Weak localization of electromagnetic waves in highly concentrated suspensions

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A weak localization of electromagnetic waves has been shown experimentally to occur in a randomly inhomogeneous medium. This effect manifests itself in a significant increase in intensity of the backscattering of light in a suspension of Al_2O_3 particles. A plot for the scattering parameters versus the particle density is constructed. The effect of polarization on the weak localization is determined.

The localization of various types of waves in randomly inhomogeneous media (suspensions, matrices with inclusions, etc.) has recently been thoroughly studied, both theoretically and experimentally.[1–9] By studying the localization of classical waves (electromagnetic, acoustic) it is possible to observe more directly the localization and the new characteristics accompanying it, which are different from the charactertics of the electron waves.[10] The appearance of a backscattering peak due to the interference of direct and inverse waves in a disordered medium is a characteristic effect associated with a weak localization.[11,12] This peak has been studied experimentally.[5,6,8,9] In these studies attention was focused on the multiple scattering of electromagnetic waves in an aqueous suspension of submicron latex particles, whose size a was commensurate with the laser wavelength λ. The angular dependence of the scattering intensity $I(\theta)$ revealed the presence of a sharp peak corresponding to the backscattering. The height and half-width of the peak increase with increasing concentration n of the scattering particles.The interference correction becomes appreciable when the condition $\lambda \sim a$ is satisfied, since the photon mean free path is $l \gg \lambda$ when $\lambda \gg a$ or when $\lambda \ll a$, regardless of the concentration of the scatterers.[1] The direct and inverse waves in this case lose their coherence. The effect of the particle size, the degree to which the particles lose their spherical shape, and the path length of the beam on the wave localization has also been recently studied experimentally.[8,9]

We have measured the backscattering in a suspension of Al_2O_3 microparticles in water and glycerin.We chose aluminum dioxide because its dielectric properties differ markedly from those of latex, resulting in the change of the localization parameters.[13] We have also considered a highly concentrated suspension (up to 40% by volume) and found a curve describing the behavior of $I(\theta)$ over a wide range of n.

The experimental setup is shown schematically in Fig. 1. In the experiment we used an He-Ne laser (1) with an outpout power of ~ 10 mW and wavelength $\lambda = 0.63$ μm. After passing through a polarizer (2 and modulator (3) the beam was expanded to 4 mm by a telescope (4) and at the same its divergence was reduced to 0.5 mrad. A 0.1-mm-thck glass parallel-face plate (6) was used to direct a part of the beam (~ 4 mW) on the sample which was inserted into a standard 3-mm-thick spectrometer cell (7) in the adjusting device at the center of the goniometer table. The diaphragms (8

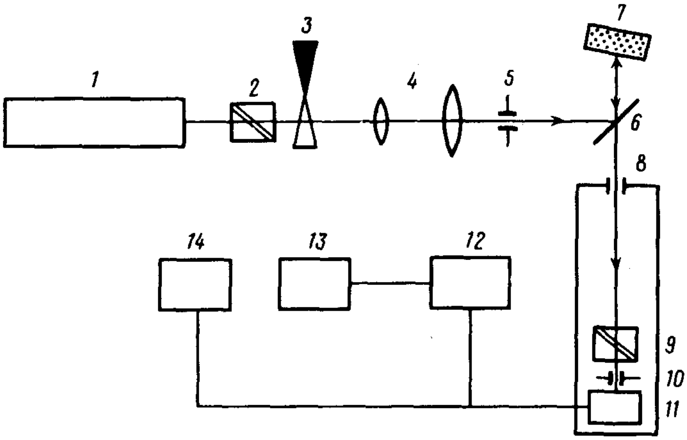

FIG. 1. Experimental setup.

and 10), analyzer (9), and photomultiplier (11) were mounted inside a lightproof casing on the rotating arm of the goniometer. The angular resolution was 1.5 mrad. The signal under study was recorded on the plotter (13) and oscilloscope (14) with the help of a synchronous detector (12). The backscattered signal was detected when both the polarizer and analyzer were placed in the vertical position (VV) and when just the analyzer was placed in the horizontal position (VH). The scattered light was scanned in the horizontal plane. A uniform distribution of particles in the volume was achieved by thoroughly mixing the suspension using an ultrasonic disperser.

Curves 1a and 2 in Fig. 2 show the angular dependence of the scattering intensity $I(\theta)$ (in arbitrary units) on the scattering angle $\theta(\theta=0$ corresponds to the exact backscattering) for concentrations of 10 and 40% by volume (for VV polarization) and curve 1b is the same plot for the VH polarization. Figure 3 shows plots of the ratio I/I_0 (I and I_0 are the scattering intensities at the maximum and at the wings, respec-

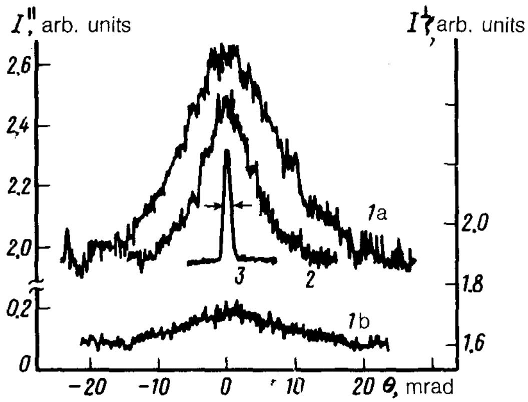

FIG. 2. Angular dependence of the backscattering.

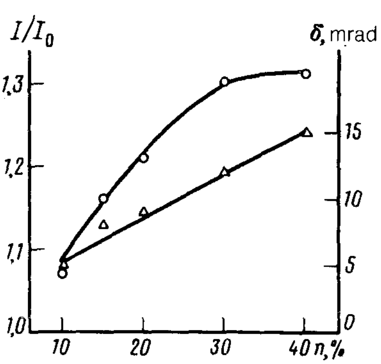

FIG. 3. Concentration dependence of the scattering parameters.

tively) and of the half-width δ of the maximum versus the concentration of the Al_2O_3 particles. Typically, the ratio I/I_0 increases and saturation occurs, beginning with certain values of the concentration $n (n = 30\%$ by volume). In the case of latex particles,[5] the saturation sets in at lower values of n. The value of δ depends linearly, as in Refs. 5 and 6, on n. This result is in agreement with the theory,[6] according to which $\delta \sim \lambda / l$. Since $l \sim I / n\sigma$ (σ is the cross section for scattering of a particle by an inhomogeneity), it follows that $\delta \sim n$. The fact that $(I/I_0)_{\text{sat}} = 1.3$ (rather than 2, as was predicted theoretically[7]) we attribute to the inelastic scattering, nonspherical nature of particles, and the presence of particles of different sizes in the suspension. Electron-diffraction measurements showed that there is a certain size distribution, where $a = 0.8\ \mu$m for the bulk of the particles. A comparison of curve 1a and 1b shows that there is no localization in the case of transverse polarization, suggesting that the localization of electromagnetic waves is of a vector nature (this effect is explained in Ref. 8).

Some estimates of the parameters are as follows. The value of l is found from the relation $\delta \sim \lambda / 2\pi l$. For $n = 40\%$ by volume, for example, we have $\delta \sim 15$ mrad, which gives $l \sim 10\lambda$. For the elastic scattering time $\tau \sim l/c$, (c is the velocity of light), which is the shortest time scale of the process, we then obtain $\tau \approx 0.2 \times 10^{-13}$ s. The phase-relaxation time τ_{ph}, which determines the interference effects, can be estimated from the relation[14] $\tau_{\text{ph}} \sim \lambda^2 / D\delta^2$, where D is the diffusion coefficient of the electromagnetic wave, which is defined as $D = cl/3$; here c is the speed of light. For $\delta \sim 10$ mrad we find $\tau_{\text{ph}} \sim 10^{-11}$ s. Let us compare τ_{ph} with the elastic scattering time, $\tau \sim l/c$. At $\lambda = 0.63\ \mu$m we have $\tau \approx 0.2 \times 10^{-13}$ s. Consequently, one of the necessary conditions for a weak localization, $\tau_{\text{ph}} \gg \tau$, is satisfied, as estimates have shown.

As is evident in Fig. 2, the $I(\theta)$ curve has a "ripple." These oscillations cannot be interpreted without a special study which we intend to carry out in the near future.

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