Image detection in a neutron microscope

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An experiment is reported in which all the necessary components of a neutron microscope are present simultaneously. These components are a specimen which is bombarded by neutrons, an optics system which creates an image of the specimen, and a measurement system which visualizes the neutron image. The neutron image detected experimentally has a contrast in terms of the material of which the specimen consists.

The idea of a mirror neutron microscope was first discussed in the early 1970s.[1] Several optics experiments have since then been carried out to test various arrangements of mirror optics systems for performing a three-dimensional focusing of ultracold or very cold neutrons.[2–5] In all cases the specimen has been a slit or a sharp edge, whose image has been analyzed by means of a scanning by an additional slit. Although the optics systems in those experiments did form an optical image, the final result of the experiment was a calculated curve, rather than a graphic "image" of the specimen.

In the present letter we describe an experiment in which all the necessary components of a neutron-microscope study have been brought together for the first time: a specimen, which is penetrated by neutrons, a mirror optics system, and a detector to visualize the neutron image.

In contrast with all other types of microscopy, the wave which probes the specimen in a neutron microscope interacts with nuclei. It could thus be expected that in this case a specific neutron contrast in terms of the type of nuclei should be manifested. The contrast should be at its greatest when very slow neutrons, in particular, ultracold neutrons, are used.

Because of the low energy of ultracold neutrons, their paths are curved significantly by the earth's gravitational force. In the optics of ultracold neutrons, there are thus some specific gravitational aberrations. One distinguishes between geometric aberrations, which are present even in the case of monochromatic radiation,[6] and a gravitational chromatism. The latter is subdivided into chromatism of position and chromatism of magnification. Optics systems which were rendered achromatic in one way or another were used in Refs. 2–4. The instrument which we are describing here was also made achromatic in first order with respect to both types of chromatic distortions, but the approach was different from that in Ref. 4.

In Refs. 2–5 the one-dimensional analysis of the image was accompanied by a relatively low intensity of the sources of ultracold neutrons. It was necessary to work with a relatively low detection rate, in some cases a few counts per hour.

Intense sources of ultracold neutrons have recently been started up at Leningrad[7] and Grenoble.[8] In addition, new detectors suitable for detecting a two-dimensional

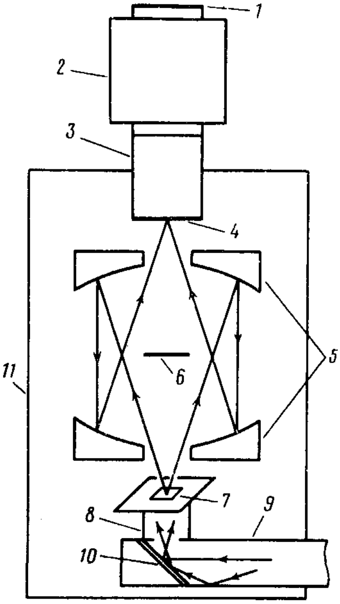

FIG. 1. The apparatus. 1—Photographic film; 2—image converter; 3—optical fiber; 4—scintillator sensitive to ultracold neutrons; 5—mirrors of optics system; 6—shielding from direct "rays"; 7—specimen; 8,9—neutron ducts; 10—auxiliary mirror.

image have been developed. It thus becomes possible to more on to a qualitatively new stage in work on the particular optics of ultracold neutrons.

The experiment which we describe below was carried out with the new source of ultracold neutrons at the Leningrad Institute of Nuclear Physics. The apparatus is shown schematically in Fig. 1. It is a modification of the apparatus which we used in Ref. 3. The optical part of the apparatus consists of two concave mirrors with radii of curvature of about 20 and 30 cm. The specimen is at the focus of the first mirror. The distance between the mirrors satisfies a simple condition which provides achromatization in first order in terms of both magnification and position:

$$R_1 + R_2 = 6d. \quad (1)$$

Here R_1 and R_2 are the radii of the mirrors, and d is the distance between them. In this geometry, the positions of the neutron and optical images should coincide.

The alloy Ni^{58}–Mo, with a boundary velocity of about 8 m/s for neutrons, is vacuum-deposited on the spherical glass mirrors.

The two-mirror optics system, with an entrance numerical aperture $A = 0.25$ and an optical magnification $m \simeq 1.4x$, results in the formation of an image in the plane of the sensitive layer of the image detector.

The detector is a scintillation ultracold-neutron detector with an image converter. The light is recorded on photographic film. Aside from this photographic recording, the apparatus is similar to the resonant-neutron detector described in Ref. 9. We use a ZnS scintillator with a thickness of 10–15 μm, on which an aluminum coating 0.2–0.3 μm is deposited; on top of the aluminum, there is a coating of the compound LiF with

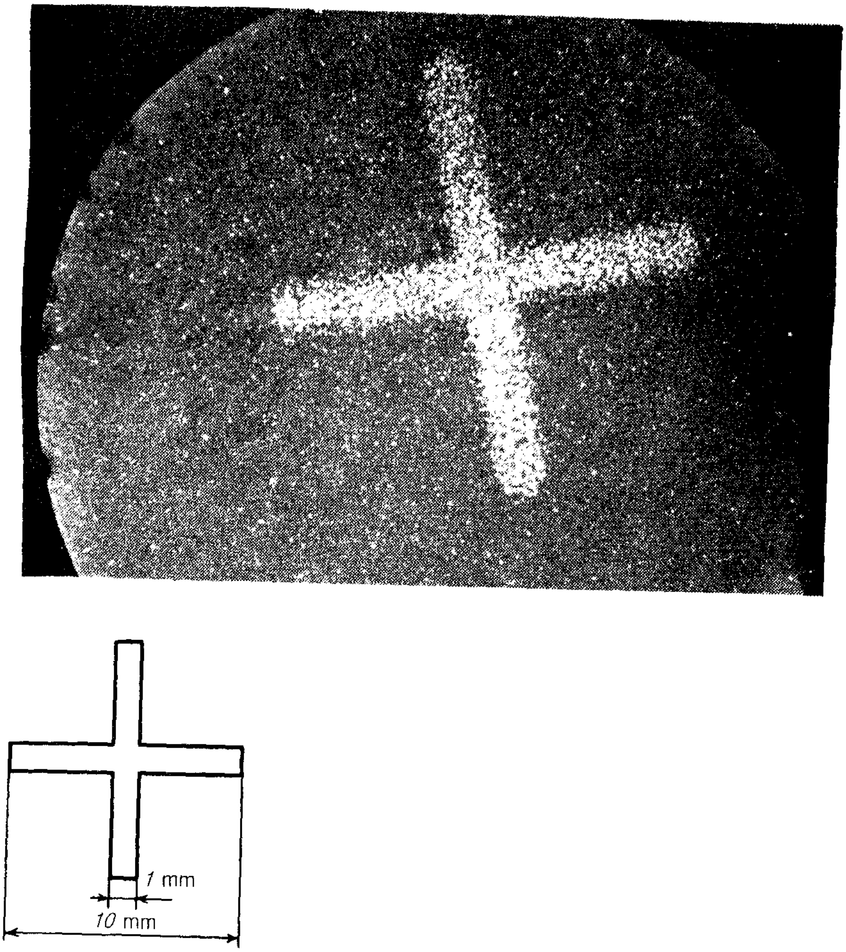

FIG. 2. Image of a cross-shaped diaphragm. The dimensions are shown in the inset.

a thickness of 100 μgf/cm^2 (Ref. 10), containing equal fractions of the isotopes Li^6 and Li^7. The Li^7 is used in order to lower the boundary velocity of the sensitive layer. The light from the scintillations which occur during the capture of ultracold neutrons by Li^6 in the reaction Li^6 $(n,\alpha)T$ is extracted from the vacuum chamber by an optical fiber, intensified by an image converter made form a microchannel plate with fiber optics at the entrance and exit windows, and then recorded on film.

The apparatus is connected to the output neutron duct of the liquid-hydrogen source of ultracold neutrons; the flux density at the output is 6×10^3 n/(cm$^2\cdot$s). After entering the apparatus, the neutrons move through internal neutron ducts to the specimen. We use a transmission geometry.

In the first case, the specimen was a cross-shaped diaphragm. Figure 2 shows the image of this specimen, recorded on the film in a half-hour exposure.

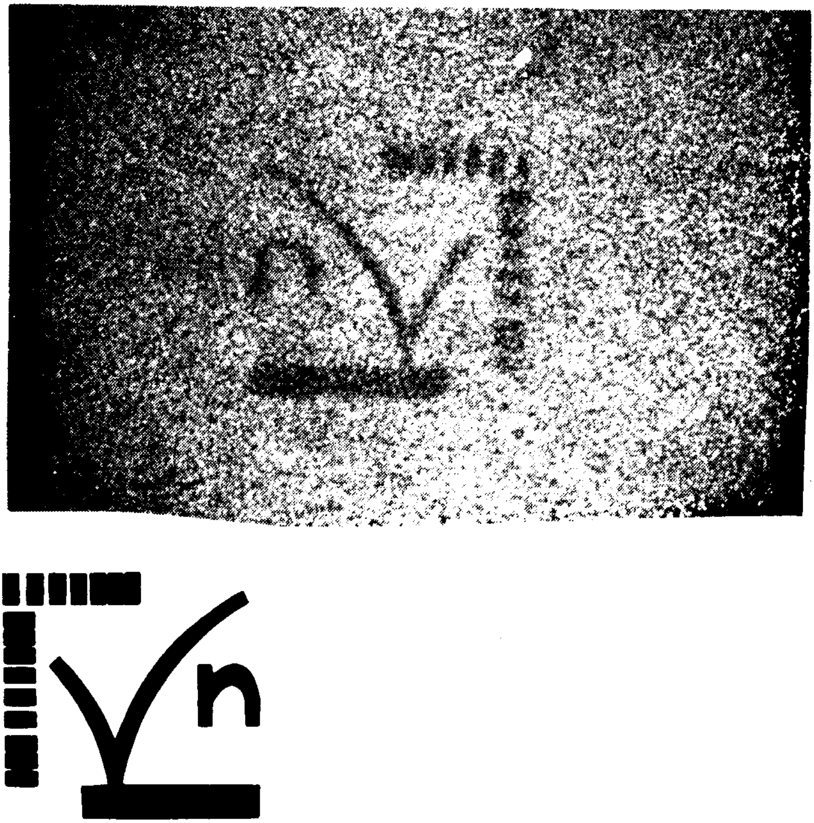

FIG. 3. Phototemplate from which the test specimen was fabricated; image of the specimen recorded in neutron "light." The dark regions correspond to the nickel coating.

In the second case, the specimen was a silicon wafer 0.35 mm thick on which a nickel figure was formed by photolithography. The thickness of the nickel layer was about 200 nm. Figure 3 shows the original from which this specimen was fabricated, along with its neutron image, obtained in an exposure of 2.5 h. To give an idea of the experimental resolution, we note that the thickness of the line in this figure, which illustrates the path of a neutron reflected from a mirror, is 200 μm. We did not make an effort to optimize the adjustment of the apparatus in terms of resolution in these experiments. The detector was placed within 0.5 mm of its nominal position; this circumstance could easily explain a possible defocusing of 150–200 μm.

In summary, an image of a specimen with a two-dimensional structure formed by a neutron-optics system has been recorded for the first time. In addition, the existence of a neutron nuclear contrast in the optics of ultracold neutrons has been demonstrated.

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