Refraction-contrast radiography

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A new method is proposed for obtaining an image in neutron radiography. The method is based on separating the unrefracted radiation and the radiation that does refract on inhomogeneities inside the object. The requisite angular resolution is ensured by successive reflection of neutrons from two perfect crystals, between which the object is placed. Our experiments have revealed a high contrast even in images of weakly absorbing objects. Neutron images of a nonuniform magnetic field have been obtained.

In radiography, information about the internal structure of an object is obtained on the basis of radiation (x-ray, γ-ray, neutron) transmission patterns. The contrast of this pattern is determined by the attenuation of the radiation in different parts of the object. Besides being attenuated, the radiation should also be refracted at interfaces, and the characteristic angular deflections are of the order of seconds of arc for thermal neutrons and x rays. 1,2 The radiographs should exhibit additional contrast, therefore, if the angular resolution is of the order of seconds, which is sufficient to separate the refracted and unrefracted radiation.

The necessary resolution is ensured by placing the object between two perfect crystals, which are parallel to each other, i.e., by using the method of the two-crystal spectrometer. 3 Our aim is to demonstrate, on the example of neutron radiography, that the contrast can be enhanced through refraction of the order of a second with the aid of a two-crystal spectrometer.

PRINCIPLE OF THE METHOD

The high angular resolution is due to the fact that successive refraction by two ideal crystals occurs only in an angular interval of a few seconds near the parallel position, even when the angle of beam collimation is of the order of a degree. 3 If the direction of the beam changes as a result of interaction with an object placed between the crystals, the beam will be reflected by the second crystal (analyzer) after a rotation from the parallel position through an angle equal to the angular deflection of the beam in the object. The two-crystal spectrometer thus ensures an effective angular resolution of the order of a second without requiring strict collimation of the primary beam. The two-crystal spectrometer is used for neutron-optical experiments in which small angular deflections are determined, e.g., observation of refraction at interfaces. 1,2 When the analyzer crystal is parallel to the monochromator crystal, only neutrons which are not refracted in the object are recorded by the detector at the Bragg angle beyond the analyzer (Fig. 1a). If the analyzer crystal is moved from this position through an angle exceeding the refraction angles, it is virtually nonreflective to neutrons, and a detector set up beyond the analyzer at zero scattering angle registers the total intensity of the refracted and unrefracted beams (Fig. 1b).

From the above it follows that two experiments, carried out with the arrangement of Fig. 1a, b, allows the transmission patterns with and without refraction contrast to be compared directly. The geometric resolution does not change in this case. Such a comparison is made in this paper.

EXPERIMENTAL PROCEDURE

The measurements were made at wavelengths of 1.5–2.5 Å on a STOIK spectrometer, 4 set up on the IR-8 reactor of the I. V. Kurchatov Institute of Atomic Energy. With germanium (111) crystals as the monochromator and analyzer, the angular resolution was ~1" (Fig. 1c). The angular collimation was 0.5°, and the beam size was ~2×2 cm.

We carried out experiments of two types: with scanning of the object by a beam of adjustable width (formed by a slit in sheet cadmium) and with direct visualization of the transmission pattern. In the scanning experiments the transmission intensity was measured by the detector of the STOIK spectrometer, and visualization was accomplished with an n–β converter (gadolinium foil) and x-ray film in a "reflection" geometry.

EXPERIMENTAL RESULTS AND DISCUSSION

As the model object we chose an aluminum container with two copper rods inside it, an analog of the "Cormack phantom" (Fig. 2a). Under conditions of purely absorption contrast ("attenuation") the transmission patterns were characterized by the presence of a background, which increased as the slit was narrowed (because the fraction of the fast neutrons not absorbed in the cadmium increased) and reached ~70% of the total intensity in the absence of the object. At the same time, the background in these patterns was substantially lower under conditions of refraction–absorption contrast ("attenuation + refraction").

The contrast was characterized by the quantity

\[ k(x) = \frac{I_s - I_b}{I_b} \]

where \( x \) is the transverse displacement of the object relative to the slit, \( I_s \) is the neutron-beam intensity recorded when the beam passed next to the sample at the beginning and end of the scanning, \( I(x) \) is the transmission intensity at displacement \( x \), and \( I_b \) is the background intensity (recorded by the detector through sheet cadmium without a slit).

The values of the contrast so determined are given in Fig. 2a–d. With resolution contrast the minima corresponding to traversal of the maximum path in the container walls are ~10%, while
the minima corresponding to the maximum path in the copper rods along their axes are ±30% and ±10%, in accord with the published data on attenuation in copper. The same contrast is also observed for axial transmission under "attenuation + refraction" conditions, since the neutrons cross all surfaces along the normal, i.e., without refraction. The maximum contrast in these patterns is observed at the edges of the cylinders, where the glancing angles decrease, and total reflection should occur in the limit of small angles. For a finite geometrical resolution the contrast remains less than 100% even when the refraction is recorded.

The increase in contrast can be characterized by the ratio of its maximum levels (at the edges under "attenuation + refraction" conditions, and at the center of the cylinders under "attenuation" conditions); accordingly this increase reaches an order of magnitude. Calculation of the contrast under "attenuation + refraction" on the basis of geometrical optics with allowance for the resolution of a slit in the form of a "stage" and the instrument function (Fig. 1c) gave the curves represented by the dashed lines in Fig. 2a, c.

Comparison of photographs of the model object obtained under "attenuation" conditions (Fig. 3b) and "attenuation + refraction" conditions (Fig. 3a) also indicates a considerable increase in contrast in the second case. Indeed, the thin rod and the aluminum container are difficult to distinguish in Fig. 3b but are seen clearly in Fig. 3a, which was taken with recording of the refraction. The increase in the contrast with distance from the axis of the thick cylinder makes for a certain similarity to a three-dimensional image. We note that the enhancement of the contrast during image visualization is less pronounced than in the experiments because of deterioration of the geometrical resolution (in the scanning experiments it is determined by the slit-object distance, which is ±1 cm, and in the case of recording on film, by the film-object distance, which is ±6 cm).

As is seen from the results of experiments with a model object, the contrast of composite samples is enhanced when the refraction at the interfaces is recorded. A photograph of the internal structure of a ballpoint pen can also be an example. While the ink inside the rod (attenuation in it is high, as in any hydrogenous material) and the metallic body are visible under "attenuation" conditions (Fig. 4b), all the details of the internal structure of the writing unit, spring, and thin-walled ink reservoir are clearly distinguishable under "attenuation + refraction" conditions (Fig. 4a). One notices a brightening at the periphery of the ink column. This is attributed to the transition from primarily an absorption contrast at the center of the cylinder to primarily refraction contrast at its edges. This contrast minimum is clearly visible in the scanning pictures of the copper cylinders (Fig. 2a, c). Refraction contrast, therefore, can manifest itself to a considerable degree even for materials characterized by strong attenuation.

In the pictured neutron radiograms of composite objects recording of the refraction provides an increase in the contrast, where a role is played by the difference in the refractive indices as well as by the difference in attenuation in different parts of the object. This use of refraction contrast
FIG. 2. Results of scanning of a model object through a slit of width 0.2 mm (a, b) and 1 mm (c, d) \( \lambda = 2.26 \text{ Å} \) under conditions of "refraction + attenuation" (a, c) and "attenuation" (b, d). The dashed lines represent a calculation for copper cylinders and the dash-dot lines represent the background \( I_b \) and the intensity \( I_0 \) in the absence of a sample in the beam: a) \( 2r = 0.2 \text{ mm} \); k; %: 1) 10, 2) 30, 3) 50, 4) 65, 5) 80, 6) 90; b) k, %: 1) 35, 2) 15, 3) 10; c) \( 2r = 1 \text{ mm} \); k, %: 1) 25, 2) 40, 3) 65; d) k, %: 1) 30, 2) 10, 3) 5; e) schematic section of model object and dimensions of aluminum container and copper rods: 1) \( R_1 = 9 \text{ mm} \), \( d = 0.5 \text{ mm} \); 2) \( R_2 = 0.5 \text{ mm} \); 3) \( R_1 = 2.15 \text{ mm} \).

FIG. 3. Radiograms of a model object under "refraction + attenuation" conditions (a) and "attenuation" conditions (b). Exposure 5 h; size of aluminum container reduced in comparison with Fig. 2e.

FIG. 4. Radiograms of ballpoint pen under "refraction + attenuation" conditions (a) and "attenuation" conditions (b).
is advisable not only in neutron radiography but also in radiography with x rays, synchrotron radiation, or y rays.

Neutron radiography has the distinctive ability to reveal purely refraction contrast in the total absence of resolution contrast. This is because neutrons undergo magnetic refraction when traversing nonuniform magnetic fields. A similar effect is associated with the passage of neutrons through the domain walls in a ferromagnet, where the direction of the magnetic induction vector changes. As a result of this, new areas of application open up for neutron radiography with refraction contrast: observation of magnetic-field gradients (e.g., in magnetic systems for plasma physics research, when other methods are difficult to use) and the internal domain structure of ferromagnets.

These possibilities are confirmed by the following two experiments. In the first, a neutron beam passed through a gap between two permanent magnets (Fig. 5a), whose field increases from zero at the edge to 6 kOe in the region of the gap of width ±2 mm (Fig. 5b). In this region, the intensity of the neutron beam passing without refraction in reduced (Fig. 5c), since the deviation along path of 4 cm in a gradient of ~10° Oe/cm is ~1.5° according to Ref. 7; according to Fig. 1c, this decreases the refraction from the analyzer crystal by 20-30%. At the same time, no contrast exists, naturally, under "attenuation" conditions (Fig. 5d). The second experiment was carried out with a single-crystal plate of ferrosilicon with orientation (110) and thickness 1.5 mm. With this orientation the walls of the main domains should run along the [001] easy magnetic axis and at the plate ends, which are perpendicular to this direction the magnetic flux should be closed in wedge-shaped domains. Indeed, in the neutron transmission radiograms with refraction contrast we can see vertical domain walls which in the bulk of the crystal lie along the [001] direction, and at the ends we can see the domains of closure (Fig. 6). The average distance between domain walls is in good agreement with the value 1.4 mm obtained on the basis of measurements of the orientational dependence of neutron refraction effects at inner domain walls in the same crystal.

CONCLUSION

The proposed principle of increasing the contrast in neutron radiograms is useful for solving a wide range of problems: observation of the internal structure of opaque materials, products, and devices, diagnostics of magnetic systems, study of the internal domain structure of ferromagnets, and so forth. The refraction-contrast principle can be used in all areas of introscopy using neutron or electromagnetic radiation: radiography, topography, and tomography. We can assume that the luminosity loss due to reflection from the crystal will be compensated by the enhanced quality of the images.

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