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Progress on POLANO spectrometer for polarized neutron experiment

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Abstract. A joint project between KEK and Tohoku University was initiated with the aim of future construction of a polarized neutron spectrometer at the Materials and Life Science Experimental Facility (MLF), J-PARC and research program for functional magnetic materials in 2009. Our principal concept is to achieve higher-energy polarization analysis of inelastic scattering beyond a reactor-based neutron source. We target the energy range up to $\Delta E =$ 40 meV with using SEOP for polarizer and bender supermirror as an analyzer of $m = 5$ to 5.5 as the first step. In the second step, we focus on higher energy experiments (0 meV $< \Delta E <$ 100 meV) with a large change of its layout. The basic shield designing has been completed and shielding capability of radiation was assessed. Also, the designs of the beam transport section using $m = 4$ supermirror guide tubes are completed. In order to achieve a high flux polarized neutron experiment, we plan to adopt cross correlation method. R&D of the correlation chopper is now under way.

1. Introduction

The success of the chopper spectrometer MARI applied to materials science at the ISIS neutron facility [1], has highlighted the importance of the so-called chopper spectrometers to neutron beam line instruments. At the Japan Proton Accelerator Research Complex (J-PARC), the Materials and Life Science Experimental Facility (MLF) is a newly constructed world leading pulse neutron experimental facility, where three chopper-type spectrometers are now part of the research program. One of the remaining technical issues that should be realized in MLF is the use of a polarization neutron technique with a pulsed neutron beam. Although the polarized neutron technique has been developed and used for many years, the application of the time-of-flight (TOF) method has only been realized in recent years. In particular, with regard to the inelastic spectrometer, the polarized neutron technique finds limited practical use in wide scattering angle instruments. Some of elastic neutron instruments such as a small angle scattering instrument, a reflectometer, a single crystal diffractometer and an imaging instrument plan to use polarized neutron technique option but is not planned for the instruments dedicating the inelastic scattering yet. In the light of recent discoveries in material science, many of the observed complex phenomena are largely due to the entangled physical degrees of freedom of spins, charges, orbitals, and even lattice vibration. In neutron scattering experiments, the varying dependence of momentum, energy, and temperature can be interpreted by these of degrees of freedoms. However, a unique, effective, and direct way to observe these properties separately is via the polarization analysis. Thus, the polarized neutron experiments are quite significant for material science particularly for research on magnetism, hydrogen materials, and strongly correlated electron systems with multiple physical degrees of freedom.

A joint project between the Institute of Materials Structure Science (IMSS), KEK and the Institute of Material Research (IMR) of Tohoku University under the aegis of KEK Inter-University Research Program was initiated with the aim of future construction of the forthcoming spectrometer which enables us the inelastic polarization analysis and research program for functional magnetic materials. The project has been launched in 2009 starting as an S-type project with financial support from the KENS neutron facility. After the budget was successfully sanctioned and obtained for the project, actual construction has begun in 2013.

Our principal concept is to achieve higher-energy polarization analysis of inelastic scattering beyond a reactor-based neutron source. The suite of inelastic spectrometers involving an inverted geometry spectrometer and a spin-echo instrument in MLF can cover a relatively wide area in momentum (Q) and energy (E) space with various Q and E resolutions. Slow dynamics in soft matter to electron band excitation are targeted in the wide dynamical range of 10^{-9} eV $\leq E \leq 2\times10^{0}$ eV. For detailed dynamical studies of advanced material science, polarization analysis is an inevitable technique in addition to the wide Q-E coverage. Hence, we propose a chopper-type polarized neutron spectrometer POLANO which enables us to carry out inelastic experiments with reasonable intensity for research of dynamical properties in materials.

2. Geometrical Condition

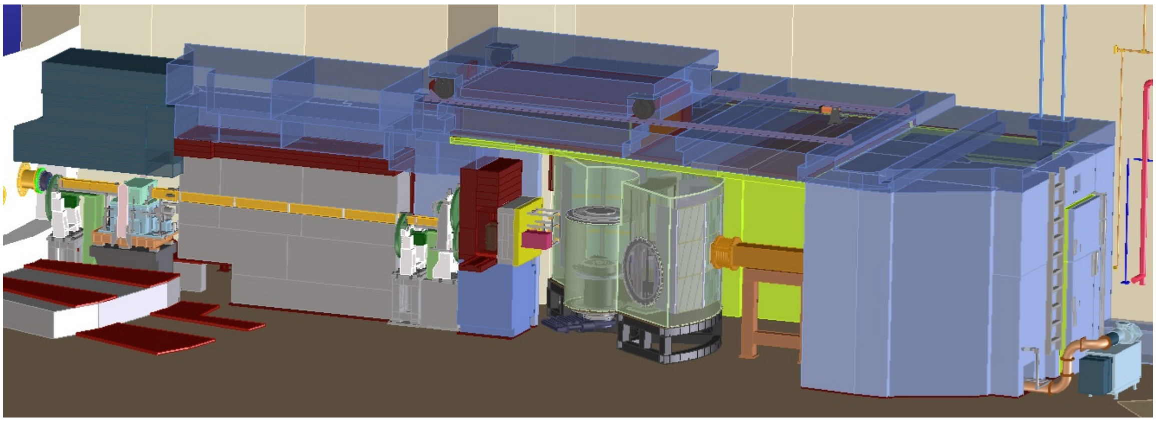

Figure 1. Schematic view of POLANO spectrometer

Schematic view of POLANO spectrometer is depicted in Fig. 1 and the instrumental parameters of POLANO were listed in Table 1 [2]-[4]. Some parameters were revised from Ref. [2]. E_i and k_i denote incident neutron energy and wave number of incident neutron, respectively in the table. The design features of POLANO are compactness with reasonably wide sample space design, higher neutron flux, higher neutron energy polarization up to 100∼150 meV, and medium resolution. The geometrical lengths were chosen as L_1 = 17.5 m (moderator-sample distance), L_2 = 2.0 m (sample-detector distance), and L_3 = 1.85 m (Fermi chopper-sample distance). We used a slightly shorter distance in L_2 from Ref. [2], but the energy and momentum resolution are not significantly affected.

Table 1. Basic instrumental parameters in POLANO

Parameters	
beam port	beam line 23 (BL23)
moderator	H_2 decoupled
L_1 (moderator-sample distance)	17.5 m
L_2 (sample-detector distance)	2.0 m
L_3 (Fermi chopper-sample distance)	1.85 m
energy resolution $\Delta E/E_i$	3∼5% at elastic position
momentum resolution $\Delta Q/k_i$	1∼2%
sample size	20 × 20 mm
detector angle (horizontal)	3° ∼120°
detector angle (vertical)	-7° ∼7°

3. Shielding

The shielding design was evaluated based on γ and neutron ray tracing by using the Monte Carlo PHITS code. Figure 2 shows an example of the calculated γ and neutron dose distribution about the designed beam line and main shielding. The POLANO is viewing a decoupled moderator that is one of three types of hydrogen moderators (coupled, decoupled and poisoned), and the view of the moderator is 10 cm square of cross section. A radiation dosage of less than 6.25 μSv/h of surface dose was achieved with concrete, steel and boric acid as shielding materials.

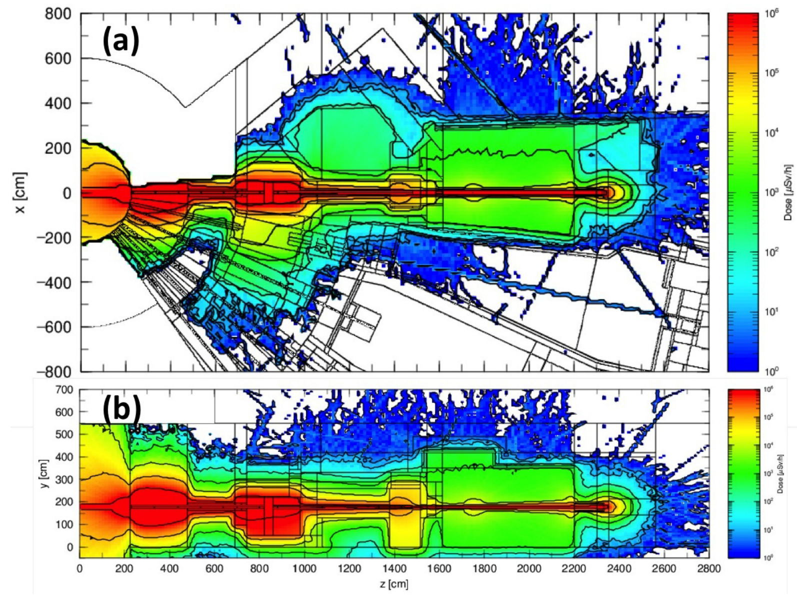

Figure 2. Typical calculated result of ray tracing Monte Carlo simulation. The sum of the γ-ray and neutron doses is mapped as a contour plot for both of top view (a) and side view (b). The neutron source is beam line BL23 viewing decoupled moderator of the MLF.

In certain parts of the shielding in the vicinity of the sample space, stainless steel was used as a non-magnetic material in order to make possible the conduction of high-magnetic field experiments. Two entrances are located at the back of the instrument and at the top of the shielding (roof) with personnel protection system (PPS) on each entrance. The PPS is the safety inter lock system involving shutter controller, emergency stopping system and door controller. The top entrance hatch is massive concrete shielding of 26 ton is electronically controlled its opening and closing by sliding on the rail.

4. Beam Transport

The 23rd beam line, where POLANO is installed, is viewing decoupled moderator with a known pulse width of $\Delta t_m = a/\sqrt{E_i}$ with a=2.5 for decoupled moderator. After moderator neutrons are transported by $m = 4$ supermirror guide tubes optimized for 110$\sim$120 meV neutron intensity [2, 3] with a McStas simulation [5, 6]. An elliptical guide optimized section by section (section length = 50 cm) can yield a neutron flux of 3.9×10^5 [n/(sec·meV·cm^2·MW)], which is almost comparable with a coupled moderator beam line at $E \sim$100 meV. The finally designed view of the guide tube is illustrated in Fig. 3. We tested several neutron energies to be optimized, namely, the range of 20-30 meV, 60-70 meV and 110-120 meV. Additionally, the evaluated neutron flux is plotted in Fig 4 as a function of neutron energy. Since the focusing guide

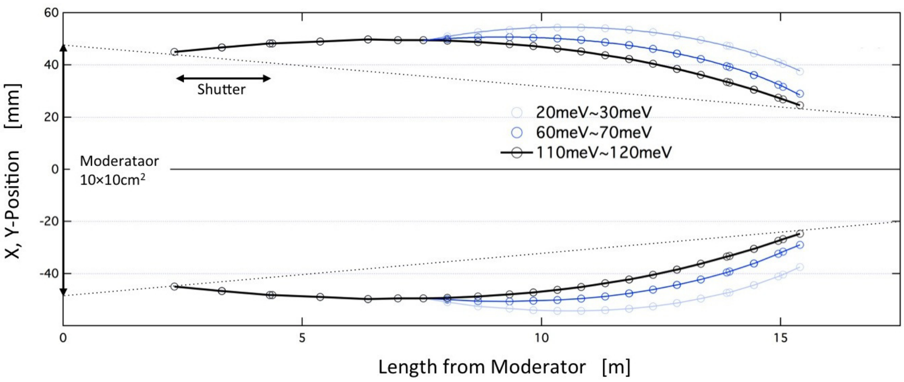

Figure 3. Evaluated guide tube cross section optimized for neutron energies 20-30 meV (light blue symbol), for 60-70 meV (blue symbol) and 110-120 meV (black symbol). Cited from Ref. [3]

tubes affect beam divergence, we estimate the beam profile as well. Figure 5 shows the intensity distribution at $L = 16.435$ m from the moderator, where a SEOP ^{3}He filter cell will be placed. The beam width at the ^{3}He filter has a full width of 8 cm at the bottom, and 4 cm at the half height. In the early stage, ^{3}He cells with a diameter of 5 cm will be used because the ^{3}He polarizing technique has already been established for 5 cm cells. Since cells with a diameter of 10 cm have now been developed, the beam exiting the polarizer will be almost fully polarized in the final stage.

Figure 6 depicts the neutron beam flux observed in an area of 2 × 2 cm^2 after the beam passed through a Fermi chopper rotating at frequencies at 200, 400 and 600 Hz. The dimensions of the Fermi chopper are rotor diameter D=80 mm, slit width d = 2 mm, and curvature radius r = 450 mm with a transmission efficiency of 0.8 as shown in Fig 7. Since POLANO is aimed at the incident neutron energy range up to E_i = 100 meV, the evaluated intensity and resolution below 100 meV are reasonable for the polarization analysis experiments. Further, to estimate the energy resolution, a vanadium cylinder with outer radius of 12.5 mm inner radius of 12 mm and height of 4 cm was set at the sample position. An energy resolution of 4$\sim$5% can be obtained below 100 meV with the integrated intensity over 1×10^5 [1/s/cm^2] at the sample position for an accelerator power of 1 MW as shown in Fig. 6(b).

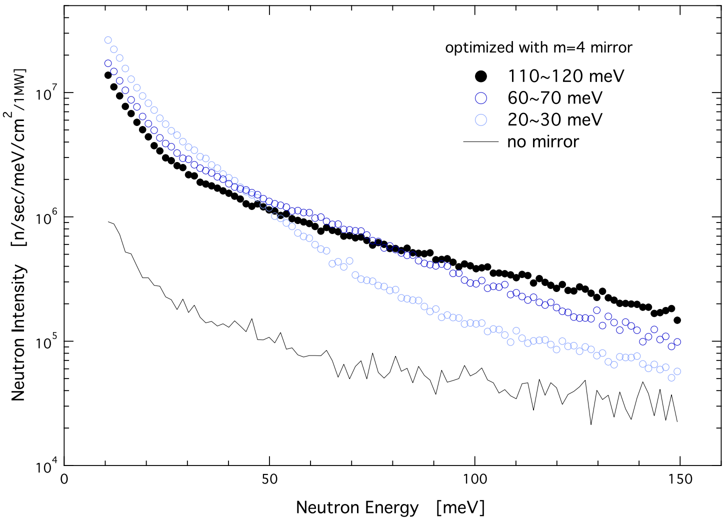

Figure 4. Simulated results of the effect of guide tubes by McStas. The m = 4 mirror is used to optimize for several neutron energies. 20-30 meV (light blue symbol), 60-70 meV (blue symbol) and 110-120 meV (black symbol) from Ref. [3].

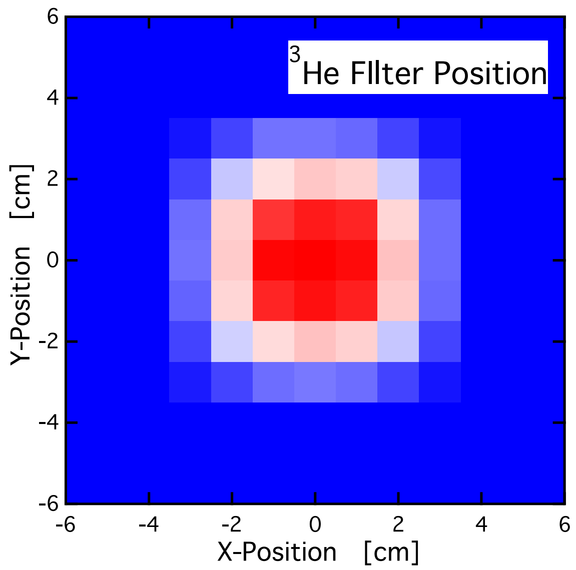

Figure 5. Neutron flux distribution at the ^{3}He SEOP cell position.

5. Mechanical Choppers

Below the exit of a biological shield, several types of choppers are placed. T0 chopper is the first chopper to eliminate fast and epithermal neutrons with a massive metal blade rotating with a maximum speed of 100 Hz. This is originally developed as a MLF standard [7]. The blade is made of Inconel X750, which is known for having high strength without using radiological elements with long lives such as cobalt. Though the weight of the blade is over 120 kg, at 100 Hz of rotating speed, less than $\pm 5\ \mu$s of jitter (phase control accuracy) was achieved.

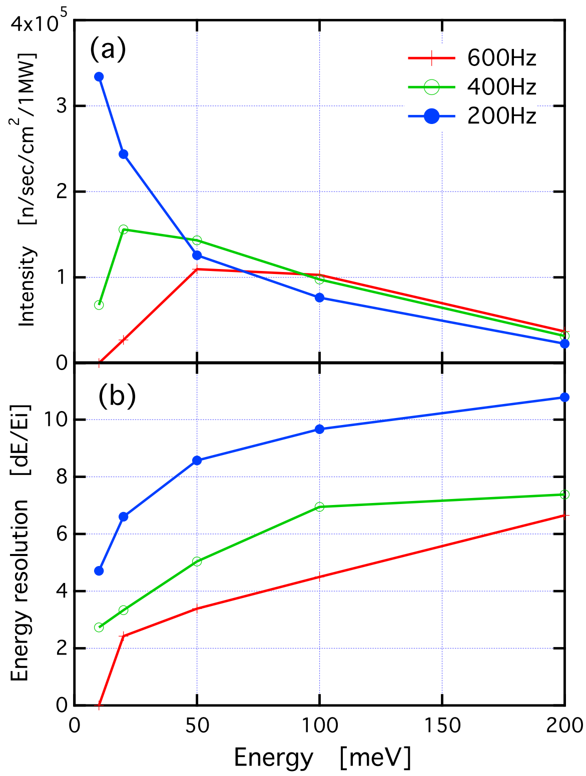

Figure 6. (a) Neutron intensity and (b) energy resolution estimation by McStas. monochromatized beam obtained by a Fermi chopper rotating at 200, 400, 600 Hz is used. Cited from Ref. [4].

In order to avoid the frame overlap of a 25 Hz proton (neutron) pulse in MLF, a slow rotating disk chopper will be installed in the beam line. Two disk choppers synchronized with neutron pulse are placed at $L = 7.5$ and 13.9 m. A Fermi chopper will be used for monochromatizing the incoming neutron energy. It is the same type of Fermi chopper developed for High Resolution Chopper spectrometer in MLF [8], which has a 600 Hz maximum speed with 0.3 μs jitter enabling high resolution and transmission experiments.

For more effective measurements, we adopt the cross correlation method that utilizes multiple wavelengths of neutrons for one inelastic measurement. Hence, we have intensity gains of a factor of ten or higher in principle. A special type of disk chopper (correlation chopper) is required to realize this correlation method. The disk diameter is ideally over 1000 mm with a rotational speed of 350 Hz. Additionally, 255 (2^N-1) open and close sequences are required to be on the disk [9]. These conditions are mechanically quite difficult to realize because the maximum stress evaluated is almost 4000 MPa at the edge of the rotating disk. Totally new designing of the disks is now under way with carbon fiber reinforced plastic (CFRP) materials to realize a mechanically rotating correlation chopper.

6. Vacuum chamber and detectors

A vacuum chamber is to be installed at the sample-detector section to avoid air scattering and to ensure evacuated insulation for the refrigerator. Figure 8 shows the design of the vacuum chamber. To ensure flexible use of the sample space, the chamber is designed to be detachable,

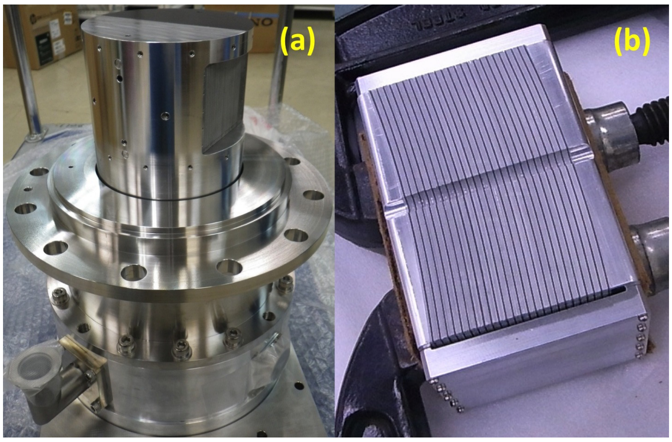

Figure 7. (a) The rotor of Fermi chopper installed in POLANO. (b) Slit package

and it is composed of three parts. The sample chamber is the first chamber, in which the sample is placed and the sample environments are set. The second is a connecting chamber that connects the sample chamber and scattering chamber. Both the sample and scattering chambers are sealed by thin (t=1.5/2.0 mm) aluminum windows, and the chambers are completely isolated from air. Certain magnetic devices such as the spin flipper (positioned after the sample) will be installed in this section. The third is the scattering chamber wherein the suite of analyzer mirror and detectors are placed. In addition, B_4C vanes and liners are planned to be installed in the chamber [4].

At the end of the scattering chamber, position sensitive detectors (PSDs) are to be installed on the inside of the chamber. For energy range of the POLANO, large pressure of ^{3}He gas is not required to achieve reasonable detector efficiency. Therefore, we adopted the use of a 10 atm gas pressure PSD with 600 mm effective length and 3/4 inches of diameter. An efficiency of about 70% is expected for 100 meV neutrons. The PSDs are arranged in three layers in the vacuum chamber. The horizontal scattering angle (detector angle) ranges from -30° to 130°, and the range is ±25° along the vertical direction. At first, only horizontal (center) layers are to be fully installed for polarization analysis experiments. The detectable vertical angle is ±8°.

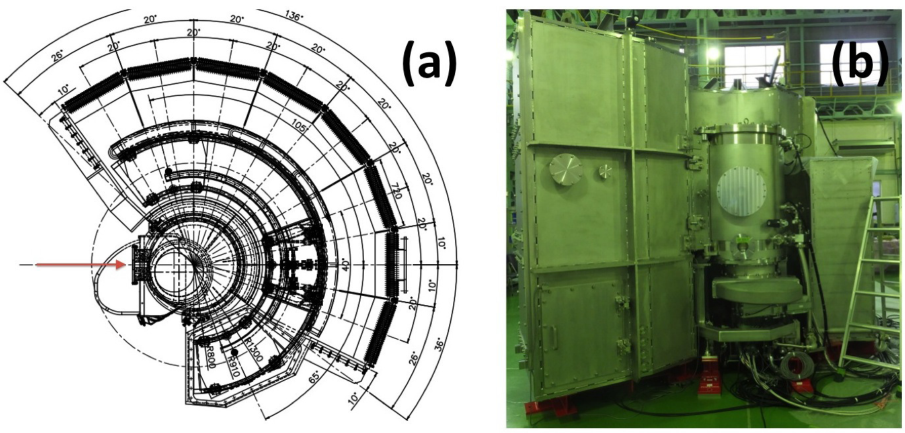

Figure 8. (a) Top view drawing of the vacuum chamber. Neutron beam is injected from lift along red arrow. (b) View of the manufactured vacuum chamber from the front.

7. Polarization Devices

The polarizer, analyzer, and other magnetic devices installed in the POLANO are currently under development [10, 11]. As the polarizer, a cylindrical ^{3}He spin filter (HeSF) based on the spin-exchange optical pumping (SEOP) technique will be used to polarize neutrons in the wide energy range. During the experiments, the HeSF is operated in the on-beam mode to maintain ^{3}He polarization. A HeSF with a diameter of 3 cm will be installed in the POLANO in the spring of 2015. HeSF systems with larger diameters (5 to7 cm) are now under development. We have already succeeded in preparing a GE180 cell with a diameter of 10 cm.

One of the serious technical issues affecting POLANO is the choice of a spin analyzer with a large solid angle. Since the technology concerning polarized ^{3}He in GE180 glass cells with "large solid angles" is not currently available in Japan, a phased approach needs to be adopted for the spin analyzer to be used in POLANO. In the first stage, a 5.5 Q_c supermirror bender analyzer with a covered scattering angle of about 18° will be installed on a rotatable stand around the sample because it is most practical in the thermal neutron range. The distance between the sample and the aperture of the supermirror will be 850 mm. The 5.5 Q_c supermirror can cover up to $E_f \sim 40$ meV, corresponding to an energy excitation range of 50 to 60 meV. This energy range is of great scientific interest, corresponding to phenomena such as spin-lattice couplings in multiferroic systems, geometrical spin frustration systems, and multipole orderings in rare earth compounds. On the other hand, since we have installed a focusing guide tube between the moderator and the Fermi chopper to obtain high flux at the sample position, it is necessary to ensure matching of the angular divergence of the focusing guide tubes and analyzer.

We also keep developing dynamic nuclear polarization (DNP) system. As neutron-proton scattering length of the triplet channel is much smaller than that of the singlet channel [12], the neutron beam transmitted through a polarized proton target gets polarized. A brute force way to polarize sufficient number of protons in the target is applying strong external magnetic field to it and cooling it down to low temperature. However, even if we cool it down to 1 K and apply external magnetic field of 5 T to it, the thermal equilibrium Boltzmann polarization of the protons is less than 1% and the target cannot be used as a practical neutron polarizer. To highly polarize proton spins, we can use the dynamic nuclear polarization (DNP) method. In the above mentioned situation, although the polarization of protons is less than 1%, that of unpaired-electrons is nearly equal to unity as the magnetic moment of electron is much larger than that of proton. To test the enhancement of the proton polarization by this method for several target materials that contain protons and unpaired-electrons and estimate their performance as neutron polarizers, we are preparing instruments for DNP of proton spins.

To cool a target down and apply external magnetic field to it, we use the cryostat that was used by Crabb [13]. The ^{4}He evaporation refrigerator can cool the target down to 1 K and the split coil superconducting magnet can apply the magnetic field of 5 T. To measure the enhancement of the proton polarization, we prepared instruments, which are used in studies of continuous wave nuclear magnetic resonance (CW NMR) spectroscopy. Our system uses a coil that acts as a transmitter of the radio wave that is irradiated to the target and a receiver of the radio wave generated by the target material. When the energy difference between the two proton spin states due to the static magnetic field is equal to the photon energy of the radio wave generated by the coil, the radio wave is absorbed and the amplitude of the reflected voltage from the coil decreases. As this signal depends on the polarization of the protons and the radio wave frequency [14], we can estimate the polarization enhancement by measuring the radio wave frequency dependence on the reflected voltages. To test the CW NMR system, we installed a Teflon sheet, which contains fluorine nucleus whose magnetic moment is 6% smaller than that of proton. We scanned the radio wave frequency over the range around the Larmor frequency of fluorine and observed a clear signal at the expected frequency as shown in Fig 9.

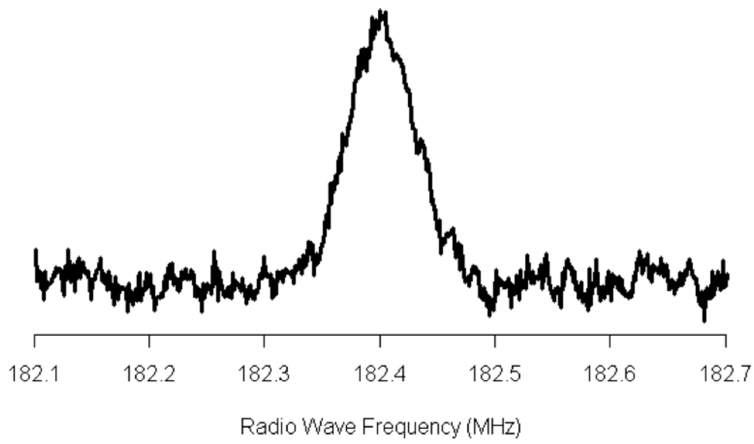

Figure 9. Observed NMR signal of Teflon sheets.

Acknowledgments

This work and POLANO project was approved by the Neutron Scattering Program Advisory Committee of IMSS, KEK (Proposal No. 2009S09 and No.2014S09). The authors TY and SI were partly supported by Grant-in-Aid for Scientific Research (C) (24540352) also TY was supported by Grant-in-Aid for Scientific Research (C) (26400376) from the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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