Letters to the Editor

REDUCTION OF THE PENETRATING CAPACITY OF INTENSE LIGHT DUE TO SCATTERING ON REFRACTING HALOS OF OPTICAL DISTURBANCES OF THE MEDIUM NEAR INHOMOGENEITIES

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THE scattering of very intense light in a medium with inhomogeneities may differ considerably from the scattering of low-intensity light. Thus, for example, it has been recently established [1] that the scattering of a laser beam in a liquid is strongly increased by the generation of bubbles at small inhomogeneities present in the liquid and heated by the light beam. The increase of scattering due to changes in the medium near inhomogeneities is characteristic not only of boiling liquids but also of any gaseous, liquid, or solid medium.

In fact if the inhomogeneities have a high absorption coefficient then in any medium they will give rise to local heating around them and to a disturbance of the optical properties of the medium, both because of local thermal expansion of the medium and because of volume waves starting from the pulse heating center. The formation of such a refracting halo may be also related to the diffusion or gas-kinetic propagation of the vaporized substance away from inhomogeneities.

Even a small change of the refractive index N of the medium (for example on thermal heating of air $\Delta N \approx 10^{-3}$ near inhomogeneities), producing bending of the rays passing through the halo by an angle $\Delta\theta \approx \Delta N$, is sufficient to make the rays nonparallel, particularly when the light beam must be highly parallel for distant reception. (Virtual or real foci are located at a distance $f \approx r/\Delta N$, where r is the dimension of the halo and ΔN is the difference in the refractive index, and therefore $|f|$ will not be very large because of the small r, even when $|\Delta N| \ll 1$.)

If the formation of a halo is connected with the diffusion of heat or matter from the inhomogeneities which produce the quasistatic thermal expansion or change of composition, then the halo dimension varies according to the well-known diffusion law $r \sqrt{Dt}$. If the halo is related to the fast volume expansion of the medium and volume waves from pulse heating at an inhomogeneity, which is characteristic of high light intensities, then the halo dimension is $r \sim c_S t$, where c_S is the velocity of the volume waves in the surrounding medium, i.e. the halo may expand at a high velocity. Let us first consider this case.

The scattering cross section $\sigma \approx \pi \{a_0 + c_S (t - t')\}^2$ depends very strongly on the duration of growth of the halo, which started at the moment t' of the passage of an intense light-wave front exceeding the threshold of formation of a fast halo. For the intensity of the transmitted light, taken from this moment, we obtain the attenuation equation

$$\frac{\partial}{\partial x} I(x, \tau) = -I(x, \tau) n\pi \{a_0 + c_s\tau\}^2,$$

where $\tau = t - t'$, and n(x) is the number of inhomogeneities in a unit volume of the medium. Consequently

$$I(L, \tau) = I_0(\tau) \exp\left\{-\int_0^L n(x)\, \pi [a_0 + c_s\tau]^2\, dx\right\} \approx I_0(\tau) \exp\{-n_{av}\, \pi L (a_0 + c_s\tau)^2\},$$

where L is the depth of the layer of the medium. The variable scattering depth is $l(\tau) = 1/\pi n(a_0 + c_S\tau)^2$. When scattering by the halos dominates (when $c_S\tau \gg a_0$), the time for transmission of the light beam is $\tau_m \approx 1/(\pi n_{av} L)^{1/2} c_S$. This time may be very small. For example, if $n \approx 10^2$ cm^{-3}, $L \approx 10^4$ cm we find that $\tau_m \approx 10^{-7}$ sec.

Consequently for a medium with inhomogeneities the penetrating capacity of high-intensity light may be considerably smaller than the penetrating capacity of light of moderate intensity. In particular, cases are possible when layers of a medium with inhomogeneities which are transparent or semitransparent for normal light ($nL\pi a_0^2 \ll 1$) become completely opaque and turbid even a very short time after the passage of the front of a strong flash. For flash durations $t \lesssim \tau_m$ almost the whole energy passes through the layer, while for longer durations only a small part of it is transmitted.

An estimate of the threshold powers at which the fast halo is formed may be obtained from the condition of strong rapid heating of an inhomogeneity by a temperature $\Delta T_{th} \approx \alpha I_{th} \tau_m \xi / a\rho C$, where

α is the fraction of the energy transformed into heat, C is the specific heat, ρ is the density of the substance of the inhomogeneity, and ξ is the fraction of the time for the formation of a halo. For example if $\Delta T_{th} \approx 100°K$, $\alpha \approx 1$, $a \approx 10^{-3}$ cm, $\xi\tau_m \approx 10^{-7}$ and ρC is of the order of several joules per 1 cm^3, we find that $I_{th} \approx 1$ MW/cm^2.

Although at lower intensities of the light beam the rate of increase of the halo dimensions is much smaller, the halo may still have a considerable effect in the case of long flashes. Then the halo overlap time is $\tau_m \approx 1/\pi nDL$, where D is the diffusion coefficient of heat or matter from the inhomogeneity. For slow heating of the medium near the inhomogeneity the thermal expansion accompanies the diffusion of heat quasistatically without generating volume waves which could have transported the disturbances or the medium density at a much higher rate.

In the case of the diffusion halo the transmitted intensity is

$$I(L, \tau) = I_0(\tau)\exp\{-n_{av}L\pi(a_0^2 + D\tau)\},$$

i.e., the scattering depth is $l_m(\tau) \approx 1/n\pi(a_0^2 + D\tau)$ and the transmission time is $\tau_m \approx 1/nDL$. For example for $n \approx 10^2$ cm^{-3}, $L \approx 10^4$ cm, $D \approx 0.1$ cm^2/sec (the diffusion coefficient for heat in air is of this order), we find $\tau_m \approx 3\,\mu$sec.

The possible linking of halos does not remove the residual optical inhomogeneity of the medium because of the continuing spatially nonuniform evolution of heat at inhomogeneities and because of edge nonuniformities at halo overlaps.

For short flashes the elimination of the inhomogeneities by vaporization, burning out, or fracture does not remove the scattering centers since the disturbances of the refractive index of the medium (vapors or gases of the substance forming the inhomogeneity, local heating from the interaction events, etc.) still remain and a long time is needed for them to disperse.

These ideas stress the importance of allowing for trace substances and inhomogeneity halos in the problem of the scattering of intense light.

It would be useful to study this effect not only under natural conditions (clouds, fog, dust, smoke) but also under laboratory conditions: in emulsions, colloidal solutions and suspensions in liquids, in gases, as well as in solids with absorbing occlusions. Such systems could be used as cells with rapidly varying scattering properties to limit or modulate intense light beams.

Concluding, the author expresses his gratitude to Professor M. S. Rabinovich and to Corresponding Member of the Academy of Sciences A. M. Prokhorov for their interest in this work and valuable comments.

[1] Askar'yan, Prokhorov, Chanturiya, and Shipulo, JETP 44, 2180 (1963), Soviet Phys. JETP 17, 1463 (1963).

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NEUTRON DIFFRACTION INVESTIGATIONS OF SOLID OXYGEN

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WHEN the temperature is lowered below its melting point (54.39°K) liquid oxygen goes successively through three solid phases, (γ, β, and α) with respective transition temperatures 43.76 and 23.88°K. Measurements of the specific heat and of the susceptibility have disclosed anomalies at these temperatures, pointing to noticeable changes in the properties of solid oxygen in the region of low temperatures[1-3].

The difference in the phases of solid oxygen was investigated by x-ray diffraction numerous times. Patterns of diffraction by solid oxygen, measured at various temperatures, have been published[4-9]. An examination of the crystallographic and magnetic data on the modification of oxygen shows that the phenomena observed in this substance at low temperatures have a complicated and still unclear character, and to difficulties in the experimental investigations by the indicated methods.

In the present investigation, neutron-diffraction studies of solid oxygen were made with an aim at using the capabilities of neutron diffraction to ascertain the crystalline and magnetic properties of oxygen at low temperatures.

The research technique has already been described[10]. An exception is the procedure for working with condensed gases. Its main elements were a cryostat and a system for filling and storing the gas. The cryostat used was, as before[11], a Kapitza hydrogen Dewar[12]. In the new model of the cryostat, however, it is significant that the