VIII-II-1. Project Research

Project 7

PR7 **Development of Neutron Optical Devices and Its Application to New Neutron Spectrometer and Imaging**

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OBJECTIVES AND ALLOTED RESEARCH SUBJECTS :

The aim of this project research is the development of neutron optical devices and its application.

ARS-1 Improving the utilization activity on KUR and HL in KURRI under strategic promotion program for basic nuclear research

ARS-2 Application of neutron imaging for botanical research

ARS-3 Visualization and measurement of air-liquid two-phase flow using neutron imaging

ARS-4 In-situ observation of supercritical water reaction field using neutron imaging

ARS-5 Quantitative evaluation of liquid film in forced-flow boiling system

ARS-6 Neutron spin phase imaging for visualization of electric current

ARS-7 Recent development of large-m supermirror and very small d-spacing wide-band multilayer at KURRI

ARS-8 Demonstrations of neutron resonance spin echo for pulsed source

ARS-8 Fabrication and characterization of high quality polarized neutron mirrors for neutron spin phase imaging

MAIN RESULTS AND THE CONTENTS OF THIS REPORT :

Y. Kawabata et. al (ARS-1) proceeded a project for improving the utilization activity on KUR and HL in KURRI under the Nuclear energy initiative, Research reactor and hot laboratory utilization program. As KUR was not operated in 2009, this program was proceeded using accelerators and RI.

U.Matsushima et al. (ARS-2) did not perform their experiments in KURRI because of no KUR operation.

N.Takenaka et al. (ARS-3) did not perform their experiments in KURRI because of no KUR operation.

T.Tsukada et al. (ARS-4) did not perform their experiments in KURRI because of no KUR operation.

N.Umekawa et al. (ARS-5) did not perform their experiments in KURRI because of no KUR operation.

S.Tasaki et al. (ARS-6) has improved Neutron spin phase contrast (NSPC) imaging, which is a method to visualize the magnetic field integral along the trajectory of neutron. The principle of NSPC is to measure additional phase difference between spin eigen states of Larmor precessing neutron, by means of neutron spin interferometry. In NSPC imaging, neutron intensity changes sinusoidally, via the phase difference of incident neutron. When magnetic field exists on the way of neutron, the sinusoidal curve is shifted, and the shift is proportional to the magnetic field integral. Moreover, the contrast (visibility) of the sinusoidal curve may change depending on the homogeneity and direction of the magnetic field. In the present study, they apply NSPC method to measure magnetic field induced by electric current, to develop NSPC imaging to visualize electric current distribution.

M.Hino et al. (ARS-7) have developed large-m supermirrors and very small d-spacing wide-band multilayers at KURRI. A multilayer with small d-spacing and supermirror with large-m are desirable to enlarge utilization efficiency for neutron scattering experiments (Here m is a maximum critical angle of the mirror in unit of critical angle of nickel). In order to fabricate small d-spacing multilayer with high reflectivity, even in theoretically smooth surface and ideal layer structure, the required number of layer increase the fourth power of m. Then it is very difficult to fabricate to small d-spacing multilayer and large-m supermirror.

M.Kitaguchi et al. (ARS-8) have demonstrated neutron resonance spin echo（NRSE) for pulsed source. Neutron spin echo (NSE) is one of the techniques with the highest energy resolution for quasi-elastic scattering by measuring rotation of the neutron spin. In NRSE, two resonance spin flippers (RSFs) replace a homogeneous static magnetic field for spin precession in the conventional NSE. The RSF using dipole magnet with iron poles for the static magnetic field had been developed. Test experiments to observe MIEZE signals with high frequency by using the RSFs have been successfully performed using the cold neutron beam line MINE1 at JRR-3 reactor at JAEA.

H.Hayashida et al. (ARS-9) did not perform their experiments in KURRI because of no KUR operation.

採択課題番号 21P7　中性子光学機器の開発とその新型中性子散乱装置及びイメージングへの展開　プロジェクト

（京大・原子炉）川端祐司

PR7-1 Project for Improving the Utilization Activity on KUR and HL in KURRI under Strategic Promotion Program for Basic Nuclear Research (II)

Y. Kawabata

Research Reactor Institute, Kyoto University

INTRODUCTION: A project for improving the utilization activity on KUR and HL in KURRI is in progress under the Nuclear energy initiative, Research reactor and hot laboratory utilization program. As KUR was not operated in 2009, this research program was proceeded using accelerators and RI. Now, it is ready to restart the utilization of KUR.

RESEARCH ACTIVITY: The outline of this program consists five main research items.

1) A two dimensional real time neutron fluence evaluation system for BNCT has been developed. The characteristics of this system was measured at BNCT cyclotron based neutron source in the innovation research laboratory. The good linearity between the thermal flux and the monitor signal was shown in the range of 10^8 - 10^9 (n/cm²/s). The insensitivity to γ-ray was also shown in the ^{60}Co γ-ray irradiation facility.

2) Total micro-element analysis system including short-lived neutron activation analysis, prompt-γ ray analysis systems, X-ray fluorescence analysis system and ICP-AES is developing. The summary of this system is shown in Fig.1.

3) Neutron imaging for two phase flow research requires boiling circuit, high electric power supply and cooling system. A neutron imaging system using CCD camera has been installed in B4 (supermirror neutron guide) beam line.

4) As we had no neutrons, electron irradiation by electron linac in KURRI and proton irradiation in QSEC were performed for material irradiation research. The tensile tester with high temperature sample controller and electron microscope with sample temperature controller has installed.

5) The effectiveness of an annual education was shown by a questionnaire investigation.

CONCLUSION: KUR will restart in May and neutron experiments will start from June 2010. The real experiments will give us fruitful scientific results.

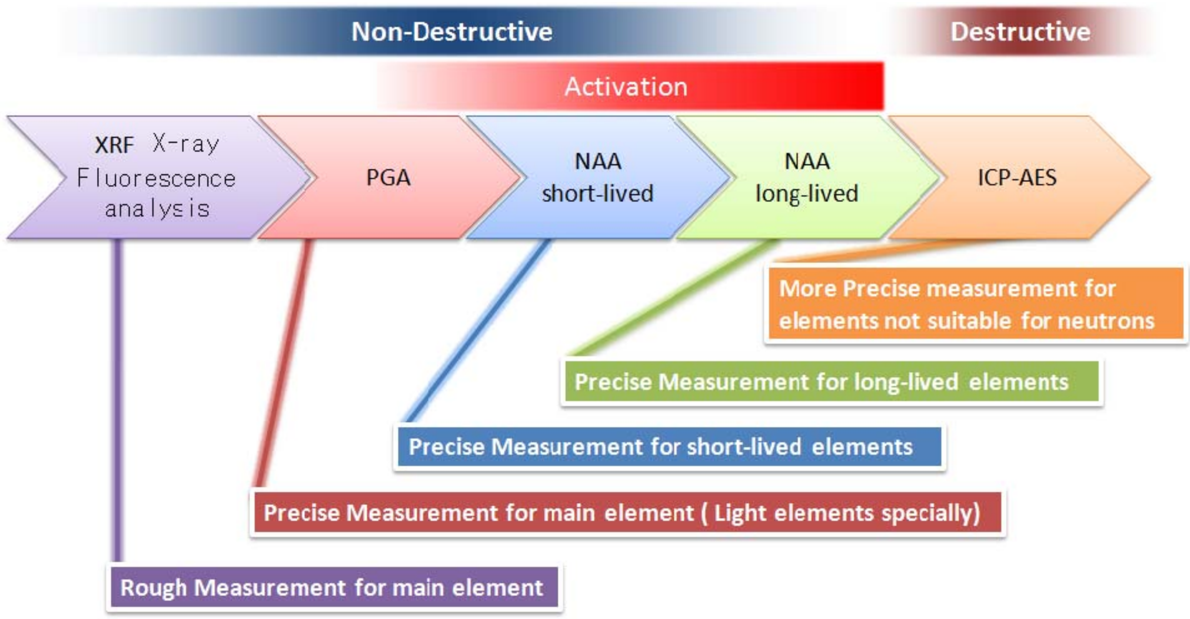

Fig.1. Summary of total micro-element analysis system.

採択課題番号 21P7-1　京大炉（ＫＵＲ）及びホットラボの利用高度化に関する研究　プロジェクト
（京大・原子炉）川端祐司、田中浩基、桜井良憲、高宮幸一、福谷　哲、太田朋子、関本　俊、齋藤泰司、沈　秀中、徐　虬、佐藤紘一、高橋千太郎、（首都大学東京）海老原　充、（石巻専修大）福島美智子、（神戸大）竹中信幸、（東北大）塚田隆夫、（関西大）梅川尚嗣、（大府大）堀　史説、（広島国際大）向田一郎

PR7-2 Neutron Spin Phase Imaging for Visualization of Electric Current

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Department of Nuclear Engineering, Kyoto University
[1]Research Reactor Institute, Kyoto University

INTRODUCTION: Neutron spin phase contrast (NSPC) imaging is a method to visualize the magnetic field integral along the trajectory of neutron. The principle of NSPC is to measure additional phase difference between spin eigen states of Larmor precessing neutron, by means of neutron spin interferometry. In NSPC imaging, neutron intensity changes sinusoidally,via the phase difference of incident neutron. When magnetic field exist on the way of neutron, the sinusoidal curve is shifted, and the shift is proportional to the magnetic field integral. Moreover, the contrast (visibility) of the sinusoidal curve may change depending on the homogeneity and direction of the magnetic field.
In the present study, we apply NSPC method to measure magnetic field induced by electric current, to develop NSPC imaging to visualize electric current distribution.

EXPERIMENTS:
Schematic view of the present sample is shown in Fig.1. A Al-cylinder with 10mm-diameter and 20mm-length is sandwiched by Cu plate. The electric current flows along with the black arrow in the figure. Such current produces the magnetic field inside and outside of the Al-cylinder.
Neutron experiments were performed at C3-1-2-2 beam port of JRR-3M in JAEA. Wavelength of the neutron beam is 0.88nm ($\delta\lambda/\lambda$=2.7%), available beam size is 10mm in width and 30mm in height.
Experimental set-up is shown in Fig.2. Incident neutron is polarized vertically with 5Q-supermirror polaizer fabricated with Ion Beam Sputtering system in KUR. Then the spin of the neutron is half flipped with resonance neutron flipper. In the middle of the set-up, PI-flipper is installed in order to cancel outer magnetic field and to introduce phase difference ϕ between two spin states of neutron. The sample is located after the PI-flipper and then PI/2-flipper and spin analyser is set for analyzing the phase of neutron spin wave. Neutron spin analyser is V-shape polarizer with 5Q-polarizing supermirror and the transmitted neutron is measured with 2D-RPMT with Li-glass scintillator. Interference fringe is obtained from the change of neutron intensity via the phase between neutron spin states.

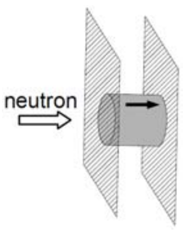

Fig. 1. Schematic view of the sample.

RESULTS: An example of measured result is shown in Fig.3. The electric current through Al-rod is 7.5A, and ϕ is 72 degree. The measurements were performed for other values of ϕ, and the phase induced by the magnetic field caused by the electric current is to be analysed.

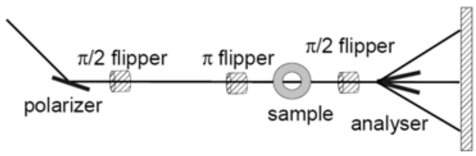

Fig. 2. Experimental set-up.

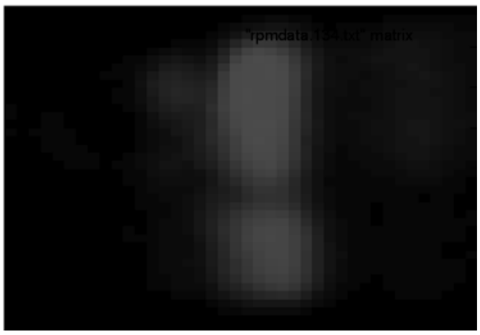

Fig. 3. An examples of measured result.

採択課題番号 21P7-6　　多層膜中性子偏極反射鏡の性能改善　　プロジェクト
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PR7-3 Recent Development of Large-m Supermirror and Very Small D-Spacing Wide-Band Multilayer at KURRI

M. Hino, M. Kitaguchi and Y. Kawabata
Research Reactor Institute, Kyoto University

INTRODUCTION: A multilayer with small d-spacing and supermirror with large-m are desirable to enlarge utilization efficiency for neutron scattering experiments (Here m is a maximum critical angle of the mirror in unit of critical angle of nickel). In order to fabricate small d-spacing multilayer with high reflectivity, even in theoretically smooth surface and ideal layer structure, the required number of layer increase the fourth power of m. Then it is very difficult to fabricate to small d-spacing multilayer and large-m supermirror.

EXPERIMENTS: Recently, we fabricated m=2.9 supermirror on an ordinary silicon wafer in which surface roughness (σ) is about 0.4 nm. By increasing number of layers and improving layer structure, the measured reflectivity at m<2.8 was clearly better than the expected theoretical lines with σ=0.3 nm. It was well reproduced by the theoretical line with ideal smooth layer structure in which surface and interface roughness is nothing or very little (σ<0.1)[1]. In this study, by using this technique and stacking multilayer mirrors, we tried to realize large-m and small d-spacing wide-band monochromator with high reflectivity.

RESULTS: Figure 1 shows measured reflectivity by m=7 NiC/Ti supermirror which consist of stacking two mirrors. Each mirror consists of two multilayers. First multilayer is m=5 NiC/Ti supermirror deposited on thin silicon wafer in which thickness is 0.3 mm. The number of layer is 4766. The layer thickness of the first multilayer (m=5 supermirror) is gradually increased from silicon surface. The second multilayer is wide-band multilayer deposited on back side of the thin silicon wafer. The design d-spacing is from 5.82 to 4.76 nm and total number of layer is 7131. The layer thickness is gradually decreased from silicon surface. The gap around m=5.5 shows that the control of layer thickness is still insufficient level after vacuum vent. Though we have to improve thickness control technique, m=7 NIC/Ti supermirror was realized by using stacking mirror technique.

The Stacking technique is more effective for wide-band monochromator case. The effective reflectivity was increased and the band is enlarged. As shown in Fig.2 d-spacing at maximum intensity is 2.89 nm and reflectivity is higher than 0.4. The monochromator consists of four mirror and each mirror coated both surface. These number of layer at first and second multilayers are 10336 and 10929, respectively. The total number of layer for the monochromator is 85060. This mirror set have already installed to Doppler shifter at BL05 in J-PARC as most important key device. Very recently, our collaborators succeeded to observe ultra cold neutron(UCN) [2].

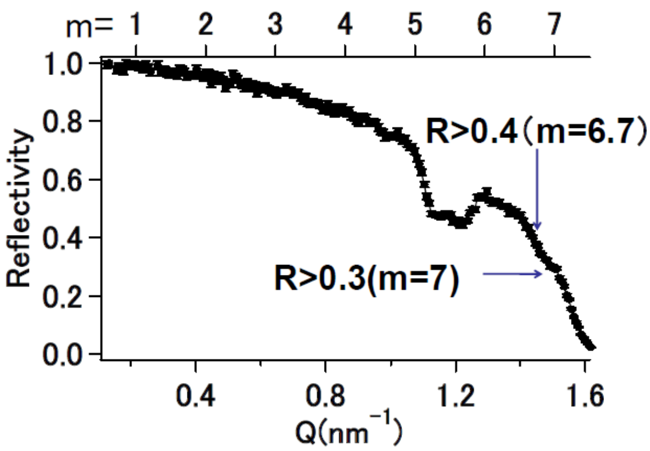

Fig. 1. Measured reflectivity by m=7 NiC/Ti supermirror which consist of stacking two mirrors (4 multilayers).

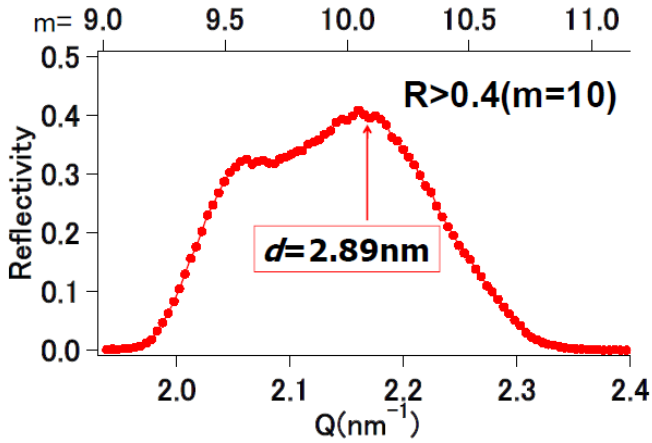

Fig.2. Measured reflectivity by m>10 wide-band monochromator which consist of four mirrors(8 multilayers).

REFERENCES:

[1] M. Hino, et al., Nucl.Inst.Meth. A **600** (2009) 207.
[2] K. Mishima, private communication.

採択課題番号 21P7-7　スパッタ膜応力を利用した曲面多層膜中性子ミラーの開発　プロジェクト
（京大・原子炉）日野正裕、川端祐司、北口雅暁（京大・工）田崎誠司、（阪大・理）阿知波紀郎

PR7-4 Demonstrations of Neutron Resonance Spin Echo for Pulsed Source

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[1]Department of Nuclear Engineering, Kyoto University
[2]JAEA

INTRODUCTION: Neutron spin echo (NSE) is one of the techniques with the highest energy resolution for quasi-elastic scattering by measuring rotation of the neutron spin [1]. In neutron resonance spin echo (NRSE), two resonance spin flippers (RSFs) replace a homogeneous static magnetic field for spin precession in the conventional NSE [2]. An RSF, which flips the spin of a neutron by exchanging energy between the neutron and an oscillating magnetic field, gives the difference of wavenumber between up- and down-spin components of the neutron. The relative phase between the two spin components, which is equivalent to spin rotation, is provided by the difference of wavenumber in the area between the RSFs.

A RSF consists of a static magnetic field and an oscillating magnetic field. The static field is proportional to the frequency of the oscillating field. The energy resolution of NRSE spectrometer is proportional to the frequency of the oscillating field. The static field of 17mT is required for the frequency of 500kHz. The RSF using dipole magnet with iron poles for the static magnetic field had been developed in order to provide strong magnetic field with less current. Test experiments to observe MIEZE signals with high frequency by using the RSFs have been successfully performed using the cold neutron beam line MINE1 at JRR-3 reactor at JAEA. The frequency of the first RSF was 300kHz and that of the second RSF was 600kHz. The contrast of the observed MIEZE signal was about 0.6 [3].

EXPERIMENTS: The RSFs and the devices for MIEZE spectrometer was set on a beam branch of BL05 NOP beam line in MLF at J-PARC. At the branch pulsed cold neutron beam with the wavelength from 0.3nm to 1.0nm is provided with fine beam divergence. The RSF can be applied pulsed neutrons by using the dumping amplitude of RF magnetic field synchronized with the time of flight of the neutrons. In the case of pulsed neutrons, the contrast of MIEZE signal is always high for all time channel of detector because the beam in each wavelength region is monochromatic due to the pulsed source. We observed clear MIEZE signals with the effective frequency from 0.5 kHz to 600 kHz.

RESULTS: We demonstrated MIEZE spectrometer for pulsed neutrons. We are continuing to develop MIEZE spectrometer for pulsed source for practical uses. We are now discussing to build a neutron spin echo spectrometer at J-PARC [4].

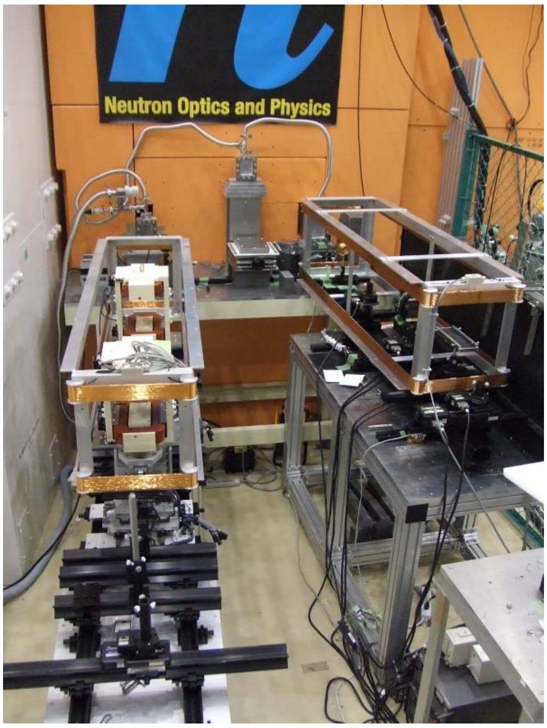

Fig. 1. MIEZE spectrometer in the beam line BL05 NOP in MLF at J-PARC (left side).

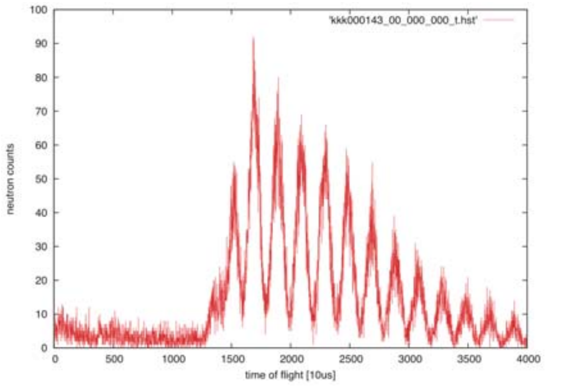

Fig. 2. Observed MIEZE signal with the frequency of 0.5 kHz.

REFERENCES:
[1] F. Mezei, Z. Phys. **255** (1972) 146.
[2] R. Gaehler, R. Golub, Z. Phys. B**65** (1987) 43.
[3]M. Kitaguchi, et. al., Physica B, **404** (2009) 404.
[4]Y. Kawabata, et. al., Nucl. Instr. And Meth. A**574** (2006) 1122.

採択課題番号 21P7-8　　中性子共鳴スピンエコー装置のためのデバイス開発　II　　プロジェクト
（京大・原子炉）北口雅暁、日野正裕、川端祐司（京大院工）田崎誠司
（原子力機構）丸山龍治、海老澤徹