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A Multilayer Cold Neutron Pulser Working under an External Magnetic Field Less than 50 Gauss

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A multilayer of Permalloy/Ge(PGM) has been evaporated on a Si wafer in a magnetic field of about 130 Gauss parallel to the surface of the wafer. A neutron pulse was obtained by applying a pulsed magnetic field of about 30 Gauss parallel to a PGM polarizing cold neutron mirror. The results of the performance tests of a multilayer cold neutron pulser are as follows:(1)the pulse contrast of the neutron beam reflected from a cold neutron pulser increased reasonably by another reflection through the analyzing mirror placed behind of the cold neutron pulser;(2)one of the countermeasures to improve the pulse contrast was to limit the zero field region in order to avoid the adiabatic spin flip. The PGM was used as a part of a composite neutron mirror which was used in the delayed choice experiment. The results showed the feasibility of the PGM as a cold neutron pulser.

KEYWORDS: Permalloy/Ge multilayer, cold neutron, cold neutron polarizer, cold neutron pulser, composite neutron mirror, delayed choice experiment

§.1. Introduction

The de Broglie wave property of the massive neutron becomes remarkable in the cold neutron energy region. Cold neutron optics using multilayer neutron mirrors have been developed at the Kyoto University Reactor (KUR) to investigate the quantum mechanical phenomena.[1]

A multilayer neutron mirror is an artificial lattice with a large interplanar spacing and gives the simple one-dimensional neutron optical potential including the magnetic one for cold neutrons. The width and height of the potential are controlled arbitrarily. The potential width is determined by the distribution of layer thicknesses during vacuum evaporation and the height by selecting layer materials.[2,3]

The magnetic neutron devices for cold neutron optics are required to satisfy the following three conditions: (1) they should be as small as possible to set compactly in a restricted space; (2) the stray fields from the magnetic devices should be small enough not to give magnetic effects to the nearby devices; (3) they should control the neutron spin states easily and precisely. A multilayer polarizing cold neutron mirror must be magnetized to saturation under a very low external magnetic field in order to fulfill the above conditions.

We have already developed a multilayer polarizing cold neutron mirror working under the external magnetic field less than 50 Gauss[4] and used it in various experiments to investigate the fundamental physics [5,6]

We call "a multilayer polarizing cold neutron mirror placed in the pulsed magnetic field" a multilayer cold neutron pulser, or in abbreviation a cold neutron pulser. A cold neutron pulser functioning in a very low pulsed magnetic field must be developed in order to do a delayed choice experiment using a multilayer cold neutron interferometer.[7] The cold neutron pulser utilized for a delayed choice experiment must still satisfy the following additional conditions: (1) it should produce a rectangular neutron pulse having no fluctuations; (2) a rising time of a neutron pulse should be in the order of magnitude of 100 μs.

Devices to generate polarized neutron pulses without a mechanical chopper have been used so far in the fields of the neutron optics and neutron scattering spectrometers. A pulsed π-flipper coil generates polarized neutron pulses easily and efficiently[8] compared with a cold neutron pulser. However, this device can not be used in the delayed choice experiment because it doesn't work as a wave splitter. A ferrite crystal ($^7Li_{0.5}Fe_{2.5}O_4$) in the pulsing magnetic field of the order of 1000 Gauss has been used to supply short neutron bursts for the time-of-flight (TOF) spectrometer.[9] The crystal material is not suitable for polarizing cold neutrons with wavelengths longer than about 6 Å. It is difficult to produce large single crystals and a strong external pulsed magnetic field. Above all it is not able to take a role such as a composite neutron mirror which consists of a magnetic part and a nonmagnetic part. This feature is the peculiar one of the artificial neutron mirror.

We report the results of the performance tests of the cold neutron pulser.

§.2. Production and performance tests of Permalloy/Ge multilayer cold neutron pulser

Permalloy (Fe(55%)Ni(45%))/Ge multilayer (PGM) neutron mirror is fabricated by vacuum evaporation onto Si wafer in a magnetic field of about 130 Gauss. The magnetic mirror consists of alternating parallel layers of Permalloy and Ge. The refractive index of Ge for neutrons is approximately equal to that of the Permalloy for neutrons with spins aligned antiparallel to the magnetization of the Permalloy layer. The bilayer consisting of Permalloy layer and Ge layer functions as a single layer. Artificial interplanar spacing of the PGM is determined according to the experimental conditions. The pulsed monochromatic beam can be produced if the magnetic induction orientation in a ferromagnetic layer can be changed by an external magnetic field. The neutron pulse length and frequency can be varied by changing the length and frequency of the current pulse that generates the magnetic field.

A commercial bi-polar power supply was used to supply current pulses to the pulsing magnetic coil surrounding a PGM cold neutron mirror so that neutron pulses can be produced. The input signal code to the power supply is sent from the commercial oscillator. The trigger pulses to energize TOF spectrometer are also supplied from the oscillator.

An experiment for producing neutron pulses was done first using the polarization analysis instrument(PAI) at the E-3 neutron guide tube of KUR. PAI consists of a polarizer, a π-flipper coil of Mezei type, and the PGM analyzing mirror in the pulsed magnetic field. The pulsing coil of PAI consisted of a pair of solenoids: each was made from 200 turns of copper twisted wire of a 3.5 mm^2 cross section, and an inside diameter of solenoid was 70 mm. The pulsing current to produce the field of 50 Gauss at the central site of the opening between the two solenoids was 5 A in case of a 3 cm opening. An opening was used as a neutron path. The PGM mirror was so placed in the solenoids that the mirror surface was parallel to the axis of the solenoids.

The time spectrum of neutrons reflected from the PGM cold neutron mirror in the pulsed magnetic field (PGM cold neutron pulser) was measured using a TOF spectrometer. Figure 1 shows the time spectrum of 4 Å neutron beam reflected from the PGM cold neutron pulser. The rising time of the neutron pulse is about 300 μs. The duration time of the positive voltage pulses sent from the oscillator is 1.67 ms and the repetition rate of the pulses is 300 Hz.

Figure 2 shows the current flowing into the pulsing magnetic coil used in case of Fig. 1. The fluctuation with a deep gorge is shown. This is due to the eddy current produced in the coil. The results show that the time spectrum of neutrons follows approximately the current pulses.

We tried to use a PGM cold neutron pulser for a delayed choice experiment since its feasibility is suggested by the results shown in Fig. 1. The pulsing magnetic system consisting of the PGM cold neutron mirror and the pulsing magnetic coil was, however, required to be small enough to be set in a small space (14 cm × 14 cm × 14 cm) of the phase/spin echo interferometer,[5] which was installed at the research reactor JRR-3M of JEARI. The pulsing magnetic coil used in the previous experiment was interchanged with the small one, and the twisted wire to a single wire (1 mm dia.) to make a coil volume small. The results were not desirable because of the large fluctuations in the current pulse and thus in the neutron pulse as shown in Fig. 3. This is caused by that the effect of eddy current is larger in a thick wire than that in a thin wire.

In order to enhance the pulse contrast (a ratio of a hill-value to the valley-value) we set a analyzing mirror

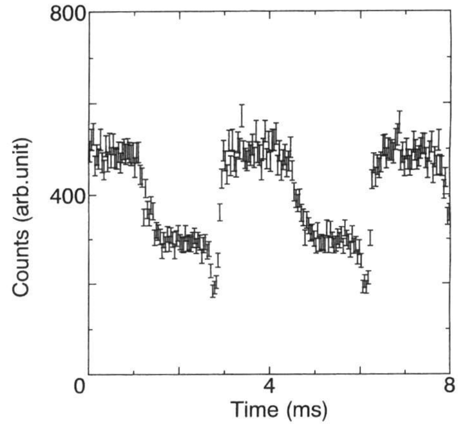

Fig.1. The time spectrum of 4 Å neutron beam reflected from the Permalloy/Ge multilayer neutron mirror in the pulsed magnetic field (PGM cold neutron pulser).

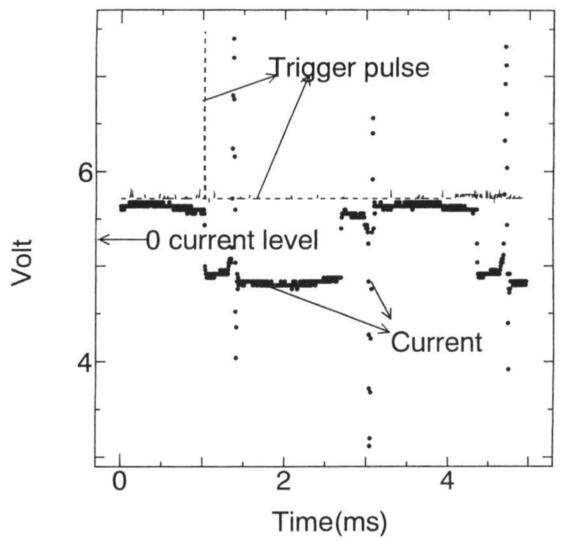

Fig.2. The current flowing into the pulsing magnetic coil used in case of Fig.1 which was measured by the oscilloscope. The current was converted into the volt by a current monitor. The trigger pulse denotes the signal sent from the oscillator to the bi-polar power supply and also was measured by the oscilloscope.

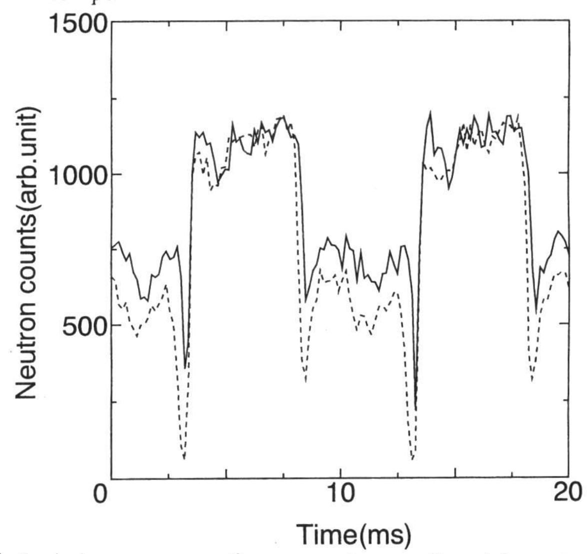

Fig.3. A time spectrum of a neutron beam reflected from the PGM cold neutron mirror in the pulsed magnetic field (solid line) and that from the analyzing cold neutron mirror (dotted line) placed behind the PGM cold neutron mirror.

downstream of the PGM cold neutron pulser. The pulse contrast from the analyzer mirror installed behind the PGM cold neutron pulser is reasonably better than that from the PGM cold neutron pulser as shown in Fig. 3. Furthermore, the improvement of the pulse contrast was obtained by setting the supplementary coils at the front and rear side of the pulsing magnetic coil. The increase of the pulse contrast was about 16%. These supplementary coils contribute to the decrease of the depolarization induced during neutrons' passage through the spot of zero field.

§.3. An attempt of a delayed choice experiment

The twisted wire was used again instead of the single wire and the magnetic coil system was improved. Although the fluctuation in the neutron pulse did not diminish, we tried to do a delayed choice experiment[10] using the composite neutron mirror consisting of a Ni/Ti multilayer ((Ni:92 Å / Ti:92 Å) × 5 (bilayers)), a Ge gap layer (4000 Å), and a semitransparent Permalloy/Ge multilayer(PGM) ((Permalloy:92 Å / Ge:92 Å) × 5 (bilayers)), evaporated in series on the single Si wafer. The top PGM functions as a wave splitter and the Ge gap layer takes the role of a phase shifter.

Schematic experimental arrangement is shown in Fig. 4 and this arrangement is analogous to a Jamin interferometer. The pair of identical composite neutron mirrors was set at parallel positions about 40 cm apart. Polarized 12.6 Å neutrons with a FWHM bandwidth of 3.5 % is incident on the first composite mirror and divided into two coherent partial waves as shown in Fig.4. The phase difference induced between the two partial waves at the first composite mirror is compensated by the second because the two partial waves reflected from the second one are superposed upon each other. When the second composite mirror rotates by a small angle $\delta\theta$ on a vertical axis parallel to the mirror surface, the phase difference changes, and interference fringes are observed by varying $\delta\theta$. This is a Jamin type interference fringes.

The delayed choice experiment was attempted using the arrangement mentioned above. In the case of the delayed choice experiment, the second mirror is set in the pulsing magnetic field of 30 Gauss to make a condition of whether the PGM of the second composite mirror to be or not to be for the polarized neutron when the neutron is passing the second mirror. The meaning of "delayed choice" in the delayed choice experiment is that the trigger pulse to energize the TOF spectrometer is switched on after a neutron passed the first composite mirror. We measures the TOF spectra by making relative angles of the second to the first fixed, and obtains the change of the counting rates as a function of the relative angles on the condition of the "delayed choice" from the time spectra.

Let's firstly assume that the neutron behaves like a wave, that is, the incident neutron has been split into beams I and II with equally weights at the first mirror. After a neutron passed the second composite mirror, an interference fringe would be appeared as a Jamin interferometer if the PGM of the second composite mirror works so as to be for the polarized neutron; and interference fringes would diminish and only the broad peak due to the first Bragg reflection

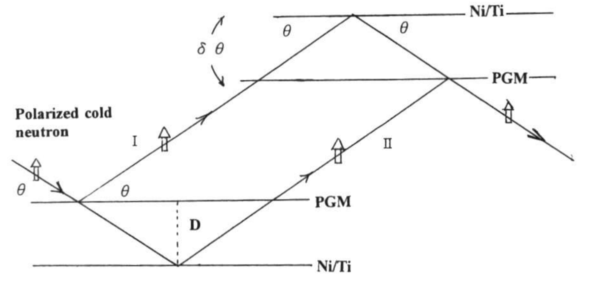

Fig.4. Schematic experimental arrangement of a delayed choice experiment.

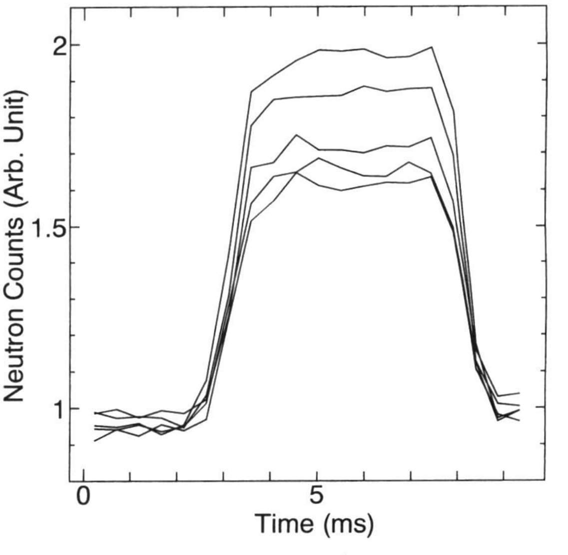

Fig. 5. The time spectra of the neutron beam reflected from the second composite mirror in the pulsed magnetic field at the several fixed relative angles within one period of the fringe. The each curve corresponds to the neutron time spectrum at the different relative angle within one period of the fringe.

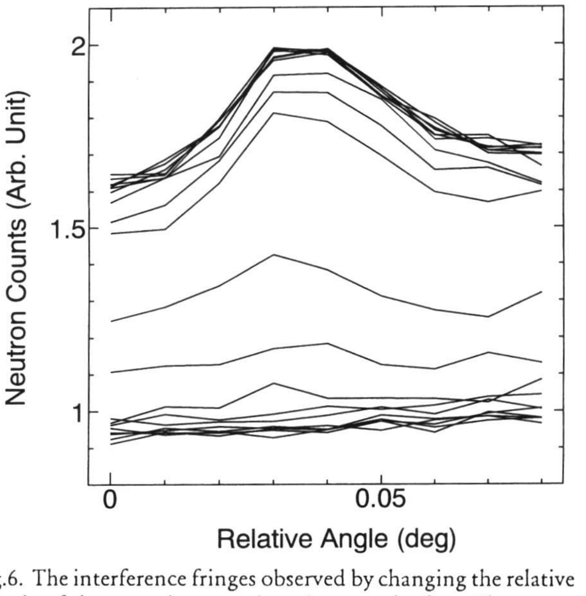

Fig.6. The interference fringes observed by changing the relative angle of the second composite mirror to the first. The curves were obtained from the time spectra of Fig.5 by replotting the counting rates at the fixed flight time which corresponds to the condition of the delayed choice as a function of the relative angles.

from the multilayer could be observed if the second PGM works so as not to be for the polarized neutron.

If the neutron behaves like a particle, that is, the incident neutron takes either the path I or II, we could not obtain the interference fringes on the condition of the "delayed choice", regardless whether the second PGM is to be or not to be.

Such an experiment would thus verify the wave like property of the neutron if we get an interference fringe when the second PGM is to be for the polarized neutron and an interference fringe diminish when the second PGM not to be, on the condition of the delayed choice.

The time spectra of neutron beam reflected from the second composite mirror in the pulsed magnetic field were measured at the several fixed relative angles within one period of the fringe.

The results are shown in Fig. 5. The value at the each hill corresponds to the case in which the second PGM mirror works for the polarized neutron. The valley values correspond to the cases in which the second PGM mirror does not work for the polarized neutron.

The change of the counting rates as a function of the relative angles were obtained from the time spectra of Fig.5 by replotting the counting rates at the fixed flight time which corresponds to the condition of the delayed choice as a function of the relative angles. The results are shown in Fig 6.

Interference fringes were obtained in case of which the second magnetic mirror is to be for the neutron (the upper bunch of curves), and the interference fringes diminished in case of which the second magnetic mirror is not to be for the neutron (the lower bunch of curves) although the trigger to the TOF spectrometer is switched on after the neutrons had passed the first composite mirror (on the condition of the delayed choice). This suggests the evidence of the wave like property of the neutron.

Although measurements are not satisfactory from the viewpoint of the statistical accuracy, the feasibility of the PGM cold neutron pulser to the delayed choice experiment was shown.

Fig. 5 shows also the performance of the cold neutron pulser. The rising time of the neutron pulse is about 0.5 ms and some small fluctuations are still seen.

We now try to diminish the fluctuation of the current pulse flowing into the pulsing magnetic coil and decrease the rising time of the neutron pulse down to 100 μs.

§.4. Concluding remarks

A neutron pulse was obtained by applying a pulsed magnetic field of about 30 Gauss parallel to the Permalloy/Ge multilayer (PGM) cold neutron mirror. The pulse rise time was about 300 μs but the fluctuation with a gorge was observed. Other results are as follows: (1) the pulse contrast of the neutron beam reflected from the cold neutron pulser increased reasonably by another reflection through the analyzing mirror placed behind the cold neutron pulser; (2) one of countermeasures to improve the pulse contrast was to limit the zero field region to avoid the adiabatic spin flip.

The PGM was used as a part of the composite neutron mirror used in the delayed choice experiment. The results show the feasibility of the PGM cold neutron pulser to the delayed choice experiment. The rising time of the neutron pulse was about 0.5 ms and some small fluctuations were still seen.

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