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COMISSIONING OF THE FERMI-CHOPPER SPECTROMETER 4SEASONS AT J-PARC—BACKGROUND STUDY

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ABSTRACT

Suppressing background scattering is critical especially for an inelastic scattering instrument which observes faint inelastic scattering signals. In this paper, we describe our experience on the background problem and how we investigated its origin on the Fermi-chopper spectrometer 4SEASONS at J-PARC.

1. Introduction

Inelastic neutron scattering technique is very important tool for materials science, because it can directly observe dynamical properties of atoms and spins in samples taking advantage of the fact that a neutron can have a similar energy and a wave length to those of elementary excitations. However, intensity of inelastic scattering is usually very weak, and is in the order of 10^{-4}–10^{-6} compared with that of elastic scattering. In order to observe such a weak signal, improvement of signal-to-noise ratio, in other words, suppression of unwanted scattering (background) is critically important. In this paper, we describe how we investigated origins of the background and tried to suppress them on the Fermi-chopper spectrometer 4SEASONS at Japan Proton Accelerator Research Complex (J-PARC).

2. The Fermi-Chopper Spectrometer 4SEASONS

2.1. Basic Specification

4SEASONS is a Fermi chopper spectrometer for the spallation neutron source in Materials and Life Science Experimental Facility (MLF), J-PARC [1]. It is intended to provide high counting rate up to ~300 meV neutron energy with medium resolution to efficiently collect weak inelastic signals from novel spin and lattice dynamics especially in high-T_c superconductors and related materials. For this purpose, the spectrometer is equipped with advanced instrumental design such as an elliptic-shaped converging neutron guide with high-critical angle supermirrors inside [2], long (2.5 m) position sensitive detectors (PSDs), and a Fermi chopper feasible for multi-incident-energy (multi-E_i) measurement [3,4]. It is installed at BL01 beamline in MLF to see a coupled moderator, which provides a high flux of cold and thermal neutrons [5]. The distances between the moderator and the sample, the sample and the detector, and the Fermi chopper and the sample are 18 m, 2.5 m, 1.7 m, respectively. The spectrometer also has a T0 chopper at 8.5 m, and two disk choppers at 9 m and 12 m downstream the moderator. The spectrometer accepted the first neutron beam on September 2008, and its first inelastic scattering data was produced on June 2009 [4].

2.2. Shielding in 4SEASONS

Figure 1 shows schematic views of 4SEASONS. The neutron guide tube starts at L (distance from the moderator) = 2.3 m and ends at L = 15.8 m. It is housed inside the shutter at L = 2.3–4.3 m and the biological shield at L = 4.3–7.5 m. At L = 7.5–12 m, the neutron guide is under the pre-shield, which is a combination of iron and concrete blocks whose thickness is ~1.8 m in total. At L = 12–16 m, the guide tube is covered with a 360 mm thick iron shield, and a ~1.2 m thick concrete shield surrounds the iron shield. At L = 16.3 m, there is a Fermi chopper. It monochromates the incident neutron beam, and at the same time, it scatters neutrons around it. In order to suppress these unwanted scattered neutrons, the Fermi chopper is surrounded by iron and concrete blocks. The monochromated neutrons are scattered by a sample at L = 18 m, then are detected by 2.5 m tall PSDs installed in a cylindrical arrangement at 2.5 m downstream the sample. PSDs are also installed at and around the direct beam position (scattering angle ~ 0°). To prevent the PSDs from intense incident beam, a 50 mm thick B_4C resin plate (beam catcher) is placed in front of the PSDs. Very high energy neutrons which cannot be stopped by this beam catcher penetrate the PSDs, and then are stopped by a beam dump at ~3.5 m downstream the PSDs. The beam dump is made of very thick iron (~1.2 m thick) and concrete (~1 m thick) to completely stop the high energy neutrons. Both the sample and all the PSDs are inside a large (22 m^3) vacuum chamber. The vacuum chamber is inside a house whose wall is ~70 mm thick concrete except a hatch on the roof through which we access the sample environment.

With the shielding described above, the radiation level outside the shields is low enough to meet the regulation of the facility even when the accelerator power reaches at 1 MW. However, required counting rate of background for an inelastic scattering measurement is much lower than that required for radiation safety. Therefore, we added extra shielding to the instrument. We inserted several thick polyethylene blocks, whose total thickness is 1 m along the beam line, between the neutron guide and the surrounding iron shield to prevent leaked neutrons from propagating to the sample area. We placed B_4C-resin plates right downstream the choppers to suppress scattering of neutrons by the choppers. The inner wall of the vacuum chamber is covered with 20 mm thick B_4C resin plates to suppress scattering of neutrons by the wall. Most of the outer wall of the vacuum chamber is covered with 100–200 mm thick polyethylene plates or polyethylene beads to prevent neutrons coming in from the outside of the chamber. The beam catcher has vanes on its every edge to stop neutrons scattered by its surface. Although these measures were quite effective for suppressing background, we still found unwanted and annoying scattering in our inelastic measurement data. Further efforts to investigate and suppress background are described below.

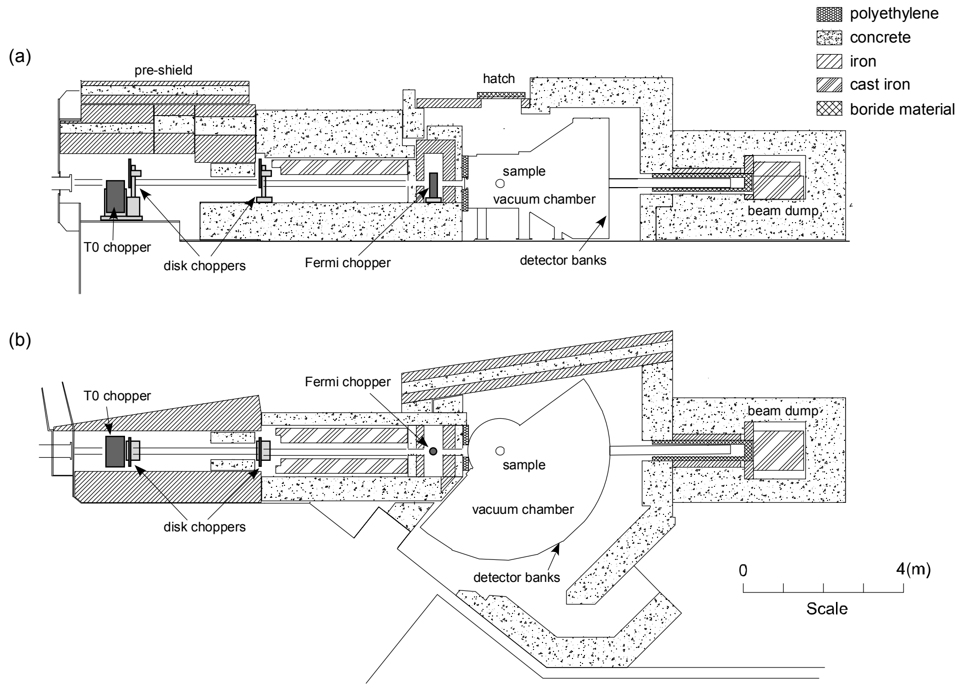
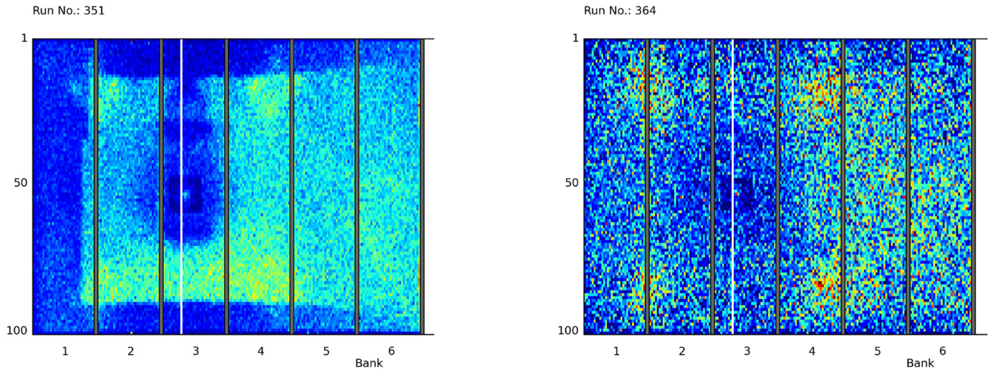


Fig. 1. Schematic views of 4SEASONS. (a) Side view. (b) Top view.

3. Background Study

3.1. Background due to Scattering by the Beam Window of the Vacuum Chamber

On 4SEASONS, neutron beam comes into the vacuum chamber through a thin beam window. This window is a 0.3 mm thick aluminium plate. Even with this thinness, we found that the window produces considerable scattering. Figure 2(a) shows an intensity distribution on the PSDs when E_i = 16.2 meV neutrons are delivered to a single crystal sample. This time, the beam window was attached on the surface of the vacuum chamber, which was 850 mm upstream the sample. In addition to four-fold symmetric spots from the sample, a wide range of the PSDs is covered with diffuse signals. This diffuse background originates from scattering by the beam window. Since the flight distance for neutrons scattered by the beam window is similar to that of neutrons scattered by the sample, the window scattering disturbs true signal from the sample especially at a low energy transfer (E). In order to suppress it as much as possible, we tentatively added a 50×50 mm^2 square-pipe collimator of cadmium just downstream the window. It had a profound effect on reducing the background scattering as shown in Fig. 2(b). In order to suppress the scattering by the beam window more efficiently, it should be placed as far from the sample as possible. Then, we extended the entrance duct of the chamber to displace the beam window to the position 1420 mm upstream the sample. Now there is a 45×45 mm^2 B_4C-resin collimator between the beam window and the sample. To suppress reflection by the resin on the surface of the collimator, we tentatively placed cadmium sheets inside the collimator, which will be replaced in the future by ones made of sintered-B_4C or boron nitride for high-energy neutrons. Furthermore, the instrument has two sets of adjustable sintered-B_4C slits just after the Fermi chopper and just before the sample to cut unnecessary neutrons.



(a) (b)

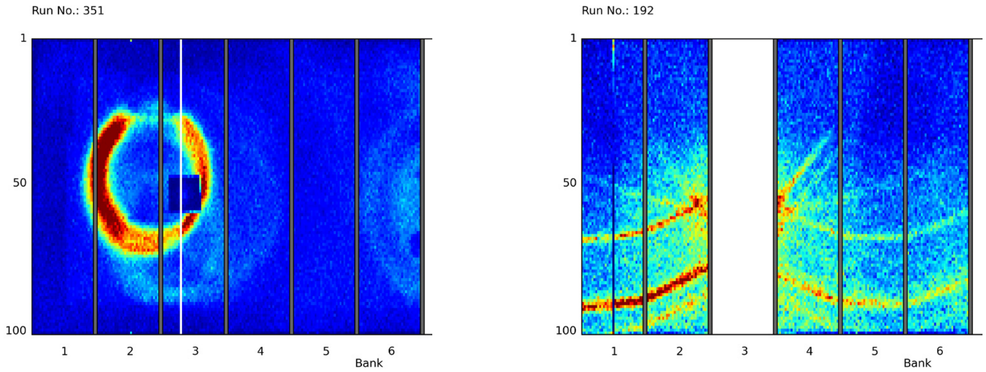
Fig. 2. Intensity distributions on the PSDs for measurements on a single crystal sample (a) without and (b) with a beam collimator just downstream the beam window of the vacuum chamber. They were observed at E = 2–4 meV with E_i = 16.2 meV at (a) 5 K and (b) RT.

3.2. Background due to Scattering by Sample

Neutrons scattered by a sample sometimes hit the wall of the vacuum chamber or a sample environment device, and then produce unwanted scattering. The problem becomes severe when the sample is a single crystal, because it produces intense Bragg reflections. Since the chamber or the device are usually made from polycrystalline materials, scattered neutrons form a so-called Debye-Scherrer rings on the PSDs. By observing the shape of the rings carefully, one can determine the origin of the scattering. This kind of background scattering is usually observed at a considerable energy transfer, because the flight distance for the contributing neutrons is longer than that for neutrons scattered by the sample.

Figure 3(a) shows an example when the unwanted scattering was produced by the wall of the chamber. It shows an intensity map on the PSDs when a single crystal was irradiated by neutrons of E_i = 30.3 meV. An intense ring-shape scattering was observed at $E \sim 18$ meV. Since this scattering was observed near the direct beam position, we could find that the origin was near the beam path. This time, the c axis of the crystal was almost parallel to the incident beam. Then, a Bragg reflection with an index $00l$ produced a backward scattering with a scattering angle of ~180°. At that time, though the inner wall of the vacuum chamber was covered with B_4C resin plates, there was a small (~10 mm) aperture right by the beam window. The 180° Bragg reflection may hit this aperture. After we sealed this aperture with a neutron absorber, the ring-shaped scattering disappeared.

Figure 3(b) shows another example when the unwanted scattering was produced by a sample environment device. This time, many semicircular rings were observed on the lower part of the PSDs. Furthermore, these rings are bilaterally symmetric. Note also that the single crystal sample was aligned symmetrically against the incoming beam, i.e. the b axis was parallel to the beam. These facts imply that the ring-shape scattering was produced at somewhere above the beam path. When this measurement was done, a cryostat which cools the sample was mounted on the vacuum chamber. We speculated that Bragg reflections reflected by the sample toward upward directions may hit some part of the cryostat, and then produced Debye-Scherrer rings. Then we attached a cadmium ‘hat’ on the sample can to prevent upward scattering from the sample, and found it successfully vanished the ring-shape scattering. Now we regularly use boron nitride pieces instead of cadmium for this purpose for higher energy neutrons.



(a) (b)

Fig. 3. Intensity distributions on the PSDs for measurements on single crystal samples with (a) E_i = 30.3 meV and E = 17–19 meV, and (b) E_i = 45.4 meV and E = 10–20 meV. In (b), detectors were not installed on the third detector bank.

3.3. Background due to High-Energy Neutrons and T0 Chopper

Since 4SEASONS has a short and straight beam path, it suffers from high-energy neutrons whose energies spread over keV or MeV. These very high-energy neutrons are emitted from the source just after protons hit the neutron target, i.e. at t (time-of-flight) ~ 0. Therefore, naïvely speaking, we can eliminate the high-energy neutrons from the data by cutting it off around t = 0. In reality, however, they are scattered and reflected by many parts of the instrument, are sometimes slowed down, and then reach the detectors later than t = 0, resulting in severe background of the data even at a low E_i region. Therefore, to suppress the high-energy neutrons as much as possible is crucially important for an inelastic scattering instrument, but they are very difficult to stop due to their high energies.

A T0 chopper is the most effective device to suppress the high-energy neutrons. This chopper rotates a thick metal hammer, which blocks the beam path at t ~ 0. We adopted a 300 mm thick Inconel X-750 block as the hammer of our T0 chopper [6]. Unfortunately, on 4SEASONS, the installation of the T0 chopper was delayed, and we could perform its on-line test only after January 2010, about half a year later than the starting of inelastic scattering measurements. Soon after we operate the T0 chopper, we realized its effectiveness. Figure 4 shows time spectra measuring a vanadium sample with and without the T0 chopper rotating in 25 Hz. It shows that the background is dramatically decreased by the T0 chopper e.g. by a factor of 10^{-2}–10^{-3} at E_i ~ 300 meV.

Interestingly, in Fig. 4, the suppression of the background is quite evident even at a low E_i. For example, the background is decreased by a factor of ~1/10 at E_i ~ 50 meV. This fact evidences that the high-energy neutrons can be origins of background at a low E_i region. Figure 5 shows this fact from a different viewpoint. It shows intensity maps when the two disk choppers were ‘closed’. Even with this condition, we found quite a high background on detectors at a higher scattering angle (right part of the figure) at a time region of a few thousands microseconds [Fig. 5(d)]. Judging from the position of the detectors, we first thought that our shielding was insufficient at a side part or a higher-angle part of the instrument. However, after carefully investigating the time dependence of the distribution of the background [Figs. 5(a)–(d)], we concluded that the origin is high-energy neutrons, whose energies are so high as to penetrate the disk choppers, coming along the beam line. The high-energy neutrons comes into the detectors with a low scattering angle at t ~ 0. They may be scattered on the surface of the detectors, or penetrate the vacuum chamber to be scattered by the shield outside of the vacuum chamber. Then, they propagate toward higher-angle detectors as time advances. This interpretation was confirmed by the fact that this type of background almost disappeared after the installation of the T0 chopper.

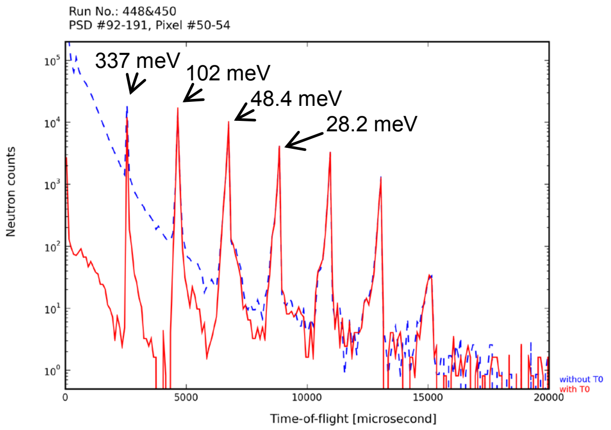
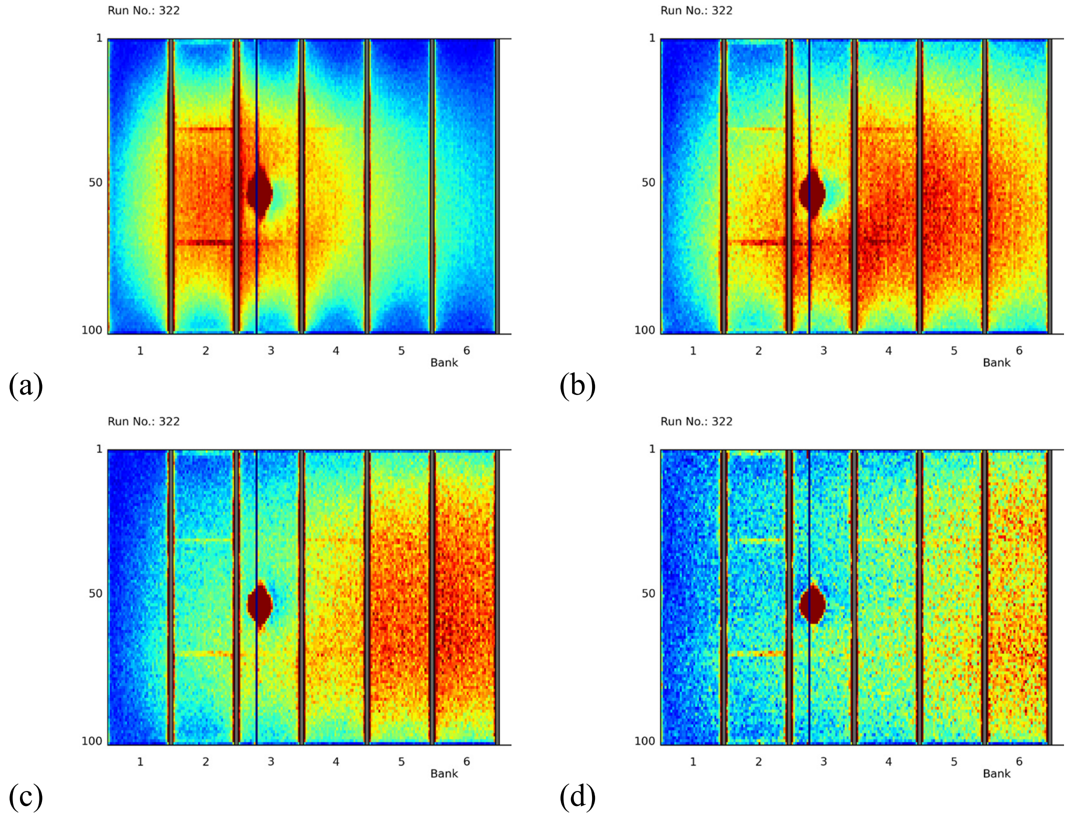


Fig. 4. Time spectra measuring a vanadium sample with (solid line) and without (dashed line) the T0 chopper. The Fermi-chopper rotated in 300 Hz, and some of the selected E_i's are also indicated in the figure.



(a) (b) (c) (d)

Fig. 5. Time dependence of intensity distribution of high-energy neutrons on the PSDs with the disk choppers being closed. (a) $t = 500-600$ μs, (b) $t = 800-900$ μs, (c) $t = 1100-1200$ μs, (d) $t = 2000-2500$ μs.

4. Summary

In summary, we briefly described the design of the shielding of the Fermi-chopper spectrometer 4SEASONS, and our experience on investigation and suppression of background. Though the countermeasure against background is critically important for an inelastic scattering instrument, which observes faint inelastic scattering signal, it is a really tough work. We hope our experience would be of help in future designing of instruments.

Acknowledgements

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