PROCEEDINGS OF THE YEREVAN STATE UNIVERSITY

Physical and Mathematical Sciences 2014, № 3, p. 49–55

Physics

IMAGE CONTRAST FORMED BY SCATTERED X-RAYS

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It is experimentally established that, in the majority of cases, the X-ray radiation scattered on different constituent parts of a weakly absorbing object provides sufficient information on inner structure, different types of structural inhomogeneities and morphological characteristics, such as shapes, sizes and location of invisible defects of the object. In this study a new method, based on recording of the scattered X-ray radiation, for investigation of the inner structure of noncrystalline materials is developed. It is demonstrated that the image contrast, formed by the X-ray radiation scattered on weakly absorbing objects, can be considerably higher than the absorption contrast.

***Keywords*:** X-ray radiation, scattering contrast, invisible defects.

Introduction. Studies of internal structure of non-crystalline bodies, in particular, biological objects, carried out by X-ray methods, are based, as a rule, on the fact that the X-ray radiation passing through different parts of the studied object suffers different attenuations corresponding to internal inhomogeneities and defects of the object. Attenuation of radiation transmitted through matter occurs in two ways: absorption and scattering. Considering absorption and scattering as independent processes, the linear coefficient of attenuation μ can be represented as a sum of linear coefficient of absorption τ and linear coefficient of scattering $\sigma : \mu = \tau + \sigma$.

Contrast of an image, where the externally invisible regions of different absorptions are seen clearly, is called absorption contrast. If attenuation of X-ray radiation in regions with internal inhomogeneities (defects) differs weakly from attenuation in the matrix, the absorption contrast in these defects is weak or cannot be formed. In these cases we should use either phase-contrast method or study of secondary radiation, i.e. Compton, Rayleigh or fluorescence scatterings. The essence of the phase-contrast method is a local deviation of phase of the wave at propagation through inhomogeneities in studied sample. Via interference, local deviations of wave phase transform into local changes in the wave intensity and the image is a topographic map of regions corresponding to different deviations of wave phase [1–3].

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Radiation scattered by an object also carries information, which may in many cases be sufficient for studies of inner structure of non-crystalline objects, revealing inhomogeneities of different kinds, determination of shapes, sizes, and other peculiarities of different inclusions and defects (see, e.g., [4]). Contrast of image formed by scattered radiation, will be termed below the scattering contrast.

For obtaining an object image formed by X-ray radiation scattered by this object and providing unambiguous correspondence between the object and image, X-ray analog of fiber–optical cable was used in [5, 6], the so-called "Kumakhov optics".

For formation of object image by scattered X-ray radiation, the method of modulated X-ray radiation of harmonic analysis was employed in [7, 8]. For producing a modulated X-ray image, different periodic structures were used, placed in front and behind the studied object on the path of radiation.

In the present work, a new scheme is developed for formation of topographic map of regions of a weakly absorbing object with different abilities to scatter X-ray radiation. As an optical unit ensuring unambiguous correspondence between the object and its image, we used a *Camera Obscura* and obtained the first images produced by radiation scattered by a weakly absorbing object. We revealed some peculiarities of the contrast of scattering of X-ray radiation.

Contrast of Scattering. Let consider some peculiarities of formation of scattering contrast, without pretending to be very rigorous. We represent the studied sample as a plate of the thickness t. Intensity of scattered (in all directions) radiation, $\Delta I_0(z)$ for a thin layer Δz in the depth z from the sample surface, is proportional to the intensity of radiation reaching the depth $\left(I(z)=I_0e^{-\mu z}\right)$ and to the layer thickness Δz with the coefficient of scattering σ of the layer material:

$$\Delta I_0(z)=I(z)\sigma\Delta z=I_0e^{-\mu z}\sigma\Delta z,$$

where I_0 is the intensity of incident radiation.

Intensity of scattered radiation decreases second time when passing through the remaining layer of the sample. Beam of scattered radiation deflected by a small angle from the primary beam, passes, before emerging from the sample, the remaining thickness $t-z$ of the sample, therefore, finally the intensity of scattered radiation deflected from primary beam by a small angle within a small solid angle $\Delta\omega$, equals

$$\Delta I(z)=\Delta I_0(z)e^{-\mu(t-z)}\frac{\Delta\omega}{4\pi}=I_0\sigma e^{-\mu t}\frac{\Delta\omega}{4\pi}\Delta z.$$

Thus, the intensity of radiation scattered by a layer of the thickness Δz and deflected by a small angle from the primary beam, does not depend on the depth, where this layer is located. For the integral intensity of radiation scattered by a plate with thickness t, we obtain $\left(\text{omitting factor } \dfrac{\Delta\omega}{4\pi}\right)$

$$I(t)=I_0\sigma te^{-(\sigma+\tau)t}. \qquad (1)$$

By introducing dimensionless parameters $U=\sigma t$ and $V=\tau t$, we can write formula (1) in the form $I=I_0Ue^{-(U+V)}$. If the studied sample has regions of inhomogeneities (inclusions) with parameters U and V differing from those of the matrix, these regions will be displayed in the image formed by scattered radiation as regions of inhomogeneities on the homogeneous background of the matrix.

The quantity $C=(I_2-I_1)/(I_2+I_1)$ or $C=\Delta I/I$, with I_1 the intensity scattered by matrix and I_2 the intensity scattered by inclusion, is called the contrast of image. Taking into account that

$$\Delta I=\frac{\partial I}{\partial U}\Delta U+\frac{\partial I}{\partial V}\Delta V,$$

we obtain

$$C=\frac{\Delta I}{I}=\frac{1-U}{U}\Delta U-\Delta V=C_1+C_2. \tag{2}$$

The first term C_1 depends on parameter U and gives the contrast caused by scattered radiation. At $U<1$, the coefficient of contrast $\frac{\partial I}{\partial U}>0$ (positive contrast). The second term C_2 is the contrast caused by absorption and the coefficient of contrast $\frac{\partial I}{\partial V}<0$ (negative contrast). At $U=1$, the contrast of scattering is not formed, in spite that scattering of radiation by the sample is maximal (Fig. 1). At $U>1$, the scattering contrast is also negative, i.e., in the contrast formed by scattered radiation, the absorption contrast will be dominant. Thus, necessary condition of formation of scattering contrast is the condition $U=\sigma t<1$. However, this condition is necessary, but not sufficient.

Sufficient condition is

$$\frac{1-U}{U}\Delta U-\Delta V>0, \tag{3}$$

i.e. the positive contrast of scattering should dominate over the negative contrast of absorption. Since $\Delta U\le U$, the inequality $(1-U)\frac{\Delta U}{U}<1$ is always valid at $U<1$. Condition (3) is fulfilled better at $U<<1$ and small values of ΔV.

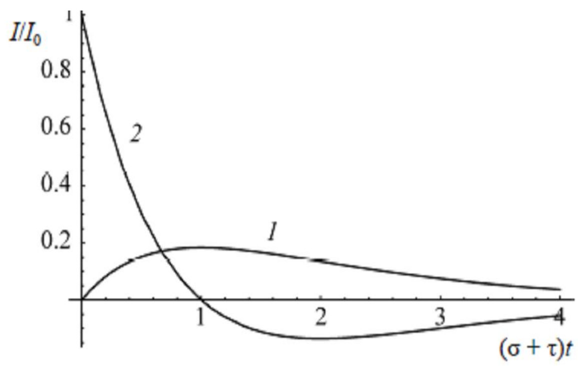

Fig. 1. Dependence of relative integral intensity I/I_0 (1) and relative coefficient of contrast $\partial(I/I_0)/\partial(\sigma t)$ on the dimensionless parameter $(\sigma+\tau)t$.

For simplicity it is taken $\sigma=\tau=\mu/2$.

In the case, where variations in parameters $U=\sigma t$ and $V=\tau t$ of two compared regions is caused by only the difference in their thicknesses, we have $(1-\sigma t)\Delta t/t>\tau\,\Delta t$ or $\mu t<1$. In this case $(\sigma_1=\sigma_2,\ \tau_1=\tau_2)$ scattering contrast is formed for only those thicknesses, where $\mu t<1$.

When the thicknesses of two compared regions are equal the positive contrast will be formed due to difference $\Delta\sigma=\sigma_2-\sigma_1$ while the negative contrast will be formed via the difference $\Delta\tau=\tau_2-\tau_1$. Which of these contrasts will be dominant, depends on the quantities $\frac{1-U}{U}\Delta U$ and ΔV.

In the case, where $\Delta\tau=\tau_2-\tau_1$ is smaller, then contrast of absorption is, it is formed weakly (or is not formed), the contrast of scattering can become essential, since, at $U<<1$ the factor $\frac{1-U}{U}$ can be considerable. In this case contrast of scattering may become predominant, in spite that $\sigma<\tau$ usually. Thus, due to this peculiarity of scattering contrast, it becomes possible to reveal and study internal inhomogeneities, defects of different kinds or other deviations of weakly absorbing amorphous bodies, such as biological objects or living organisms.

Scheme of Experiment and Results. In order to obtain topographic mapping of the studied object with use of scattered X-ray radiation we employed the simplest analogy of a photographic camera, i.e. a *Camera Obscura*, where a diaphragm plays the role of objective. In our case, it is a funnel-shaped orifice of diameter $10-50\mu m$ in a 1 *mm*-thick tantalum plate. Fig. 2 shows diagram of the experiment. ‘A’ is anode of the X-ray tube, ‘O’ is the window in lead limiting the primary radiation, ‘C’ is the *Camera Obscura*, ‘SM’ is the studied object, ‘D’ is diaphragm and ‘P’ is the photographic plate or other coordinate-sensitive detector. Dashed line shows scattered radiation. Primary radiation passing through window ‘O’ enters the studied object ‘SM’ and partially scattered in all directions, *Camera obscura* is placed so that only scattered radiation is passing through diaphragm and on the photographic plate, an image formed by scattered radiation is obtained. Diaphragm ‘D’ works in this case as a thin lens and every point of the object (SM) corresponds to a point of the image (S’M’). Magnification of camera is $K=L/l$ with ‘*L*’ and ‘*l*’ the distances of photoplate from diaphragm and from object respectively.

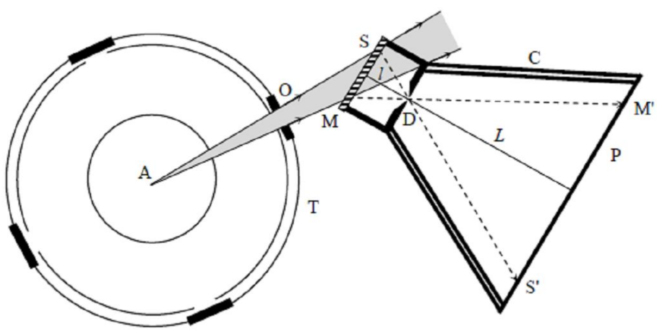

Fig. 2. Diagram of the experiment.

Fig. 3 demonstrates images of a cherry seed formed by (3, a) transmitted X-ray radiation (image–invert, negative contrast) and by (3, b) scattered X-ray radiation (image–invert, positive contrast). Image in Fig. 3,a gives the main features of the inner structure of the seed. Outline of solid coat, kernel inside it and the gap between the coat and kernel, are seen clearly. In addition, from this image the shape, size, and position of the kernel can be obtained.

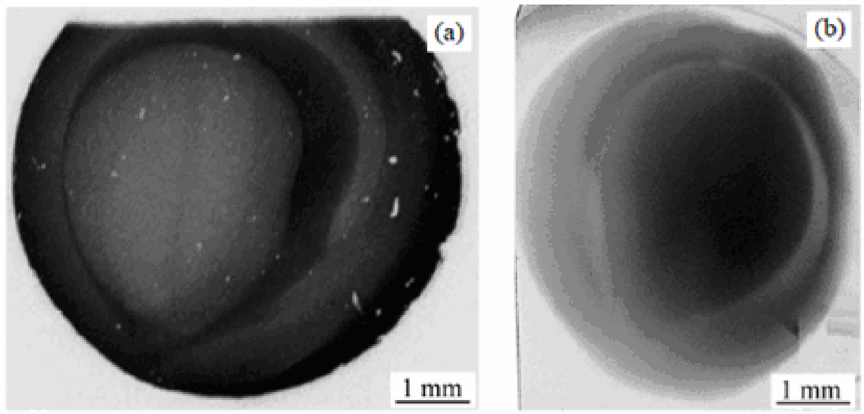

Fig. 3. Images of a cherry seed formed by: a) transmitted; b) scattered radiation.

Image in Fig. 3,b is seen to contain the same information on the inner structure of the seed, but it is less clear. This is explained by the fact that the X-ray radiation passing through the studied object, suffers unavoidably local attenuations on inhomogeneities of the object independent of when scattering occurs, before or after attenuation. Thus, radiation scattered by the object, "remembers" the topographic map of regions producing local changes in intensity. In other words, scattered radiation is modulated by the image formed by transmitted radiation. Therefore, for any technique of recording the scattered radiation, the contrast of image is determined as the sum of two contrasts, and contrasts of absorption and scattering are opposite. Since the contrast of image in Fig. 3,b is positive, i.e., $(1-U)\frac{\Delta U}{U}-\Delta V>0$, the scattered radiation dominates during formation of image. As it was indicated, when $(1-U)\frac{\Delta U}{U}-\Delta V\le 0$, the contrast of scattering cannot be formed. Fig. 4 demonstrates the image of a piece of a pigeon feather formed by (4, a) transmitted radiation (invert, negative contrast) and by (4, b) scattered radiation (invert, positive contrast). It is apparent that images in Figs. 4,a and 4,b are mainly identical. We clearly see in both pictures the rachis of the feather, barbules, as well as the thin string along the rachis axis. We can also see some peculiarities of rachis walls (e.g., their double-layered structure).

We observe in Fig. 4,b also relatively weak (compared with background) black lines parallel to the rachis axis. Absence of these lines in Fig. 4,a indicates that the increment of the parameter $\mu t=(\sigma+\tau)t$ in this non-uniformity is insufficient for formation of the absorption contrast. It could be thought that in this case the increment of the parameter $U = \sigma t$ also is small. However, at small increments $\Delta\mu$ the scattering contrast can become very essential, since the factor $\frac{(1-U)}{U}$ can be considerable at $U << 1$.

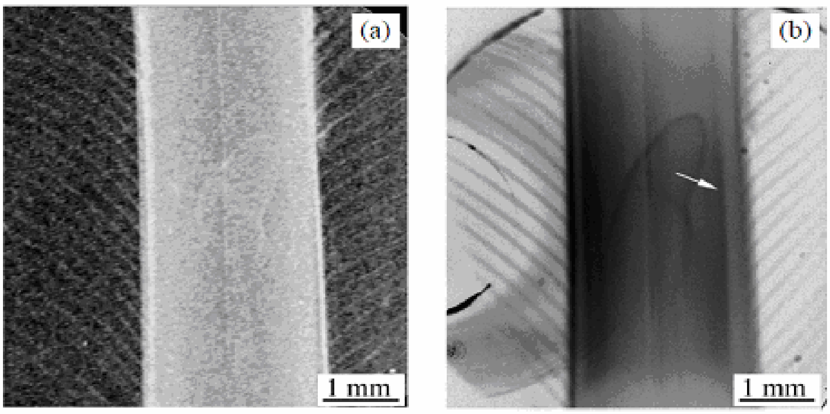

Fig. 4. Images of a fragment of a pigeon feather formed by:
a) transmitted; b) scattered radiation.

Fig. 5,a shows the image of a wooden layer ~1 *mm*-thick, formed by scattered X-rays. Two holes 0.8 *mm* in diameter were made in the layer to align the images obtained in two ways. The object under study was irradiated by a Bremsstrahlung beam (Mo anode, voltage 36 *kV*). The maximum intensity of continuous radiation corresponds to ~25 *keV*. The horizontal black stripes (negative pattern) are the images of the generatrices of cylinders, whose cross sections are annual growth rings. Bright circles are the images of the holes.

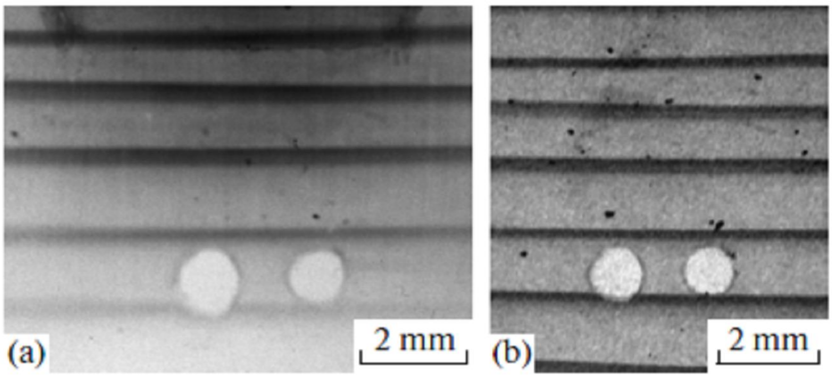

Fig. 5. Image of a wooden layer formed by (a) scattered X-rays and (b) passing X-rays.

Fig. 5,b shows an image of the same object formed by passing X-rays (positive pattern). The total identity of these patterns and clear images of the holes give a ground to say that the image formed by scattered X-rays is a topographic map of sample regions with different scattering properties. This image makes it possible to reveal portions with different scattering properties in objects and determine the shapes, sizes, and locations of various defects.

Fig. 6 shows the results of studying a polyethylene tube ~3 *mm* in diameter, formed by scattered X-rays. It can be seen that the reconstructed distribution of layer thicknesses along the diameter coincides with the true distribution. This coincidence indicates that the image formed by scattered X-rays contains sufficient information to reconstruct the shapes, sizes, and some other specific features of object inhomogeneities.

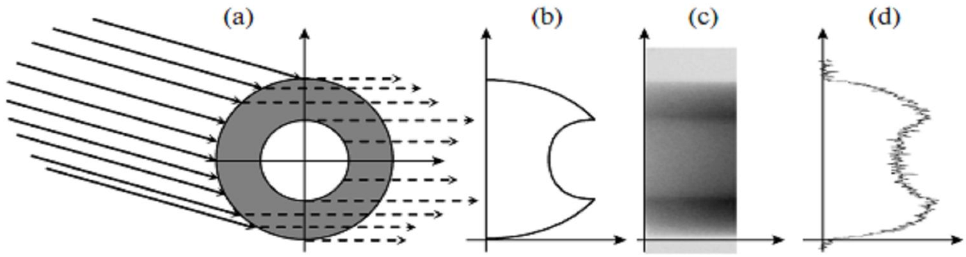

Fig. 6. Results of studying a polyethylene tube: a) tube cross section; b) distribution of layer thicknesses along the tube diameter; c) tube image formed by scattered X-rays; d) reconstructed (based on image blackening) distribution of layer thicknesses along the tube diameter.

The first obtained images are evidence that new scheme can work. Scattered X-ray radiation contains sufficient information on the internal structure of the object. *Camera obscura* enables formation of the positive-contrast image of object by scattered X-ray radiation. Obviously, the quality of first images is low because optimum conditions of obtaining a high-quality image are not yet revealed.

Received 30.09.2014

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