CO1-1 Improvement of multilayer mirrors for neutron interferometer

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INTRODUCTION: Neutron interferometry is a powerful technique for studying fundamental physics. 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. 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 extremely important, since the sensitivity of interferometer for small interaction increases with the neutron wavelength. A large scale of interferometer also has the advantage to increase the sensitivity to small interactions.

One of the solutions is an interferometer using neutron multilayer mirrors [3]. We succeeded in developing a multilayer interferometer for cold neutrons in which two paths are completely separated for the first time using wide-gap etalons [4]. We can easily control parameters such as Bragg angle, reflectivity, and Bragg peak width by selecting the deposited material and tuning the bilayer thickness and the number of layers.

We have started the development of multilayer interferometer at the beamline 05 NOP in MLF. From 2019, we are continuing the experiments with etalons with monochromatic mirrors in order to demonstrate the performance of the interferometer. Figure 1 shows the interference fringes with etalons according to time-of-flight. The phase of interferogram depends on the wavelength of neutrons. We are testing the practical application of the interferometer. Neutron coherence scattering length of the material can be measured by inserting the sample into a path of the interferometer. The results of the trial measurements were consistent with the literature values.

Because the mirrors have narrow bandwidth of the neutron reflectivity, the number of neutrons contributing to the interference is limited. When the neutron supermirrors whose lattice constants vary gradually are utilized in the interferometer, the effective range of neutron wavelength can be broadened to be applicable to a pulsed source. In addition, the wavelength dependence of the interactions can be measured simultaneously by using pulsed neutrons.

EXPERIMENTS AND RESULTS: We are continuing to fabricate the neutron mirrors with wide band for the interferometer by using Ion Beam Sputtering facility in KURNS. The mirrors should have the wide and smooth top of the reflectivity with the range of momentum transfer from 0.4 nm^{-1} to 1.0 nm^{-1}. Especially, half mirrors with the wide range of neutron wavelength are needed for the interferometer. In 2022, we have been able to fabricate multilayer mirrors with stable performance. We also measured the reflectivity at MINE2 in JRR3. Figure 2 shows the reflectivity of the half mirrors on the fused silica substrates. Neutron wavelength was 0.88 nm and the bandwidth of the beam was 2.7% of the wavelength. We will try to create an interferometer with the mirrors shortly.

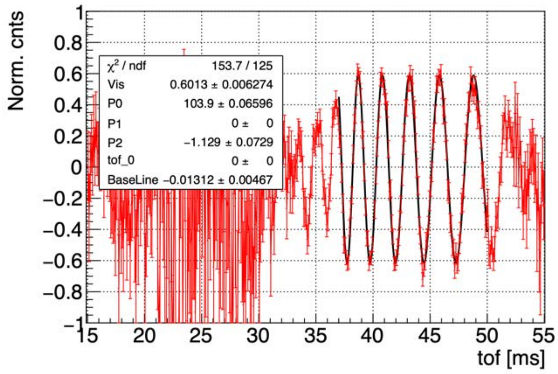

Fig. 1. Normalized interference fringes with multiplayer mirrors for pulsed neutrons.

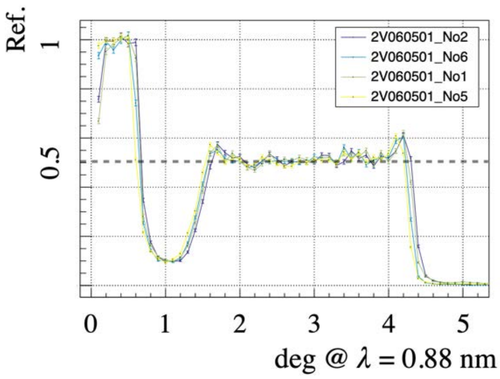

Fig. 2. Reflectivity of the half mirror with wide band of neutron wavelength. Colors represent the sample ID.

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CO1-2 Development of a Spin Analyzer for Ultra-Cold Neutron

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INTRODUCTION: Existence of non-zero permanent electric dipole moments (EDM) of the fundamental particles violates time reversal symmetry. Under CPT conservation, T violation implies CP violation. Thus, a precise measurement of an EDM may reveal the origin of the matter dominant universe. The TUCAN (TRIUMF Ultra-Cold Advanced Neutron source) collaboration aims to measure a neutron EDM with a sensitivity of 10^{-27} ecm, which is one order better sensitivity than the current best measurement.

The neutron EDM is measured by precise measurements of spin precession frequency of neutrons. Ultracold neutrons (UCNs) , whose kinetic energies are less than a few 100 neV, are used for the measurement. One of the key components of the measurement is a spin analyzer of UCNs. The kinetic energy of an UCN is so low that magnetic potential can be used as a spin filter. When iron, which has a large saturation magnetization of 2.2 T, is used for the spin filter, the effective potential V_{eff} is

$$V_{eff} = V_{Fe} \mp |\mu| \cdot |B| = 90 \text{ neV, or } 330 \text{ neV}$$

Where $V_{Fe} = 210 \text{ neV}$ is the Fermi potential of the iron, $\mu = 60 \text{ neV/T}$ is the magnetic moment of the neutron, and $B = 2.2$ T. Only one spin state of UCNs with kinetic energies between 90 neV to 330 neV can transmit the iron magnetic potential. Therefore, magnetized iron film functions as an UCN spin filter. In order to reduce UCN absorption, the iron layer should be as thin as an order of 100 nm.

EXPERIMENTS: The thin iron films were prepared by an ion beam sputtering facility at the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS). We produced thin iron on Si substrates and Al foils similar to the actual UCN spin analyzer size of 83 mm in diameter. Figure 1 shows the way of iron film fabrication by the sputtering.

We conducted experiments to evaluate the spin-analyzing power of the ion films at Beamline 05 of the Material Life Science Experimental Facility at J-PARC, where pulsed UCNs were available. Figure 2 shows the setup of the experiments. Two sets of electromagnets are used to magnetize iron films. One is used as a spin polarizer and the other is used as a spin analyzer. Two spin flippers are installed between the spin polarizer/analyzer. A UCN detector is used to measure the UCNs transmitted through those components. The spin polarizer/analyzer performance is evaluated from the UCN counts with the spin flippers on and off. Using the time-of-flight information, we can evaluate the performance according to the energy of the UCNs.

Fig. 1. Thin iron film

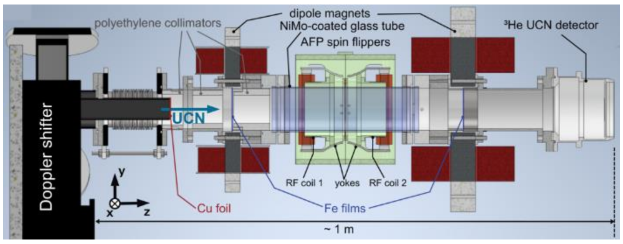

Fig. 2. Experimental Setup

The iron films on the Si substrates and on the Al foils were tested. As we reported last year and [1], the iron films on the Si substrates have much smaller coercivity than that on Al foil. In order to evaluate the dependence of polarizer/analyzer performance on the applied magnetic field, several measurements with different magnetic fields were conducted.

RESULTS:

Figure 3 presents the preliminary results of the measurements. The polarization/analysis power shows as a function of UCN wavelength. In figure 3(a), a comparison between the iron films on the Si substrates and that on the Al foils in the same magnetic field on 120 Oe. The iron film on Si substrates has slightly higher performance. Figure 3(b) shows a comparison of different magnetic fields. We can observe a significant increase between 60 Oe and 120 Oe, On the other hand, it looks saturates higher magnetic fields. However, further analysis is required to finalize the analysis.

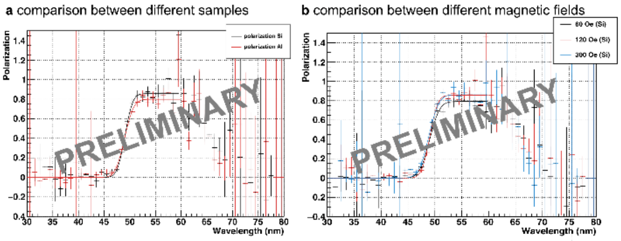

Fig.3. Preliminary Results. The solid lines indicate a fit to a model. (a) The energy dependent polarization of UCNs of iron films on Si substrates and on Al foils. (b) The magnetic field strength dependence on the UCN polarization.

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CO1-3 Development of High-resolution Cold/Ultracold Neutron Detectors Using Nuclear Emulsion

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INTRODUCTION:

Experiments measuring spatial distributions of ultracold neutrons in the Earth's gravitational field have been conducted [1-3]. Quantum behaviors of neutrons in the gravitational field have been studied and unknown short-range forces have been searched by them. In order to measure the spatial distributions with a higher resolution, authors have been developing a high-spatial-resolution cold/ultracold neutron detector [5] using a fine-grained nuclear emulsion [4] whose silver halide crystals' diameter is 40 nm. The detector is fabricated by sputtering a converter layer of $^{10}B_4C$(50 nm)-NiC(60 nm)-C(20 nm) on one side of a 0.4 mm-thick Si wafer and applying the fine-grained nuclear emulsion gel of 10 μm-thick directly on the converter layer. The sputtering was done by an ion-beam sputtering system in KURRI (KUR-IBS) [6]. The detector has a spatial resolution of less than 100 nm [5]. We conducted test experiments at Institut Laue-Langevin (ILL) to obtain spatial distributions of ultracold neutrons in the gravitational field in collaboration with qBOUNCE group, and the distribution was successfully obtained [9]. Also, studies for applications to high-resolution neutron imaging started [7, 8]. To prepare for the next measurement of spatial distributions at ILL and studies for neutron imaging, we sputtered the converter layer on Si wafers and checked its stability by applying the fine-grained nuclear emulsion gel, exposing it to α-ray, developing it, and observing the emulsion layer under the microscope.

EXPERIMENTS:

Six Si wafers with thickness of 0.5 mm were sputtered of $^{10}B_4C$(200 nm)-NiC(50 nm)-C(10 nm) layer by KUR-IBS. A piece of wafer of 1 cm×2 cm was cut out from one of the sputtered wafers. Next, fine-grained nuclear emulsion gel was applied on the piece and dried under the room temperature. Next, the piece was exposed to α-ray using ^{241}Am source. After that, it was developed with a developer, XAA, for 20 minutes in 20℃. The sputtered layer and the emulsion layer were checked of their stability during the development. Finally, the emulsion layer was observed by epi-illumination microscope.

RESULTS:

The both layers were stable during the development. Tracks of α-particles were clearly observed without decrease of grain densities. There was no fog increase. It was confirmed that the mechanical and chemical stability of the converter layer was sufficient for experiments.

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CO1-4 Towards to ultra small *d*-spacing neutron monochromator

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INTRODUCTION: Slow neutrons are very powerful and useful in various research fields, such as material and life sciences, particle physics, fundamental engineering. It is necessary for production of neutron beam to use any nuclear reaction and it requires, in general, large facility to obtain high intensity of the neutron beam. More effective neutron intensity is still desired even in advanced large facility. It is quite important for transportation and shaping of neutron beam from the source to the experimental instrument. Recently a big project of new research reactor at the "Monju" site in Fukui prefecture has been started[1]. In case of a continuous neutron source like reactor, monochromator is very useful and smaller d-spacing multilayer is also very significant to enlarge utilization of neutron beam.

EXPERIMENTS:. The multilayer coating was conducted with ion beam sputtering machine at the KURNS (KUR-IBS) [2]. It is necessary for actual production of multilayer neutron mirror to realize large homogeneous deposition area without roughness growth. Figure 1 shows photograph of silicon wafers and glass plates placed on a substrate holder of KUR-IBS. We have optimized the deposition process by considering the deposition rate, gas pressure, the sputtering targets and geometrical condition. Then we found some parameters to fabricate smooth thin layer of which thickness was larger than 1 nm with large homogeneous area. We fabricated NiC(nickel-carbon) and Ti(titanium) multilayer of which the designed d-spacing was gradually changed from 2 nm to 2.2 nm like supermirror. The effective number of layers was 1680. The neutron experiments were conducted at CN-3 beam line at KURNS and C3-1-2(MINE) beam line of JRR-3 at JAEA.

RESULTS: Figure 2 shows measured neutron reflectivity by the multilayer mirror deposited on the silicon wafer(U0) placed on center of the substrate holder shown in Fig.1. A clear and sharp peak was observed at q_z=3.1nm^{-1}. The average d-spacing and the peak reflectivity were estimated to be 2.03 nm 1.5 %, respectively. Here reflectivity by ideal d-spacing multilayer mirror with same number of layer without surface and interface roughness was calculated to be 8%. The reflectivity of 1.5% corresponds to that by the same multilayer deposited on a substrate of which surface roughness was roughness of 0.4 nm (rms). The roughness value 0.3 nm is almost surface roughness of silicon wafer or float glass. Then it was clear that growth of interface roughness of the multilayer was well suppressed even the total thickness of multilayer was about 1.68 μm. Figure 3 shows measured neutron reflectivity by the stacking multilayer mirrors placed on the substrate holder shown in Fig.1. The peak reflectivities of various multilayers were almost same within an area of approximately 40 cm in diameter within the holder shown in Fig.1. With increasing number of stacking of multilayer mirrors, the reflectivity was increased. In case of stacking seven mirrors, we obtained peak reflectivity 8%.

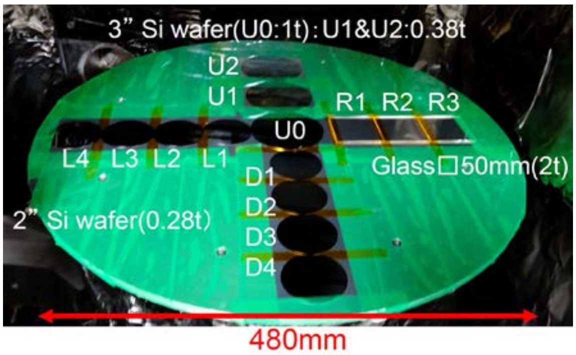

Fig. 1. The photograph of substrate arrangement on a substrate holder of KUR-IBS.

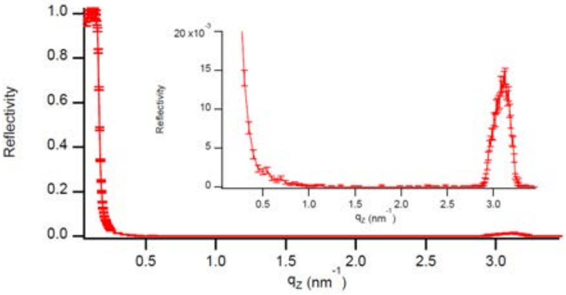

Fig. 2. Measured reflectivity of neutrons by d~2nm multilayer mirror fabricated on center position (U0) shown in Fig.1. The inserted figure is a figure with the maximum of the vertical axis set to 2%. The effective number of layers of the multilayer mirrors is 1680.

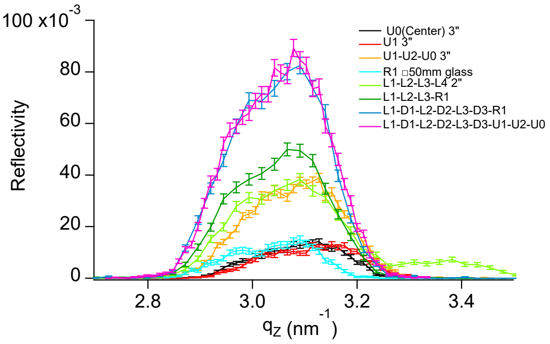

Fig. 3. Measured reflectivity of neutrons by stacking d~2nm multilayer mirrors fabricated on various positions shown in Fig.1.

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