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NONEQUILIBRIUM RADIATION FROM SHOCK COMPRESSED IONIC CRYSTALS AT TEMPERATURES ABOVE 1 eV. I

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The brightness temperature of the shock wave front is measured in five ionic single crystals (LiF, NaCl, KC*l*, KBr, and CsBr). A discrepancy between the measured and theoretical values of the brightness temperatures is observed at pressures between 0.5 and 5.0 Mbar. The discrepancy is the larger the higher the shock wave pressure in the crystal. It is lowest for LiF and highest for CsBr. Possible causes of the lower luminescence of the front are considered. One of these is the presence of a layer of matter before the wave front heated by radiation from the latter (as observed in gases) and another cause may be the high reflectance of the front. It is demonstrated that these causes are not sufficient to explain the decrease of brightness observed in the experiments. Another cause of the effect which is connected with establishment on an equilibrium temperature for electrons, is considered in detail in the second part of the paper (see[11]).

THIS paper is part of more extensive research on the behavior of ionic crystals through which shock waves of various intensities are passed. We first investigated the dynamic compressibility of five substances[1] up to pressures of 5 Mbar. In subsequent investigations[2,3] we considered the processes of emission and absorption of light by the front of a shock wave in NaCl and KCl, advanced certain hypotheses concerning the mechanism of light absorption and the conductivity of shock-compressed NaCl, and measured the temperatures of NaCl and KCl behind the front of shock waves up to temperatures (4–5) × 10^{3}°K, making it possible to trace their melting curves up to unprecedented high pressures. Similar results, obtained in this temperature range for KBr, CsBr, and LiF are now being readied for publication. The present paper reports the results of the measurement of brightness temperatures in NaCl, KBr, KCl, LiF, and CsBr in the range of temperatures above (4–5) × 10^{3}°K. As follows from[2], under these conditions the investigated substances are in the liquid phase, and questions of melting will not be touched upon here. The investigated range of shock-w wave pressures lies in the interval 0.5–5 Mbar.

EXPERIMENTAL PROCEDURE

Unlike[2], we used in the present investigation a photographic method for measuring the brightness temperature. Under conditions of much higher measured temperatures than in[2], this method affords a time resolution and a measurement accuracy which are close to those provided by the photoelectric method. The photographic method has a major advantage in that it yields the distribution of the brightness over a chosen section of the shock wave front. The photographic method was used earlier by Model'[4] to measure the temperatures of shock-compressed gases, and also in his later investigations[15].

The brightness temperature was measured in two sections of the spectrum—the red and the blue—using the SFR-2M high speed camera equipped with additional spectral filters and neutral attenuators in the optical system. The boundaries of the spectral interval in the red region of the spectrum were determined by the KS-14 red filter transmission and by the sensitivity of the type-10 Pankhrome film ($\lambda_{av} \approx 6500$ Å, $\Delta\lambda \approx 600$ Å). A section of the blue region of the spectrum was separated by a combination of three light filters: SS-4, SZS-18, and ZhS-11 ($\lambda_{av} \approx 4400$ Å, $\Delta\lambda \approx 700$ Å).

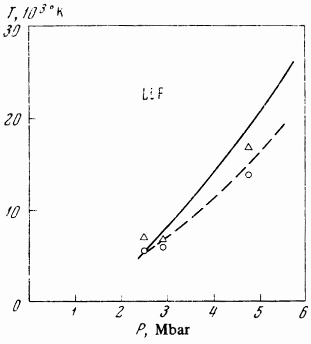

FIG. 1.

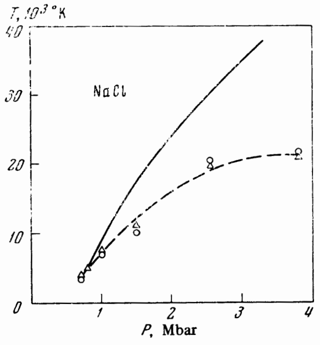

FIG. 2.

The brightness standard used in the measurement of the brightness temperature was an IFK-50 flash lamp[6], carefully calibrated beforehand against an SI-60 tungsten ribbon lamp both photographically (using the same measuring instruments as used for the brightness temperature in the red region of the spectrum), and by the photoelectric method[2] (in the red and blue regions of the spectrum). The standard and the investigated substance were mounted at the same place and photographed at a constant magnitude of the instrument slit. The data reduction, as before[2], was by the method of active fluxes[7].

RESULTS AND THEIR DISCUSSION

The results of the measurement of the brightness temperature T_b of the shock wave front, the pressure P in the wave, the degree of compression ρ/ρ_0, and certain characteristics of the investigated substances at normal pressure are listed in the table and are plotted in T-P coordinates in Figs. 1–5. The triangles

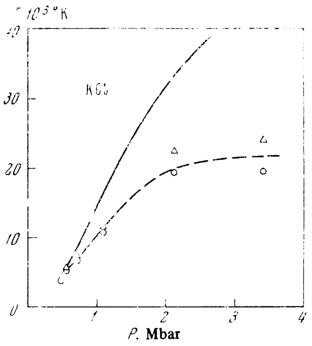

FIG. 3.

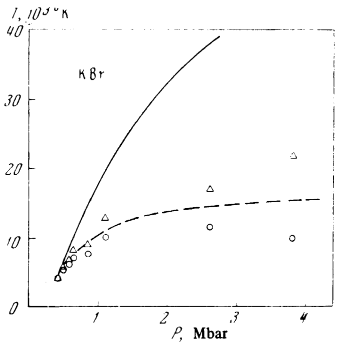

FIG. 4.

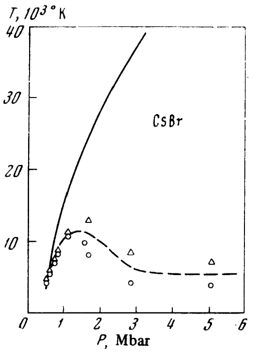

FIG. 5.

and circles on the diagrams denote the brightness temperatures measured in the blue and in the red regions of the spectrum. The solid lines show the calculated expected values of the equilibrium temperatures in accordance with[1,2]. The dashed lines are drawn through the experimental points. For a more complete picture, the table and the diagrams give, using the same notation, the data of[2] pertaining to the liquid phase (two points at the minimal pressures for NaCl and three points for KCl).

As seen from the figures, there is a very strong difference between the calculated and experimentally measured brightness temperatures for all the investigated crystals, with the exception of LiF. Thus, for NaCl and KCl at $P \approx 2$ Mbar, the brightness temperature T_b is close to 2×10^{4}°K, whereas its calculated equilibrium value T is approximately 3×10^{4}°K.

The $T_b(P)$ plot of CsBr is even more peculiar. The brightness temperature reaches a maximum of 11×10^3 °K at $P \approx 1$ Mbar. With increasing shock-wave intensity, T_b decreases to $(4-6) \times 10^3$ °K in the interval $P = 3-5$ Mbar. Such a dependence of the brightness of the front recalls qualitatively the effect of the limiting brightness of the shock-wave front in gases[8,4]. This effect is due to the existence in front of the shock wave of a layer of matter heated by the front radiation and strongly absorbing the radiation. It is easy to show that in condensed substances this effect should not play any role. Indeed, an estimate of the heat rise of the substance ΔT obtained from the condition of equality of the radiation-energy flux to the energy flux of the matter ahead of the front

$$\rho_0 DC\Delta T = n^2\sigma T^4$$

(here D—shock-wave velocity, C—specific heat, n—refractive index, σ—Stefan-Boltzmann constant) yields a value not exceeding several dozen degrees. It is clear that such heating cannot lead to the observed effect. Another possible cause of the small brightness of the front may be the fact that at high intensities the shock-wave front in ionic crystals becomes a good reflector and consequently its emissivity changes strongly. Favoring this assumption is also the fact that the strongest effect takes place in CsBr, a substance having the smallest energy gap between the valence band and the conduction band. The minimum specific heat causes the heating of CsBr in the shock wave to be the strongest among all the investigated substances, and the minimum gap w causes the highest concentration of the free electrons in the conduction band.

The foregoing considerations agree qualitatively with the observed effect also in the case of the other ionic crystals, for which a decrease of the metallic reflection is to be expected with increasing energy gap and specific heat. To check on this assumption, measurements were undertaken of the reflectivity of the front of the shock wave at maximum pressures for all crystals. The measurement method is similar to that described in[9], the only difference being that, at the suggestion of Ya. B. Zel'dovich, the illumination source was the glow of the shock-wave front itself, reflected in part by means of a mirror back in the direction of the front.

The minimum front reflection coefficient that could be registered in this manner was ~7%. However, we were able to observe the reflection of the light only for the most intense shock wave in NaCl ($P \approx 3.8$ Mbar), when observed in red light. The reflection coefficient turned out in this case to be close to 10%. In all the remaining cases, it turned out to be lower than the

Experimental results

Substance	ρ_0, g/cm^3	w, eV	$6R/M$, J/g-deg	ρ/ρ_0	P, Mbar	T_{br} °K	
						λ = 4400 Å	λ = 6500 Å
LiF	2,65	11,5	1,923	1,94	2,50	7200	5700
				2,0	2,90	7000	6200
				2,19	4,75	17000	14000
NaCl	2,165	7,7	0,8535	1,81	0,705	3850	3500
				1,85	0,79	5000	4600
				1,92	1,0	7500	7200
				2,08	1,5	11200	10200
				2,61	2,56	19800	20400
				2,86	3,83	21000	21400
KCl	1,994	7,5	0,6693	1,80	0,480	4250	3900
				1,83	0,508	4650	4250
				1,86	0,560	5600	5300
				1,97	0,715	7400	6900
				2,23	1,10	11600	11000
				2,70	2,11	22700	19600
				3,11	3,40	24400	19900
KBr	2,75	6,6	0,4194	1,84	0,415	4230	4200
				1,89	0,483	5860	5560
				1,95	0,575	6800	6200
				1,97	0,640	8260	7100
				2,10	0,849	9200	7750
				2,28	1,10	13100	10300
				2,93	2,61	17400	11900
				3,28	3,80	22200	10300
CsBr	4,45	6,0	0,2355	1,79	0,575	5200	4950
				1,81	0,607	5900	5600
				1,90	0,724	7300	6840
				1,92	0,800	8230	7420
				2,06	1,12	11100	10800
				2,23	1,60	—	9900
				2,30	1,70	13000	8200
				2,68	2,86	8600	4300
				3,28	5,06	7500	4000

sensitivity of the measurement method. It is clear therefore that actually the front does not have a high reflectivity, whereas to explain the observed effect it is necessary to have very high reflection coefficients R. Thus, for NaCl and KCl at pressures 2–3 Mbar it is necessary that R be of the order of 50–60%, and in CsBr at $P \approx 5$ Mbar it is necessary to have $R \geq 99\%$. Even at a pressure of 1.12 Mbar ($\rho/\rho_0 = 2.06$), the reflection coefficient in CsBr should be $R \approx 60\%$, whereas the measured value[10] turned out to be $R = 4$–5%. Thus, the high reflectivity capable of explaining the low brightness of the front was not observed experimentally.

At the same time, the performed experiments have shown that in transparent solid substances there exists some mechanism that limits the brightness of the front with increasing shock-wave intensity, or even decreases the brightness as in the case of CsBr. This effect could be satisfactorily explained only recently. A detailed analysis of the mechanism whereby the brightness temperature lags in shock waves of high intensity is presented in the second part of the present paper[11]. It turns out that layer with nonequilibrium electron temperature exists behind the density discontinuity and its emission determines the brightness temperature of the shock-wave front. The emission from the deeper layers, where the electron temperature is in equilibrium with the lattice, is completely screened by this layer.

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