Many-mirror optical system for obtaining a neutron image—a possible prototype of a neutron microscope

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A many-mirror optical system for spatial focusing of ultracold neutrons (UCN) is described. The system is used to obtain a neutron image of a slit. This system provides an approach to the solution of the problem of decreasing the gravitational chromatic aberrations.

In recent years, a number of papers have appeared on the problems of focusing ultracold neutrons (UCN) and of neutron microscopy.[1–7] This branch of neutron optics was founded by Frank,[1] who was the first to point out the possibility of obtaining a neutron image with the help of a concave mirror and posed the problem of developing a neutron microscope. The problems involved in using a neutron microscope are discussed in Refs. 5 and 7.

One of the considerable difficulties in focusing very slow neutrons is the large effect of the earth's gravitational field on the trajectory of a neutron, giving rise to velocity dependent optical distortions—gravitational chromatic aberrations. Such aberrations can be decreased by preliminary monochromatization of the neutrons. This, however, leads to a marked drop in the luminosity. The absence at the present time of sufficiently intense sources of UCN precludes such a possibility. In Ref. 2 it was proposed that a new optical element be used: a zone mirror. In such a zone mirror the gravitational chromatism is cancelled over a certain range of neutron wavelengths by its intrinsic chromatism. This optical element was successfully tested.[3] In Ref. 4 it was proposed that a nonuniform magnetic field with an appropriate magnitude of the

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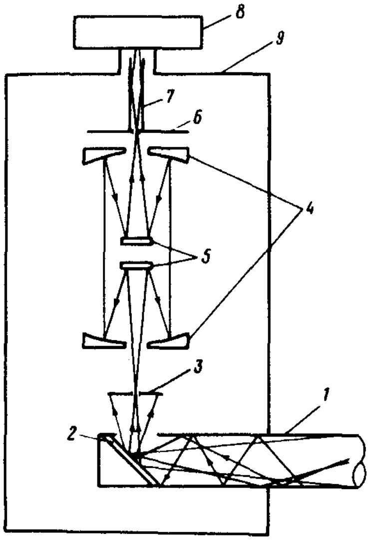

FIG. 1. Diagram of the optical system. 1) Neutron guide, 2) auxiliary mirror, 3) input slit, 4,5) mirror of the optical system, 6) analyzing slit, 7) additional neutron guide, 8) detector, 9) vacuum chamber.

vertical component of the gradient be used to cancel the gravitational force. Another approach has also been proposed for obtaining an achromatic neutron image, based on the use of a system consisting of several simple optical elements positioned at different heights.[5]

This paper is concerned with the description of such an optical system and the results of experimental tests.

A four-mirror optical system with a vertical optical axis consists of two bi-mirror pairs. Each pair consists of a spherical and a flat mirror (Fig. 1).

Let us clarify the principle of achromatization. The focal length of a concave mirror can easily be calculated in the paraxial approximation by focusing the neutrons

$$f_1 = \frac{R}{2} - \frac{gR^2}{8v^2}. \quad (1)$$

Here R is the radius of the mirror, v is the velocity of neutrons at the moment of reflection, and g is the acceleration of gravity. The mirror is positioned horizontally and the neutrons fall on it in the direction of the force of gravity. A flat mirror is then positioned above the concave mirror at a height $h < R/2$. The focal length of such a system in the approximation $2gh \ll v^2$ is

$$f_2 = 2h - \frac{R}{2} + \frac{gR}{v^2}\left(h - \frac{R}{8}\right). \quad (2)$$

The terms containing g in expressions (1) and (2) represent the displacement of the position of the focal point for neutrons relative to the focal point for light. It is evident that at $h < R/4$ this displacement for a bi-mirror system is less than for a single mirror. The focal length for a pair which was inverted relative to the force of gravity is

$$f_3 = 2h - \frac{R}{2} - \frac{gR}{v^2}\left(h - \frac{R}{8}\right). \quad (3)$$

A comparison of (2) and (3) shows that the terms containing g have different signs. This circumstance accounts for the achromatization of the system.

The geometry of the device providing the achromatization was chosen by the method proposed in Ref. 6. In this case, the vacuum was assigned an index of refraction $n(z) = \sqrt{1 - (2gz)/v^2}$ and an optical system was designed for such an optically inhomogeneous medium. A resolution of the device on the order of 100 μm for neutrons with wavelengths 700–120 nm was obtained by the Monte Carlo method.

All mirrors were prepared from optical glass coated with a layer of nickel about 150 nm thick. The diameter of the flat mirrors was 2.6 cm and the diameter of the spherical mirrors was 6 cm. The radii of curvature of the concave mirrors were approximately 20 and 30 cm. The distance between them was 12 cm. The source and the image were situated near the focal points of each pair of mirrors, so that between the concave mirrors the neutrons moved almost vertically. The object was the input slit with dimensions 4×10 mm. An analyzing slit was placed in the plane of the image. The image was analyzed by scanning with this slit. A He^3 proportional counter was used as a detector.

The experiment was performed in the curved channel of very slow neutrons from the IR-8 reactor at the I. V. Kurchatov Institute of Atomic Energy. The flux density of UCN with velocities from 3.2 to 5.7 m/s was 3.6 neutrons/cm$^2\cdot$s.

The dependence of the counting rate of the detector on the position of the analyzing slit is shown in Fig. 2. The measurements were performed in two geometries, corresponding to optical magnification magnitudes of $1.375\times$ and $0.725\times$. The width of the analyzing slit was 2.0 and 1.3 mm, respectively, and its height was 10 mm. The distribution width at half-height in the magnification and reduction geometry was 5.42 ± 0.12 and 2.93 ± 0.09 mm, respectively, which within the limits of the statistical accuracy corresponds to the expected values of 5.5 and 2.9 mm. The shape of the

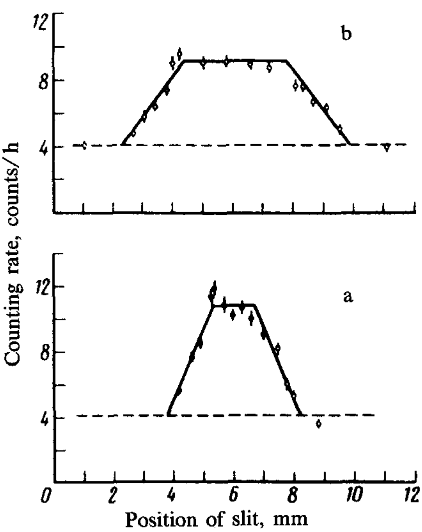

FIG. 2. Dependence of the counting rate of the detector on the displacement of the analyzing slit in the magnification (2a) and reduction (2b) geometry. The solid line shows the results of a least squares analysis assuming a trapezoidal distribution.

curve, which corresponds to the dimensions of the bases and lateral sides of the trapezoid, is consistent with the predicted shape within the limit of statistical accuracy.

It should be noted that the agreement between the obtained width and the expected width does not justify the conclusion that the system has a good resolution. The resolution can be estimated quantitatively by using a more intense source in the measurements and a much smaller analyzing slit than that which has been used. It is even more preferable to use a coordinate-sensitive, high-resolution detector.

For this reason, we view the results of the experiment as a first demonstration of the possibility of using achromatic neutron-optical focusing systems with many elements, which, as the estimates show, permits creating a neutron microscope with resolution on the order of several micrometers. To obtain higher resolution it is probably necessary to use schemes which partially cancel the gravity by a nonuniform magnetic field.[4]

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