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The emission spectrum of the ballistic gel impacted by the projectile

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Received March 28, 2022
Revised May 6, 2022
Accepted May 6, 2022

Results of studying the glow that occurs when a bullet passes through a ballistic gel are presented. This phenomenon is all the more interesting as the glow occurs in various areas of the gel, including those that have not contacted directly with the bullet. The emission spectrum of the gel consists mainly of a continuous component with atomic lines superimposed on it. The continuous component can be explained in different ways: one of the options is thermal radiation; however, the description of the observed phenomenon as luminescence is also not improbable.

Keywords: ballistic gel, bullet, emission.

DOI: 10.21883/TPL.2022.07.54028.19204

Glowing of mechanically impacted liquids is a rather old problem that has not been solved yet. The best known type of glow is sonoluminescence [1,2] that is the liquid glow under an ultrasonic impact. This phenomenon discovered in 1934 was observed in many easily realizable experiments; however, a rigorous theoretical proof for this process is still not available. By at least outward appearance, sonoluminescence is resembled by hydroluminescence [3] that is a liquid glow occurring under a high pressure in a narrow channel. Generally, such a glow can arise under various conditions (for instance, authors of [4] investigated the glow taking place during a collapse of a bubble created by a laser−induced spark).

One of the most exotic cases of the glow appearance in condensed matter is a flash in the ballistic gel after bullet passage through it. This phenomenon is observed quite frequently; however, to our knowledge, it has not been yet studied scientifically. Investigation of cavitation caused by the bullet−target interaction is a quite well−developed research area (see, e.g., [5–7]); however, we are interested in only one of specific aspects of such a cavitation, namely, glow generation.

In our experiments, ballistic gel produced by „TechnoChemProduct" (Saint-Petersburg) was used as a target. Density of the ballistic gel that is a thermoelastoplast species equals 852 kg/m^3; its exact chemical composition is a commercial confidentiality. The gel samples were $150 \times 150 \times 400$ mm in size; the shot was made in a standard manner, i.e. along the longest sample side.

The shot was made from a rifle using cartridge BPZ FMJ 8.0 g 7.62×39, the bullet speed at the muzzle outlet was 749 ± 7 m/s. The bullet was coated with copper. At the moment of shooting, the rifle muzzle end was at the distance of 3 m from the gel.

Spectroscopic measurements were performed using spectrometer AvaSpec-2048 that is a sensitive diffraction spectrometer 2.4 nm in resolution; its operating spectral range is 200 to 1100 nm, however, the range edges are rather noisy. The process was visualized by using a high−speed camera Phantom VEO-E 310L with the frame frequency of 1000 fps. Below are described the results of an experiment in which video recording was performed concurrently with the spectrum measurement (the spectrum was being collected during the entire experiment).

The bullet flight within the gel sample is accompanied by its strong deformation. First, an irregularly shaped cavity arises within the gel along the bullet flight path; second, deformation occurs even in gel areas not contacting the bullet directly. The last fact is not surprising: the flying bullet generates within the gel expansion−compression waves that, among other things, reflect from the gel surfaces.

The gel sample deformation gives rise to bright flashes inside it; the flashes are observed for a relatively long time. Notice that the glow does not occur while the bullet remains inside the gel, it appears later during the sample deformation. Fig. 1, *a* demonstrates the gel glow in 16 ms after the shot when the bullet has already left the sample under study. It is worth noticing that the glow arises also in the gel zones that have not contacted the bullet directly (Fig. 1, *b*, in 59 ms after the shot).

To interpret the emission spectrum, it is important to know the gel absorption coefficient μ that helps describing the emission attenuation by factor $\exp(-\mu x)$, where x is the distance the emission has passed within the gel. Since the emission may reach the spectrometer after, e.g., a series of internal reflections, x may exceed the sample thickness. We have measured the absorption coefficient μ during the gel illumination with a continuous−spectrum emission source. The results are presented in Fig. 2.

The gel emission spectrum is shown in Fig. 3, *a*, *b*. One can see that the most pronounced spectrum „dip" coincides with the spectral range of the most intense gel absorption

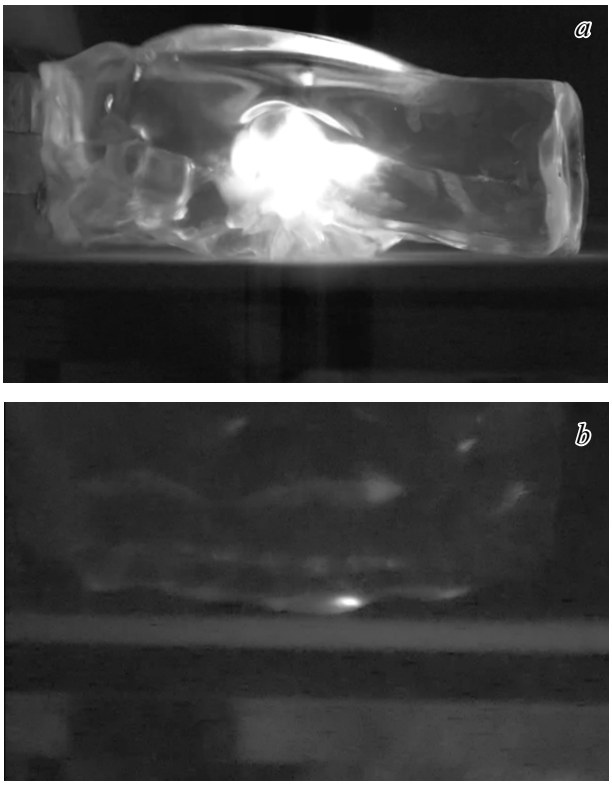

Figure 1. The glow of the gel impacted by a bullet: in 16 (a) an 59 ms (b) after the shot. In panel b, the image brightness and contrast are modified.

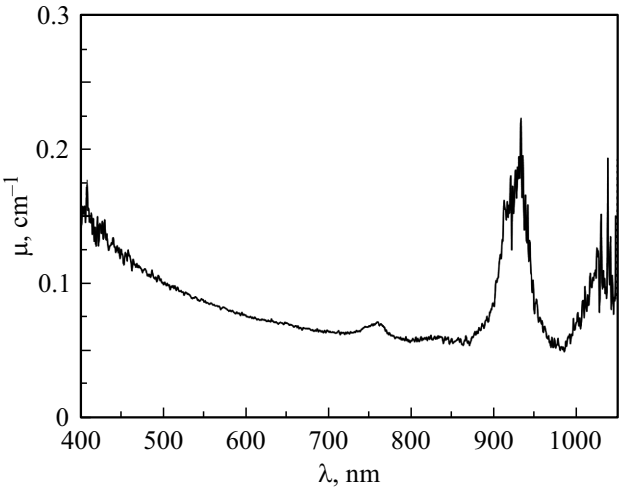

Figure 2. Spectral absorption coefficient of the gel under study.

(wavelengths of 900–950 nm). The spectrum consists almost fully of a continuous component on which rare atomic lines are superimposed. Apparently, the emission is defined by the dynamics of the cavitation pockets arising and collapsing in the gel (as in case of the sono— or hydro-luminescence); however, interpretation of the continuous spectrum may be different in different specific cases.

First of all it is necessary to check the observed spectrum adequacy to the black body radiation function taking into account that at the moment of the flash the cavity collapse temperature increases (assumably) from the initial room temperature $T_{\min}$ to a certain maximal value $T_{\max}$ and then decreases back to $T_{\min}$ (and does not merely equal $T_{\max}$). Assuming that the heating and cooling rate is uniform, it is possible to replace the time integral with the temperature integral and to consider the spectral function as

$$I(\lambda) = \frac{2A\exp(-\mu x)}{T_{\max} - T_{\min}} \int_{T_{\min}}^{T_{\max}} \frac{c_1}{\lambda^5} \frac{dT}{\exp(c_2/\lambda T) - 1}, \qquad (1)$$

where the integrand is the Planckś function;

$$c_1 = 2\pi hc^2 = 3.74 \cdot 10^{-16}\,\mathrm{W \cdot m^2},$$

$$c_2 = hc/k = 1.44 \cdot 10^{-2}\,\mathrm{m \cdot K}$$

are the Planckś coefficients. Notice that the room–temperature contribution to the emission is, certainly, negligible; however, formula (1) as a whole gives a spectrum strongly different from the Planckś curve with $T = T_{\max}$.

Fig. 3, a presents the results of comparing the experimental spectrum with curve (1) for $T_{\min} = 300\,\mathrm{K}$, $T_{\max} = 4500\,\mathrm{K}$, $x = 30\,\mathrm{cm}$; parameter A was selected, along with others, so as to ensure the best agreement with the experiment; the integral in (1) was calculated numerically. As expected, to describe the most significant spectrum „dip“ in the infrared range, it is necessary to set a dimension exceeding the gel sample sizes since the emission was detected after internal reflections. The presented temperature values are of the estimation character; since the experimental spectrum is highly noisy, it seemed unreasonable to calculate the quantitative characteristics of the mutual adequacy of the spectra, e. g. the correlation coefficient. The $T_{\max}$ determination error is doubtlessly about several hundreds of kelvins.

However, the „thermal hypothesis“, according to which the cavity flashing is caused by its strong heating at the stage of collapse, is not the only one. In work [8], the continuous spectrum observed during the sono— and hydro-luminescence in glycerin resembled, more likely, flashing of the excited luminescence center: a single peak corresponding to a certain transition energy and significantly broadened due to the uncertainty of this energy in a condensed matter. In the first approximation, the peak may be regarded as an energy–dependent Gaussian [8], which allows obtaining an expression for the spectral emission intensity distribution by wavelengths:

$$I(\lambda) = A\frac{1}{\lambda^3}\exp\left[-\left(\frac{\delta}{\lambda} - \frac{\delta}{\lambda_0}\right)^2\right]\exp(-\mu x). \qquad (2)$$

This expression describes the luminescence center flashing with the mean wavelength λ_0; the line smearing is characterized by parameter δ, amplitude A is, as before,

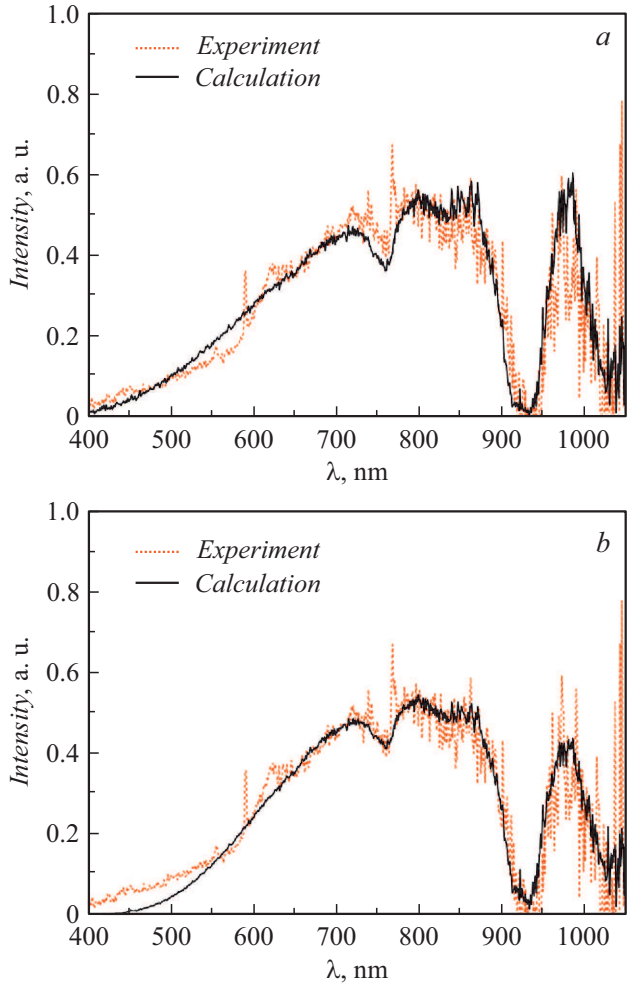

Figure 3. The ballistic gel emission spectrum in comparison with the black body radiation curve (1) (*a*) and luminescence center flashing curve (2) (*b*).

selected so as to ensure the best agreement with the measured emission intensity. Fig. 3, *b* illustrates the experimental spectrum comparison with expression (2) at $\lambda_0 = 1070$ nm, $\delta = 1700$ nm, $x = 20$ cm.

In discussing the „luminescent" hypothesis, it is necessary to consider the question concerning the possibility of the gelś own luminescence. For instance, hydrodynamic luminescence of machine oil I-40A was shown in [9] to be greatly caused by ordinary luminescence of this oil: a similar emission spectrum was observed in the case of photoexcitation. We have failed to attain photoluminescence of the studied gel; this means that in this case it is possible to consider only the hypothesis proposed in [8] which suggests formation of certain specific luminescence centers on an oscillating interphase surface.

As Figs. 3, *a*, *b* show, both theories can equally satisfactorily explain the observed continuous spectrum of the gel glow. Finally, to our mind, the question of the physical nature of the ballistic gel emission remains so far open. Possibly, some other hypothesis will appear to be true.

Conflict of interests

The authors declare that they have no conflict of interests.

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