures the heating of the gas located in front of the wave front by radiation from the shock wave strongly influences the measurement results. The gas layer heated by the radiation becomes opaque and screens the "hotter" front of the shock wave. The tempeture of this layer is always lower than the true temperature of the wave front.

In conclusion, the author expresses profound thanks to his principal coworkers Z. M. Azarkh and F. O. Kuznetsov who carried out a large number of laborious experiments and reduced the experimental results. The author also thanks the sponsors of the work, Prof. V. A. Tsukerman, Prof. Ia. B. Zel'dovich, and Prof. D. A. Frank-Kamenetskii, for valuable advice and constant help during the investigation

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Paramagnetic Absorption at High Frequencies in Gadolinium Salts in Parallel Fields

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Measurements were carried out at room temperature on the dependence of paramagnetic absorption on the intensity of a stationary field parallel to a high frequency ($\nu = 9.377 \times 10^9$ cps) field. The experimental absorption curves are in good agreement with Shaposhnikov's spin absorption theory[1]. This made it possible to determine the internal field constant and the isothermal spin relaxation time for several gadolinium salts, and to determine in absolute units the absorption coefficient of $Gd_2(SO_4)_3 \cdot 8H_2O$ as a function of the intensity of the stationary field.

PARAMAGNETIC ABSORPTION has been experimentally studied in a number of salts by Gorter and his coworkers[2], Garif'ianov[3], and Sitnikov[4], over the frequency range of 10^6-10^8 cps with the high frequency field parallel to the stationary field. Garif'ianov and Sitnikov made their measurements at room temperature at frequencies of the order of 6×10^8 cps (using electronic circuitry) and with fields from 0 to 6000 oersteds. Their experiments indicated that the experimentally determined absorption as a function of the strength of the stationary field, with fixed frequency of the variable field, is in good agreement with the values obtained from Shaposhnikov's theoretical formula[1] for spin absorption if the isothermal spin relaxation time τ_s, entering into this formula, is considered to be independent of the strength of the stationary field. This made it possible for the authors of Refs. 3 and 4 to use Shaposhnikov's formula for the experimental determination of the internal field constant b/C (b is the magnetic heat capacity constant and C is the Curie constant).

The above-mentioned experiments (Refs. 2-4) were conducted at frequencies considerably lower than the reciprocal of the isothermal spin relaxation time (τ_s^{-1}). For a more complete study of spin absorption at room temperature, the author[5] performed similar experiments at frequencies for which $\tau_s \nu \geqslant 1$. This was accomplished by using centimeter wave techniques. High-frequency power from the generator was sent through a coaxial waveguide into a cylindrical resonator in which an H_{011} wave was excited. From the resonator the power went to an indicator with a germanium detector and a mirror galvanometer. It is well known that the magnetic field of an H_{011} wave is axially symmetrical, and that near the center of the resonator the lines of force are directed along the axis of the cylinder in the form of a cable. The field near the center of the resonator is therefore quite uniform. Our experimental setup differs from others known to us in that we are able to perform absorption measurements in arbitrary units for any angle between the stationary and the high-frequency fields, made possible by a rotating flange in the coaxial guide joining the resonator and the generator. A more detailed description is given in Ref. 5. The powdery paramagnetic substance was thoroughly dried and then