Scattering of cold neutrons by a rough boundary between two media

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The scattering of neutrons with $\lambda \approx 1$ nm by a slightly rough boundary between homogeneous media was studied experimentally for the first time. The neutron scattering is in good agreement with the scattering of soft x rays. The surface scattering rather than bulk scattering is found to be the basic mechanism.

One of the promising developments in neutron optics is the use of the total external reflection effect.[1] A total external reflection of a neutron wave occurs at the glancing angles

$$\theta \lesssim \theta_{\rm cr} = \lambda \left[\frac{Nb_{\rm coh}}{\pi} \pm \frac{m}{2\pi^2 \hbar^2} \mu B \right]^{1/2},$$

where λ, μ, and m are the wavelength, the magnetic moment, and the mass of the neutron, respectively; $\hbar$ is Planck's constant; B is the magnetic induction of the medium; and N and $b_{\rm coh}$ are the concentration and length of the coherent scattering of nuclei of the medium. For most of the nonmagnetic materials (or for $B = 0$) with $\lambda \sim 1$ nm we have $\theta_{\rm cr} \lesssim 1°$. The penetration depth of a neutron wave into a medium with total external reflection is relatively large. (According to Ref. 2, the penetration depth is $\gtrsim 20$ nm for weakly absorbing materials.) As a result, the incident radiation can be scattered not only by the rough surface but also by the density fluctuations and fluctuations of the nuclear composition of the medium at the penetration depths. The following question can thus be raised: What is the relationship between the contributions of the particular features of scattering? There are several studies[3–5] dealing with this topic. Under the assumption that the surface geometry plays the key role, Steyerl[3] found a theoretical relationship between the angular distribution of reflected neutrons $J(\theta)$ (the scattering indicatrix), the reflection coefficient R with the correlation function for the rough surface, the wavelength, and the glancing angle of incident neutrons. As will be shown below, the experimental results are inconsistent with the theory, rendering its results inapplicable. At the same time, Zelenyuk[4] and Zelenyuk and Stepanov[5] found that R depends experimentally on the degree of irregularity of the reflecting surface for surfaces with no worse than grade 14 purity (the mean-square height of the irregularities is $\sigma \gtrsim 5$ nm). It is difficult to establish such a correlation for slightly irregular surfaces ($\sigma \sim 0.1$–1 nm), because the effect is relatively weak and because an independent method must be used to determine the roughness of the surface under study.

One study is based on the fact that the interaction of neutron and x radiation with the medium fundamentally has physical common features. Specifically, the corresponding scattering occurs as a result of total external reflection of x rays. The shape of the theoretical $J(\theta)$ curve plotted as a function of the parameters of the surface and the characteristics of the incident radiation[6] is the same as that obtained in Ref. 3. The scattering of x rays has been thorougly studied experimentally. A good correlation has been established between the scattering characteristics and the independently measured roughness parameters in the case of amorphous homogeneous media (glass, for example).[6,7]

In the present experiments we studied the indicatrices of the neutron and x-ray scattering for samples with a slightly irregular surface, made from boron glass, K8 glass, and glass enamelled with a liquid tin melt and with a surface of multilayer interference structures on substrates made from these glasses. An important point here is that the radiation characteristics were approximately the same as the instrumental functions. The neutron wavelength was $\lambda = 1$ nm ($\Delta\lambda/\lambda = 50\%$) and the x-ray wavelength was $\lambda = 1.3$ nm (the characteristic CuLα line). The beam half-widths and the angular resolution in both cases were 6–9′. For neutrons the range of glancing angles was limited by the narrow critical angles (20–30′). For the multilayer interference structures the measurements were carried out at angles corresponding to the Bragg reflection. Since the Bragg angles are much larger than the critical angle for glass, we were able to study the external surface of the multilayer interference structure and the substrate surface. The absorption and scattering of neutrons in the substrate (the range was about 5 cm), which were also measured, turned out to be negligible.

Figure 1 shows the neutron and x-ray scattering indicatrices for boron glass. Figures 2 and 3 show the relative intensity of diffuse scattering, I_d/I_0 (I_d is the integral intensity of diffuse scattering, and I_0 is the total intensity of the reflected beam) versus the glancing angle θ.

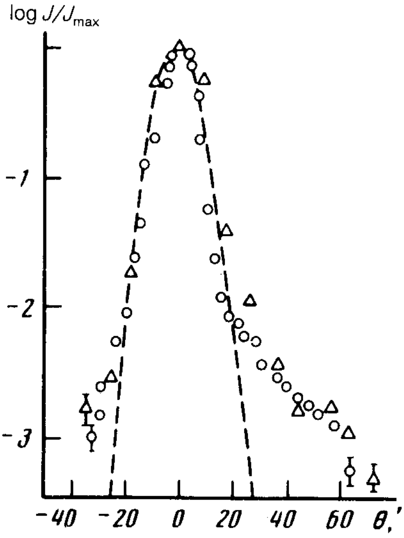

FIG. 1. Indicatrices for the scattering of neutrons (O) and x rays (△) by a boron glass sample at glancing angles of 30′ and 27′, respectively. Dashed curve—direct beam.

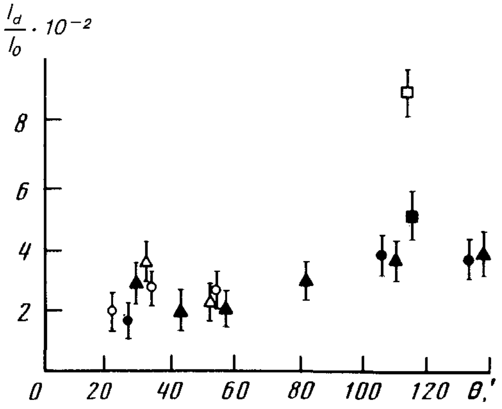

FIG. 2. I_d/I_0 versus θ for x-ray and neutron measurements. ▲,△—Boron glass (▲—x rays; △—neutrons); ●, ○—enameled glass (●—x rays; ○—neutrons); □,■—Be-Ti multilayer interference structures (MIS), as viewed from the MIS side and from the substrate side, respectively.

The scattering indicatrices and the relative intensity of diffuse scattering of neutrons and x radiation essentially coincide for glasses which absorb neutrons weakly and for glasses which absorb neutrons strongly (i.e., at various depths of penetration of neutrons into the medium). The scattering of neutrons by multilayer interference structures on the inside boundary is the same as the scattering of x radiation by the substrate surface. We thus conclude that the neutron and x-ray scattering is caused by the boundary surface irregularities, rather than by bulk inhomogeneities.

The experimental data, on the other hand, are inconsistent with the scattering theory.[3,8] Specifically, at small glancing angles θ the scattering is stronger than that predicted by the theoretical dependence $I_d/I_0 \sim A\theta$ (A is a factor which depends on the optical constants of the material and on the correlation characteristics of the surface). At large θ this dependence becomes the frequently used relation

$$I_d/I_0 = \left(\frac{4\pi\sigma\sin\theta}{\lambda}\right)^2 .$$

On the basis of the scattering of x rays at $\theta > 120'$ the value of σ for our samples is

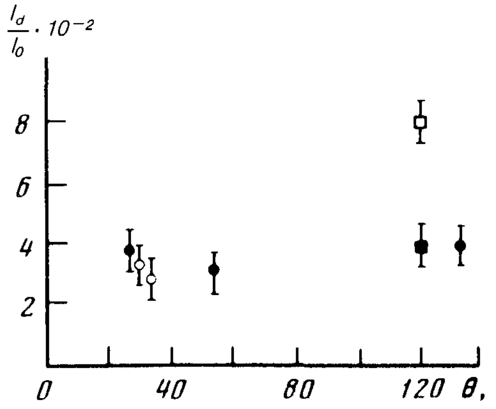

FIG. 3. I_d/I_0 versus θ for x-ray and neutron measurements. ●,○—K8 glass (●—x rays; ○—neutrons), □,■—^{58}Ni-^{62}Ni MIS, as viewed from the MIS side and from the substrate side, respectively.

estimated to be $\sigma \cong 0.5$–0.6 nm for glasses and 0.7–0.8 nm for multilayer interference structures. Obviously, neutron scattering is equally sensitive to rough surfaces, but it also has the additional advantage of revealing the roughness of a hidden boundary. In the case of multilayer interference structures, a comparison of the intensities of scattering from the external and internal surfaces can tell us the extent to which the surface roughness increases as a result of sputtering the structure.

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