ICANS-XI International Collaboration on Advanced Neutron Sources
KEK, Tsukuba, October 22-26, 1990

Crosscorrelation Method Using a Pulsed White Polarized Neutron Beam

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The application of the crosscorrelation method on a pulsed white polarized neutron beam is discussed. The key to the method is to modulate the polarization of the incident neutron beam according to a pseudorandom binary sequence and to count the scattering events by using a two dimensional time analyzer. Based on this technique, the measurement of spin wave excitations in the ferromagnetic Heusler alloy Cu_2MnAl was performed on the PEN spectrometer at KENS, KEK. The experimental result shows that the combination of the pulsed white polarized neutron beam with the crosscorrelation method with polarization modulation is quite promising for the study of the magnetic response in various materials.

I. Introduction

Polarized neutron technique is a powerful tool for studying magnetism. It has been mainly developed for the monochromatic polarized neutron beams in steady state reactors. In implementing the polarized neutron technique at a pulsed neutron beam, it is especially important to utilize as many neutrons as possible, that is, to polarize incident neutrons in a broad energy band and to utilize all of them. The combination of the filter type polarizer and the crosscorrelation method at pulsed neutron sources is expected to be a good approximation to it.

Crosscorrelation methods were firstly applied to neutron spectrometry at steady state reactors, where the monochromatic incident neutron beam is modulated in time according to a pseudorandom binary sequence (PRBS) using a disk type chopper[1] or a spin flipper chopper[2]. The conventional TOF spectrum is recovered by crosscorrelation of the count rate at detector with the modulating sequence. This method was soon applied to the unpolarized white neutron beam in a pulsed reactor using a classical statistical chopper[3]. The technique can be extended to polarized white neutron beam in pulsed neutron source, where the polarization of the incident neutron beam is modulated by using a spin flipper chopper whose driving current is modulated according to a PRBS.[4] The aim of the present work is to show the feasibility of this technique.The principle of the method is briefly described in the next section.

II. Principle of the Method

The polarization of the pulsed incident neutron beam is modulated by using a spin flipper coil whose driving current is modulated according to a PRBS $\{S_i\}$ of period L, where $S_i = 0$ or 1, which correspond to the neutron polarization anti-parallel or parallel to the guide field, and $S_{i+L} = S_i$. The sequence $\{S_i\}$ has the following auto correlation function:

$$a_j = \sum_{i=1}^{L} s_i \cdot s_{i+j-1} = \begin{cases} K & (j=1, L+1, \ldots) \\ cK & (\text{otherwise}) \end{cases} \qquad (1)$$

where $K = \sum_{i=1}^{L} s_i$, and $c = \frac{K-1}{L-1}$.

The polarization modulation is so controlled that the PRBS pattern shifts by a step cyclically at each sequential counting frame triggered by the neutron burst. The procedure continues until one cycle shift of the PRBS is finished, and then it repeats a new sequence of the counting of scattered neutrons. In this way, the scattered neutron events are counted in a two-dimensional time analyzer, one time label of which is the total TOF t_m and the other is the counting frame number j $(=1,\cdots,L)$ which corresponds to the shift number of the PRBS. Then, the count rate $I_{j,m}$ is expressed as:

$$\begin{aligned} I_{j,m} &= \sum_{i=1}^{L}\{I^{p}_{i,m}\cdot(\frac{1-P_i}{2}+P_i s_{i+j-1}) + I^{a}_{i,m}\cdot(\frac{1+P_i}{2}-P_i s_{i+j-1})\} + b_m \\ &= \frac{1}{2}\sum_{i=1}^{L}P_i\cdot I^{d}_{i,m}\cdot(2s_{i+j-1}-1) + \frac{1}{2}T_m+b_m, \end{aligned} \tag{2}$$

where P_i is the absolute value of the polarization of neutrons at the incident time channel i, and $I^{d}_{i,m} = I^{p}_{i,m} - I^{a}_{i,m}$ and $T_m = \sum_{i=1}^{L}(I^{p}_{i,m} + I^{a}_{i,m})$ with

$$I^{p}_{i,m} = \int_{t_i}^{t_i+\Delta t} dt_1 \int_{t_m}^{t_m+\delta t} dt\ \sigma_p(t_1,t) \text{ and } I^{a}_{i,m} = \int_{t_i}^{t_i+\Delta t} dt_1 \int_{t_m}^{t_m+\delta t} dt\ \sigma_a(t_1,t). \tag{3}$$

$I^{p}_{i,m}$ and $I^{a}_{i,m}$ correspond to the count rates at the total time of flight channel $(t_m, t_m+\delta t)$ for the incident neutrons with parallel and anti-parallel polarization, respectively, and with incident time within $(t_i, t_i+\Delta t)$. σ_a and σ_p represent the corresponding cross sections:

$$\begin{aligned} \sigma_p(t_1,t) &= J\left(\frac{d^2\sigma^{++}}{d\Omega dE'}+\frac{d^2\sigma^{+-}}{d\Omega dE'}\right), \\ \sigma_a(t_1,t) &= J\left(\frac{d^2\sigma^{--}}{d\Omega dE'}+\frac{d^2\sigma^{-+}}{d\Omega dE'}\right), \end{aligned} \tag{4}$$

where the signs indicate the spin states of incident and scattered neutrons, and $J = \partial E'/\partial t$. b_m is the instrument background. In Eq.(3), the effects of the incident neutron pulse shape, the spin-flipper pulse shape and other time uncertainties are not included for the sake of simplicity. Such effects can be included by convoluting appropriate shape functions.

The crosscorrelation of the count rate $I_{j,m}$ with the PRBS pattern gives:

$$\begin{aligned} C_{k,m} &= \sum_{j=1}^{L}s_{j+k-1}I_{j,m} = \sum_{j=1}^{L}s_{j+k-1}[\sum_{i=1}^{L}\{\frac{1}{2}P_i\cdot I^{d}_{i,m}(2s_{i+j-1}-1)\}+\frac{1}{2}T_m+b_m] \\ &= (1-c)K\cdot P_k\cdot I^{d}_{k,m} + \frac{1}{2}(2c-1)K\sum_{i=1}^{L}P_i\cdot I^{d}_{i,m} + K(\frac{1}{2}T_m+b_m). \end{aligned} \tag{5}$$

The first term in the right hand side of Eq.(5) is proportional to the spectrum $I^{d}_{k,m}$. The second and third terms depend only on the total TOF channel number m, and give otherwise flat background. Therefore, the first term can be easily discriminated from the others. The recovered value $I^{d}_{k,m}$ gives direct information on the magnetic inelastic scattering with incident time t_k and total TOF t_m.

III. Experiments

As an example of the application of the present technique, the observation of spin wave scattering from a ferromagnet is described here. If the magnetization of the ferromagnet is parallel to the scattering vector, the cross section of spin wave scattering is described as:

$$\frac{d^2\sigma^{\pm\mp}}{d\Omega dE'} \propto \delta(\hbar\omega \mp E_q), \tag{6}$$

where the upper and lower signs correspond to the spin wave creation and annihilation processes, respectively. Therefore, it is possible to observe the spin wave scattering by this technique with no use of spin analyzer in the scattered beam.

A neutron spin flipper system and a two dimensional time analyzer were constructed for the present work. The flipper coil is made of aluminum wire (diameter 0.6 mm) and its size is 7 x 4 x 1 cm^3. The inductance of the coil was about 100 μH. The direction of the field (along the longest edge of the coil) is perpendicular to both the neutron beam and the guide field in which the coil is placed. The guide field inside the coil is canceled by using another coil which is wound on the flipper coil along its second longer edge. The intensity of the driving current for the flipper coil is controlled to be proportional to the $1/t$ relation, where t is the time from each neutron burst, so that a 180 degree flip of the neutron spin is ensured for any incident neutron energy. The maximum current was about 3 A. The current is then switched on and off according to a PRBS. The time constant of the flipper coil circuit was τ=3 μs. The timing of switching is given by a module which generates the PRBS pattern which shifts by one step at each frame of neutron burst. The scattered neutron events are counted in the memories in the two dimensional time analyzer system according to their total time of flight and frame number.

The polarized neutron scattering experiments were carried out on the PEN spectrometer at the spallation neutron source KENS at KEK. The spectrometer produces polarized white neutrons by passing the neutrons through a dynamically polarized proton filter. Typical neutron polarizations obtained by the spectrometer are 90 % at 100 meV and 70 % at 1 eV. Details of the spectrometer are described elsewhere.[5)]

The experimental setup is shown schematically in Fig.1. The sample was a single crystal of ferromagnetic Heusler alloy Cu_2MnAl, the size of which is 3 x 2 x 0.8 cm^3. The sample position from the neutron source was 6.98 m. The crystal was so oriented that the [111] reciprocal lattice

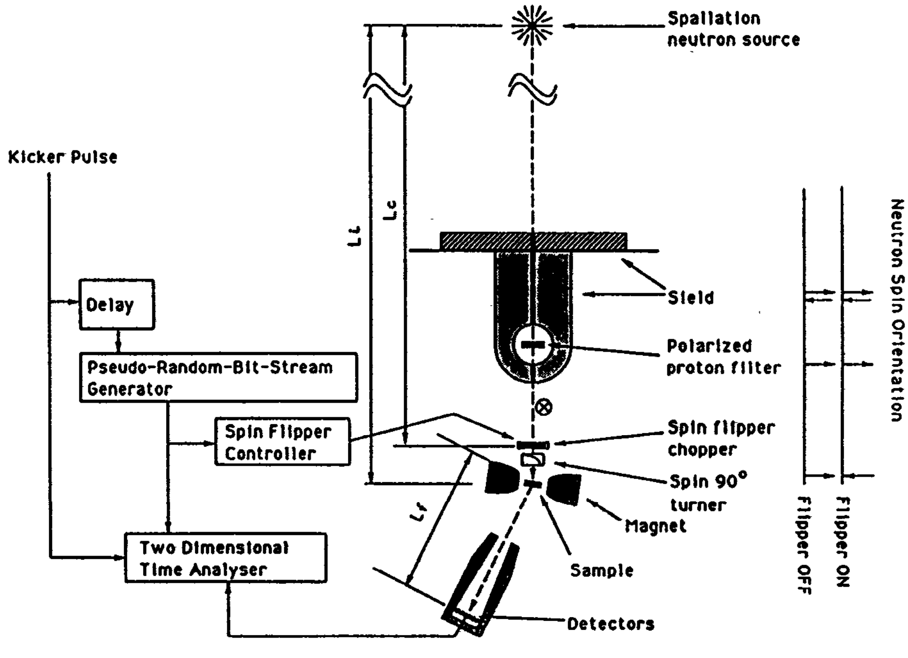

Fig.1 Experimental setup of the crosscorrelation method at the KENS pulsed neutron source.

vector coincided with the scattering vector of neutrons with initial and final energies of 50 and 42 meV, respectively, for the detector with the scattering angle of 21.8 degrees. The scattering configuration is shown in Fig.2. A magnetic field of 1 T was applied to the sample along the reciprocal lattice vector. Therefore scattering with an energy loss of about 10 meV is expected to be observed on the dispersion surface of the spin wave excitation, that is, $D(\kappa-\tau)^2$, where D is the spin wave stiffness constant (175 meVÅ^2 for Cu_2MnAl), κ is the scattering vector and τ is the (111) reciprocal lattice vector. Since the magnetization of the sample is almost parallel to the scattering vector, only those incident neutrons whose polarization is parallel to the magnetization are scattered. Therefore, the difference spectrum around $\hbar\omega$~10 meV corresponds to the spin wave creation process. The flipper coil was placed 53 cm upstream from the sample. The polarization of incident neutrons with the energy from 33 to 78 meV was modulated by the spin flipper according to a PRBS of 31 steps after a delay of 1635 µs from neutron burst. The time unit of the sequence was 30 µs. The scattered neutrons were detected by six ^3He detectors which are placed at a distance of 1.5 m from the sample and separated each together by about 1 degree. As an example, Fig.3 shows the raw data $I_{j,m}$ with the frame number j=15 at the detector 3 (2θ=21.8 degrees).

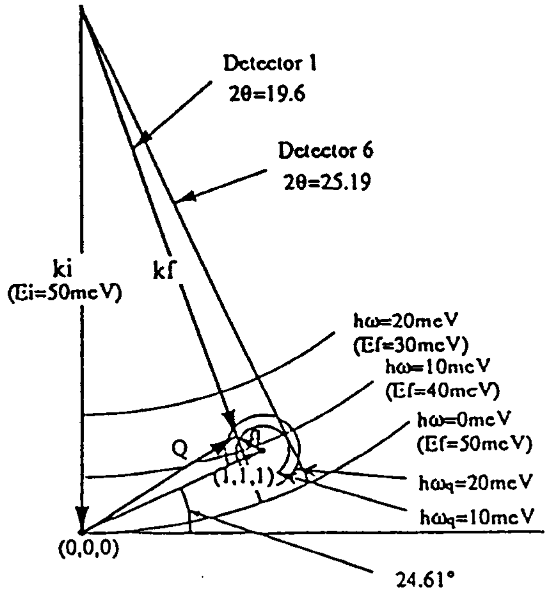

Fig.2 Scattering configration in the reciprocal space. Only the case of the neutrons with the incident energy of 50 meV is shown.

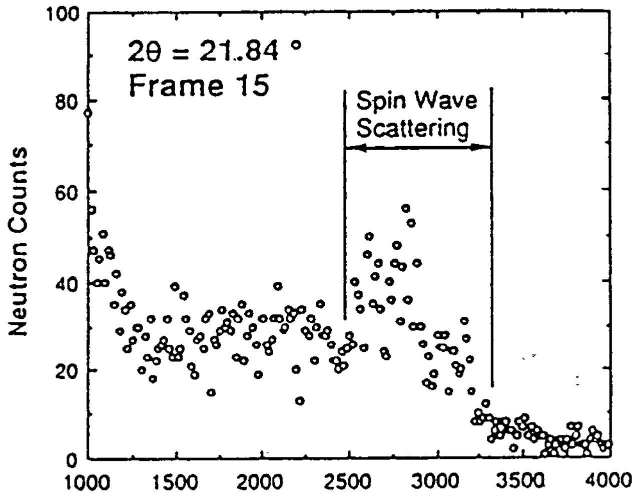

Fig.3 Raw data at scattering angle of 21.84 degrees and frame number of 15.

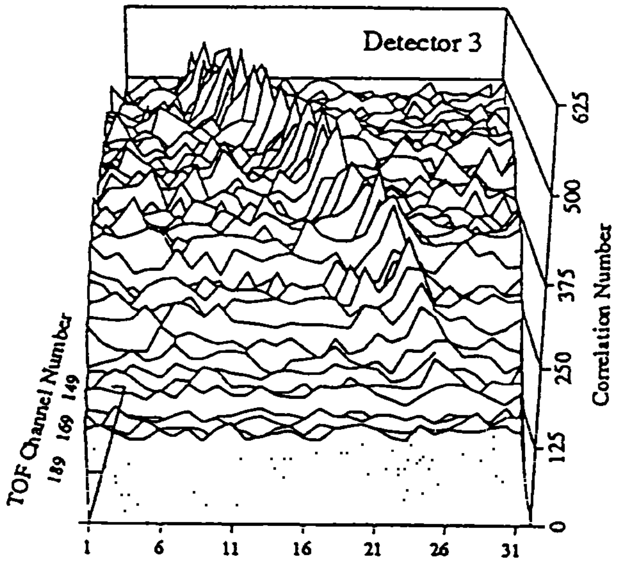

Fig.4 Result of the crosscorrelation of the count rates at the detector 3 (2θ=21.84°).

Fig.4 shows the correlation number $C_{k,m}$ obtained from crosscorrelation of the count rate $I_{j,m}$ at the detector 3 with the PRBS patterns. The channel width for total TOF was 16 µs. The spin chopper channel number k of $C_{k,m}$ corresponds to the incident time t_1 at the sample with the relation $t_1 = 6.98/6.45\cdot(1635 + 30\,k)$ µs. The ridge-like increase of the correlation number seen in the figure comes from the spin wave scattering. In order to see this more clearly, the data at total TOF from

170 to 174 channels are plotted as a function of energy transfer in Fig.5. Since their loci of the inelastic scans in the scattering plane are close each together and cross the dispersion surface twice, the scattering is expected to occur at two energy transfers, that is, around 5 and 14 meV. Although the energy resolution is not high and the counting statistics are rather low, a clear peak at around 5 meV and a hump at around 14 meV are visible in the figure. The reason that only the peak at 5 meV is distinct is due to the difference of the temperature factors between the two peaks. The solid line shows the result of a simulation of the spin wave scattering in the present configuration. In the simulation, neutron pulse shape at the moderator and time uncertainty at the spin flipper were taken into account. It can be seen that the observed spectrum is in good agreement with that of the simulation. Nearly the same results were obtained for the other data with total TOF from about 140 to 200 channels. This means that the spin wave scattering was observed with incident neutrons whose energies ranged from about 40 to 70 meV. It is in good agreement with our expectations under these scattering conditions. Almost same results are obtained for the other detectors. Of course, their positions of the spin wave ridges are shifted according to their scattering angles.

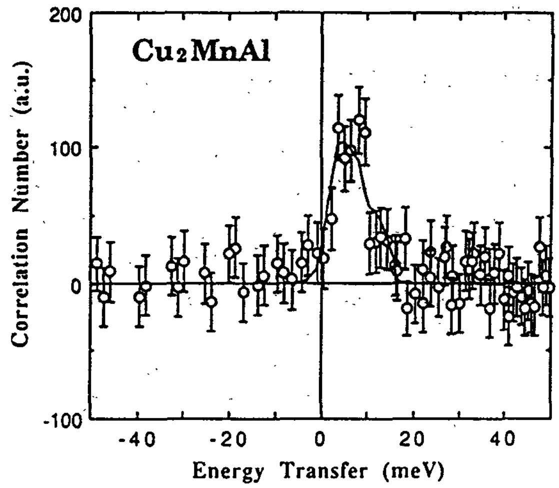

Fig.5 Example of spin wave spectrum of Cu_2MnAl obtained by the crosscorrelation method. Solid curve shows the result of the simulation.

IV. Discussion

The result of the present experiment shows that the combination of pulsed polarized white neutron beam with the crosscorrelation method with polarization modulation is quite promising for the study of the magnetic excitations or fluctuations in various magnetic materials. The resolution of the present spectrometry is determined by incident neutron pulse shape, spin flipper pulse shape and neutron flight lengths. Therefore, it can be discussed on the same basis as in the case of the conventional chopper type spectrometer. In the present experiment, the energy resolution dE/E_i was about 12 % at the incident and final energies of 50 and 40 meV, respectively. However, there is no difficulty to improve the resolution to the order of a few % if neutron source intensity permits; for example, if the time unit of modulation sequence, incident and final flight lengths are chosen to be moderate values of 10 μs, 11 m and 4 m, respectively, the resolution is expected to be 2 %.

In the present experimental configuration, no spin analyzer was used in the scattered beam. Therefore, the present technique is applied only for the measurement of spin wave excitations in ferromagnet. The equipment with spin analyzer in the scattered beam gives the full power to the technique. It allows the measurement of all kind of magnetic excitations such as the spin wave excitations, paramagnetic spin fluctuations, or crystal field excitations. The technique to make difference between spectra of vertical and horizontal field arrangements is also useful in this case. By using a broad energy band spin analyzer in the scattered beam, the crosscorrelation technique allows a dense mapping in momentum-energy space of magnetic dynamical response in a single measurement, as demonstrated by the present experiment. The spin analyzer should, of course, work in a energy band as wide as that of the polarizer. The dynamically polarized proton filter, however, is not suitable for this purpose because it is technically difficult to cover wide solid angle in the scattered beam. Therefore, although the energy band available is not so wide as the polarized proton filter, the resonance absorption filter would be a better choice in the thermal and epithermal energy region. In order to obtain results with good resolution an intense pulsed neutron source is required of course.

In summary, the technique using the crosscorrelation method with polarization modulation in pulsed polarized white neutron beam has been shown to be feasible. The combination of the technique with intense pulsed neutron source and broad energy band polarizer provides a unique and powerful tool in the study of the dynamics in magnetic materials.

References

1) F. Gompf, W. Reichardt, W. Glaser and K.H. Beckurts, Neutron Inelastic Scattering (proc. Symp. Copenhagen, 1968) 2, IAEA, Vienna (1968)417.
2) L. Pál, N. Kroó, P. Pellionisz, F. Szlávik and I. Vizi, ibid. 407.
3) N. Kroó, P. Pellionisz, I. Vizi, G. Zsigmond, G. Zhukov and G. Nagy, IAEA Symp. on Neutron Inelastic Scattering (1972), IAEA/SM-155/F-6.
4) R. Cywinski and W. G. Williams, Nucl. Instr. and Meth. 228(1985)406. For the principles of the crosscorrelation method, see also the references herein.
5) M. Ishida, Y. Ishikawa, S. Ishimoto, M. Kohgi, A. Masaike, Y. Masuda, K. Morimoto and T. Nakajima, Proceedings of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources, RAL-85-110(1985)612.

Q(W.G.Williams): What is the rise time for switching on the spin flipper and how does this compare with the typical flipper on time?

A(M.Kohgi): The inductance and resistance of our flipper coil circuit is about 100μH and 30Ω,respectively. Therefore, the time constant of the circuit is t=3μsec. There is no technical difficulty to decrease the value to about 1μ sec. For faster spin chopper, see, for example, Y.Itoh and S. Takahashi, Nucl. Instr. Method 221 (1984) 490.