Experiments with a neutron microscope

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Exploratory experiments with a mirror neutron microscope are reported. The neutron image of two slits, 40 and 13.5 μm wide, and an image of a periodic test object with a period $\approx 65\ \mu$m have been recorded. The resolution of the instrument at an optical magnification $M = 47^\times$ is estimated to be 17 μm.

Most of the research on neutron microscopy is being carried out with mirror optics based on the remarkable ability of ultracold neutrons to undergo total reflection at all angles of incidence. This approach was proposed by Frank in 1972.[1]

In the present letter we are reporting experiments with a mirror neutron microscope constructed by a team at the Kurchatov Institute of Atomic Energy in collaboration with the Leningrad Institute of Fine Mechanics and Optics.[2]

The recording of a two-dimensional neutron image with a low-magnification optics system was reported in Ref. 3. At present, the best resolution of a neutron microscope is[4] 10 μm. The present state of the field of neutron microscopy is reviewed in Ref. 5.

A distinctive feature of our own microscope is the use of an optics system with a horizontal "ray" path,[2] as proposed by M. M. Rusinov. Analysis has shown[6] that in horizontal layouts, in contrast with arrangements with a vertical optical axis, there can be only one type of gravitational chromatic aberration. This circumstance is of substantial assistance in compensating for gravitational chromatism, whose presence constitutes one of the primary difficulties in the instrumental optics of ultracold neutrons.

Figure 1 shows the optical layout of the microscope. The instrument is rendered achromatic through the use of a corner reflector. In the absence of this reflector, neutrons moving at different velocities would form images displaced along the vertical direction, with the result that the resolution would be significantly degraded. The actual design of the microscope is slightly more complicated than that shown in Fig. 1 (see Ref. 2). Some additional mirrors make it possible to use the instrument either in the mode of recording a neutron image or as an ordinary optical microscope.

The mirror has a Schwarzschild objective consisting of two concentric mirrors with radii of curvature of 14.17 and 5.41 mm. The numerical aperture of the objective is $A = 0.5$, and its magnification is $M = 47^\times$. The distance traveled by the neutrons from the object to the image plane, which is the position of the detector, is about 22 cm. The theoretical resolution of this microscope is about 5 μm when a wide velocity spectrum (4.5–7.5 m/s) of ultracold neutrons is used. All the optics elements are made of glass and coated with a 0.2-μm layer of the nonmagnetic alloy ^{58}Ni–Mo. This layer has a limiting velocity $v_{\text{lim}} = 7.8$ m/s (corresponding to a wavelength $\lambda \simeq 500$Å).

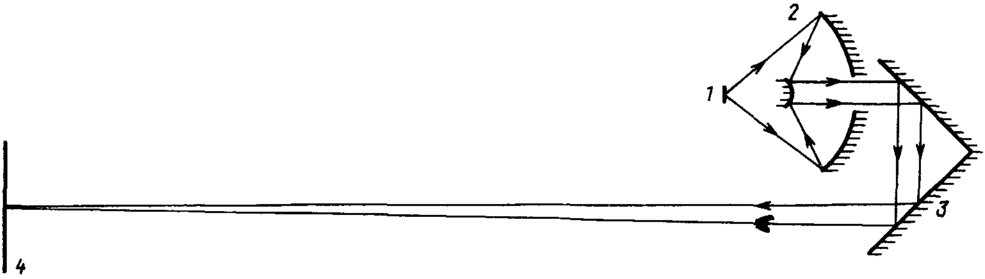

FIG. 1. Optical layout of the microscope. 1—Plane of object; 2—objective; 3—turning system; 4—plane of image.

The position-sensitive scintillation detector[7] has an intrinsic resolution of about 300 μm and thus imposes a limitation of 6–7 μm on the resolution of the microscope. The instrument was placed in a beam of ultracold neutrons from a liquid-hydrogen source at the VVR-M reactor of the Leningrad Institute of Nuclear Physics.[8] The first objects were two slits, with widths of 40 and 13.5 μm. These slits were oriented horizontally. In this case the gravitational chromatism, if it was not completely canceled, should have been manifested to the greatest extent.

An image was detected by an electronic measurement system and stored in mem-

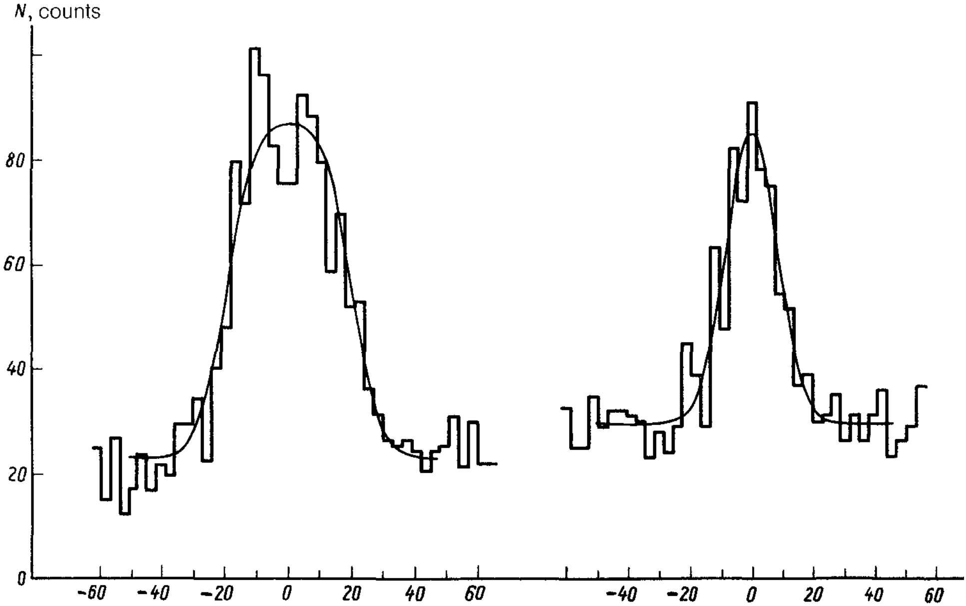

FIG. 2. Neutron count rate versus the coordinate in a cross section of the image of two slits, one 40 μm wide (at the left) and the other 13 μm wide. The smooth curve is a calculated distribution for a Gaussian resolution function with a width at half-maximum of 17 μm.

ory as a two-dimensional matrix. The histograms in Fig. 2 are cross sections of the images of the two slits, recorded by summing the corresponding matrix elements. The width of a channel is about 3 μm, when referred to the image plane. An absolute calibration of the detector and the measurement system was carried out in a separate experiment.

The full widths at half-maximum of the distributions are 40.8 and 20 μm, respectively. The dependence of the count rate on the coordinates in a joint analysis of the two images can be described well ($\chi^2 \approx 1$) under the assumption that the intrinsic resolution function of the instrument is a normal distribution with a width at half-maximum of 17 μm. This result may be regarded as an estimate of the resolution of the microscope and of the measurement system. It would seem to be a bit premature to draw any conclusions from the fact that the theoretical resolution does not agree with that observed.

The absolute count rate at the maximum of the image is lower than the expected value by a factor of several units. The reason for this discrepancy may be the presence of a fairly large nonspecular reflection component. Such a diffuse reflection might substantially reduce the contrast on the image of an object with a relatively large transparency area without having any serious effect on the quality of the slit image.

An experiment was undertaken to observe the image of a periodic test image (a resolution chart) having transparent and reflecting bands of equal width. This object

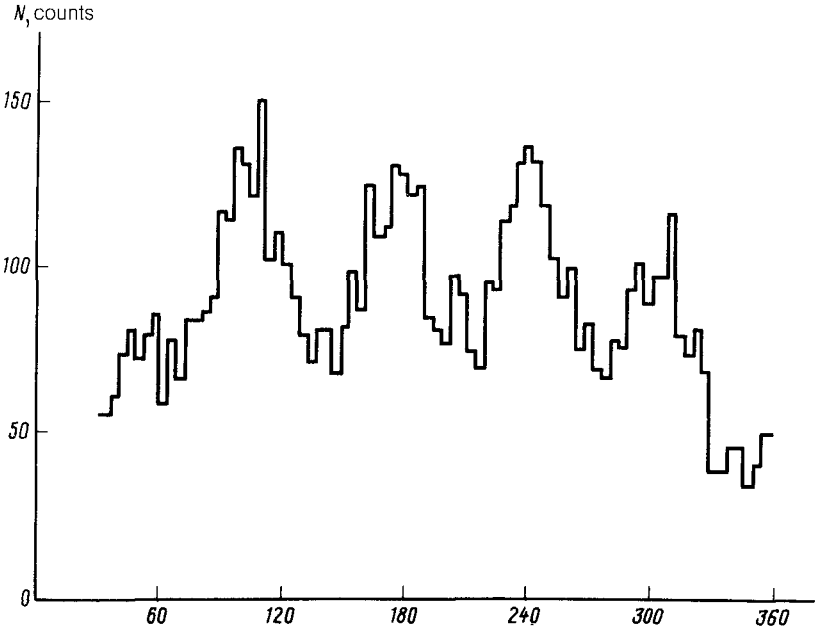

FIG. 3. Neutron count rate versus the coordinate in a cross section of the image of a resolution chart with a period of 66.7 μm.

was fabricated by photolithography of ^{58}Ni on thin (140-μm) glass (Fig. 3). The period of the resolution chart was 66.7 μm. Unfortunately, the intensity of the ultracold neutrons was lowered by a factor of about two in this experiment, so the effect-to-background ratio was degraded. Nevertheless, it was possible to observe a completely satisfactory image contrast.

In a horizontal layout, the magnification of a neutron image should be equal to the ordinary optical magnification. The experiment with the resolution chart provided direct confirmation of this conclusion.

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