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# Interferometer for cold neutrons using multilayer mirrors

Haruhiko Funahashi,[1,*] Toru Ebisawa,[1] Tomohito Haseyama,[2] Masahiro Hino,[3] Akira Masaike,[2] Yoshié Otake,[4]
Tsuguchika Tabaru,[2] and Seiji Tasaki[1]
[1]*Research Reactor Institute, Kyoto University, Kumatori, Osaka 590-04, Japan*
[2]*Department of Physics, Kyoto University, Kyoto 606-01, Japan*
[3]*Department of Physics, Kyushu University, Fukuoka 812, Japan*
[4]*Ibaraki National College of Technology, Hitachinaka, Ibaraki 312, Japan*

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We report a successful experimental test of an interferometer for cold neutrons using multilayer mirrors. Interference fringes that are analogous to the Brewster's fringes in classical optics have been clearly observed using the cold neutron beam with a wavelength of 12.6 Å and a bandwidth of 3.5% at full width at half maximum. The observed interference fringes demonstrate the coherence of the reflection off the multilayer neutron mirror and confirm the feasibility of cold neutron interferometry using multilayer mirrors. [S1050-2947(96)02806-5]

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The neutron interferometer is one of the most powerful tools for direct tests of quantum-mechanical laws and investigations of various weak neutron interaction effects. Numerous interesting experiments [1] have been performed since the first successful test of a single-crystal neutron interferometer [2]. However, the single-crystal interferometer is inherently not able to deal with a neutron that has a wavelength longer than twice its lattice constant, namely the Bragg cutoff wavelength. In order to investigate problems of fundamental physics, including tests of quantum measurement theories and searches for non-Newtonian effects of gravitation, the interferometry of cold neutrons is of vital importance, since the wave property of the neutron, the massive matter wave, is more significant at lower energy. Several attempts have been made to develop neutron interferometers for the cold and very cold neutrons. Ioffe *et al.* obtained the convincing results showing diffraction gratings to be applicable to neutron interferometry [3]. Gruber *et al.* developed a phase-grating interferometer for very cold neutrons [4].

In cold and very cold neutron optics, the multilayer neutron mirror is one of the most useful devices. Multilayer neutron mirrors consist of alternating layers of two materials with different potential energies for the neutron. The incident neutron is partially reflected at each interface of alternating layers. A convenient way of understanding the behavior of such a multilayer device is to think of it as a one-dimensional crystal in which the unit bilayer thickness is the lattice constant. The reflected intensity should be a maximum when Bragg's law is satisfied. The reflectivities of multilayer mirrors can be controlled by adjusting the total number of layers, the unit bilayer thickness, or the difference of the potential energies between the two materials. The unit bilayer thickness of a multilayer mirror is available in the range from 50 to 500 Å. The multilayer mirror with such a lattice constant is suitable for the Bragg reflection of cold and very cold neutrons with larger angle than the angle of diffraction using gratings. A magnetic multilayer mirror, in which one of the materials in the unit bilayer is ferromagnetic, is useful to polarize the Bragg-reflected beam. Depending on the polarity of the external magnetic field, a magnetic multilayer mirror functions either as a reflective mirror or as a transparent mirror for a beam of polarized neutrons.

We have proposed an interferometer for cold neutrons using multilayer mirrors [5], which is analogous to the Mach-Zehnder interferometer in classical optics. Owing to the features of multilayer mirrors mentioned above, the multilayer interferometer has advantages over other interferometers developed so far. In addition, in principle, the dimension of the multilayer interferometer is much larger than that of the single-crystal interferometer. The sensitivity of the interferometer improves with its larger dimension. However, the four multilayer mirrors must be aligned independently as optical elements, in contrast with the single-crystal interferometer in which parallel alignment of all elements is ensured by the fact that each element is cut from the same single crystal.

The purpose of the present paper is to report the successful test of a type of multilayer interferometer for cold neutrons, which is free from the difficulty in aligning the elements. The schematic diagram of the interferometer reported here is shown in Fig. 1. It consists of two pairs of

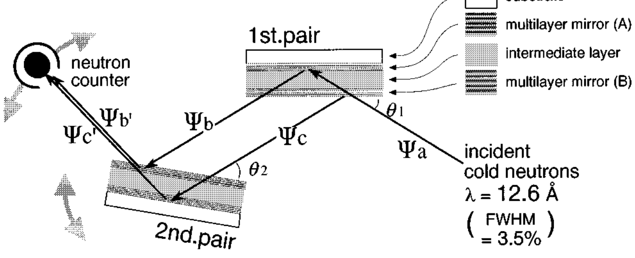

FIG. 1. Schematic diagram of the multilayer interferometer. The glancing angles off the first and the second pairs are denoted by $\theta_1$ and $\theta_2$, respectively.

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[*] Present address: Department of Physics, Kyoto University, Kyoto 606-01, Japan.

multilayer mirrors. Each pair contains two multilayer mirrors; between each multilayer mirror there is an intermediate monolayer with a thickness of $T$. The intermediate layer ensures the parallelism of the two multilayer mirrors. This is the advantage of the present multilayer interferometer over the Mach-Zehnder type, though the waves $\Psi_b$ and $\Psi_c$ in Fig. 1 overlap each other. For the following calculation, the effective distance $D$ between the two multilayer mirrors contained in a single pair is defined as

$$D \equiv T + Nd, \tag{1}$$

where $N$ is the number of bilayers in the single multilayer mirror and $d$ is the unit bilayer thickness.

The first pair divides the incident neutron into two coherent parts and gives the phase difference of $\Delta\phi_1$ between each part. When the incident neutron with the wavelength of $\lambda$ is reflected with the glancing angle of $\theta_1$, $\Delta\phi_1$ is given approximately as

$$\Delta\phi_1 = 2\pi\,\frac{2D\,\sin\theta_1}{\lambda}, \tag{2}$$

assuming the neutron refractive index of the intermediate layer to be unity. The phase difference $\Delta\phi_1$ should cause the ‘‘interference of equal inclination’’ between the waves $\Psi_b$ and $\Psi_c$ in Fig. 1 [6]. However, the interference fringes are not clear when $\Delta\phi_1$ is much larger than $2\pi(\lambda/\Delta\lambda)$, where $\Delta\lambda$ is the width of the wavelength [7].

$\Delta\phi_1$ can be compensated with $\Delta\phi_2$, which is the phase difference given in the reflection off the second pair. $\Delta\phi_2$ is expressed as

$$\Delta\phi_2 = 2\pi\,\frac{2D\,\sin\theta_2}{\lambda}, \tag{3}$$

in the same way as the first pair. The two interfering waves $\Psi_{b'}$ and $\Psi_{c'}$ in Fig. 1 are superposed with the total phase difference, $\Delta\phi_1 - \Delta\phi_2$, after the second reflection, which is given as

$$\Delta\phi_1 - \Delta\phi_2 \approx 2\pi\,\frac{2D}{\lambda}\,\delta\theta, \tag{4}$$

where $\delta\theta$ is $\theta_1 - \theta_2$. When $\delta\theta$ is scanned from $-(\lambda/2D)(\lambda/\Delta\lambda)$ to $(\lambda/2D)(\lambda/\Delta\lambda)$, the interference fringes are observed with the periodicity of $\lambda/2D$ according to Eq. (4), since the total phase difference between $\Psi_{b'}$ and $\Psi_{c'}$ is within the range of $2\pi(\lambda/\Delta\lambda)$, even if $\Delta\phi_1$ and $\Delta\phi_2$ are very large. Such kinds of interference fringes are analogous to Brewster's fringes in classical optics [7]. In the case of the present optical system, the divergent angle of the incident beam has no influence on the disappearance of the visibility since it has the advantage of being nondispersive and the glancing angle of the incident beam is small enough. This feature permits us to observe intense interference signals without fine collimation.

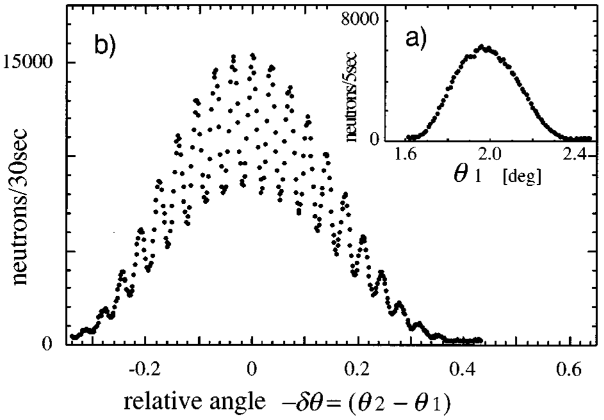

FIG. 2. Effective distance $D$ between the two multilayer mirrors contained in a single pair is 10 100 Å and the unit bilayer thickness of each multilayer mirror $d$ is 180 Å. (a) Intensity of neutrons reflected off a single pair. (b) Interference fringes observed by changing the relative angle between the first and second pairs.

The experiment has been performed using the new beamline, MINE (multilayer interferometer for neutron experiments) [8], at the cold neutron guide tube of the reactor JRR-3M at the Japan Atomic Energy Research Institute (JAERI). MINE provides the cold neutron beam with a wavelength of 12.6 Å and a bandwidth of 3.5% at full width at half maximum (FWHM), employing the monochromator system QUAD. QUAD has four multilayer mirrors to extract the neutrons from the guide tube by means of four consecutive reflections. Two slits separated by 2.6 m define the collimation of the incident neutron beam. The upstream slit is 3 mm wide by 40 mm high and the downstream slit is 1.8 mm wide by 40 mm high. The beam divergence is collimated within ±1 mrad in the horizontal direction and ±15 mrad in the vertical. The beam intensity is 3800 neutrons/sec.

The two pairs of multilayer mirrors are fabricated simultaneously by the successive vacuum evaporations of multilayer mirror $A$ in Fig. 1, the intermediate layer, and finally multilayer mirror $B$ on polished silicon substrates. These substrates have a flatness of about 6000 Å in peak-to-valley and a roughness of about 2 Å in root mean square within the diameter of 60 mm. Each multilayer mirror has five bilayers made of germanium-titanium. The thickness of bilayer $d$ is 180 Å. The intermediate layer is made of germanium whose thickness $T$ is 9200 Å. Since $N$ is 5, $D$ is calculated to be 10 100 Å. The accuracy of the parallelism between the two multilayer mirrors is estimated to be within $10^{-7}$ rad from the geometry of our vacuum evaporation system [9]. The distance between the two pairs is 13 cm.

As shown in Fig. 2(b), interference fringes have been clearly observed with the periodicity of 0.035° when the relative angle between the two pairs $\delta\theta$ changes. The observed periodicity is consistent with the expected value. The visibility of the interference pattern is 30%.

We have obtained another interference pattern, as shown in Fig. 3, using a set of two pairs, with the following parameters: $N$ is 10, $d$ is 140 Å, and $T$ is 2300 Å. $D$ is 3700 Å according to Eq. (1). Both beam collimation slits of MINE are 1 mm wide by 40 mm high. The beam intensity is 790 neutrons/sec. In Fig. 3(a), we see a slight pattern of the ‘‘interference of equal inclination’’ in the single reflection. This can be understood from the fact that $\Delta\phi_1$ is not so large compared with $2\pi(\lambda/\Delta\lambda)$. As shown in Fig. 3(b) the observed periodicity of ‘‘Brewster's fringes’’ is 0.10°, which is also consistent with the expected value of $\lambda/2D$. The visibil-

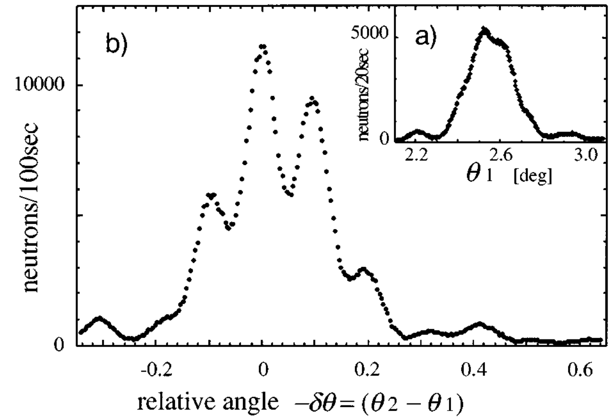

FIG. 3. Effective distance $D$ between the two multilayer mirrors contained in a single pair is 3700 Å and the unit bilayer thickness of each multilayer mirror $d$ is 140 Å. (a) Intensity of neutrons reflected off a single pair. (b) Interference fringes observed by changing the relative angle between the first and second pairs.

ity is 33%. No significant dependence of the visibility on the collimation has been observed in ''Brewster's fringes.''

The present interference fringes demonstrate the coherence of the reflection off the multilayer neutron mirror and confirm the feasibility of cold neutron interferometry using multilayer mirrors. The present results are directly associated with the feasibility of several important experiments in the field of fundamental physics, which have never been accomplished by perfect crystal interferometer or grating interferometer; we emphasize the advantages of the magnetic multilayer mirror, which can be built into the present type of interferometer without difficulty. It is well established that the magnetic multilayer mirror functions as a polarizing monochromator [10]. The interference fringes, in terms of phase difference between the divided two spin states, can be observed using this type of interferometer with magnetic multilayer mirrors. Recently the magnetic multilayer mirror made of permalloy-germanium, which can switch neutron beams on and off rapidly by pulsed magnetic field, has been developed at the Kyoto University Research Reactor Institute [11].

Several experiments are proposed [12] with the advantages of the magnetic multilayer mirror. Presently we are working on the preparation for them; for example, (1) search for the spin-dependent gravitational interaction between the neutron and the earth [13], (2) double Stern-Gerlach experiments [14], and (3) delayed choice experiments [15]. Since the magnetic multilayer mirror, which concurrently functions as an optical element of interferometer, decomposes a neutron into two spin states conserving the coherence between them, the double Stern-Gerlach experiment becomes feasible. This is an experiment to distinguish the detection step and the spectral decomposition step in the quantum-mechanical measurement process and to examine whether the spectral decomposition step plays any role in the disappearance of the coherence between the eigenstates. Magnetic multilayer mirrors also provide the interferometry of neutrons, massive quantum system, with the ability of rapidly switching neutron beams, which enable us to carry out a new type of experiment, such as the delayed choice experiment.

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