The Evaluation of a Simple Measurement Method using NaI(Tl) Scintillation Survey-Meter for Radiation Safety Management of Radioactivated Armor Tiles of LHD Vacuum Vessel

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In this study, the application of a simple measurement method using NaI(Tl) scintillation survey-meter to detect the gamma-rays in the armor tiles of LHD vacuum vessel exposed to fast neutrons during deuterium plasma experiments was evaluated to control the occupational exposure for the storage of huge numbers of the armor tiles. The gamma-ray spectrometry for an activated armor tile by high-purity germanium detector (HPGe) showed the gamma-ray peaks from \(^{58}\)Co, \(^{54}\)Mn and \(^{60}\)Co. The detection efficiencies of these nuclides for HPGe were evaluated by PHITS to estimate the concentrations of these nuclides. The radiation transport model for HPGe in PHITS were validated by the gamma-ray measurements for sealed gamma-ray sources. Then, the detection efficiencies of these nuclides for NaI(Tl) scintillation survey-meter were also evaluated by the same manner using PHITS. The predicted dose rate of the activated armor tiles in NaI(Tl) scintillation survey-meter was consistent with the actual measurement. The predicted count rate in NaI(Tl) scintillation survey-meter for \(^{60}\)Co, which will be a deterministic nuclide in the armor tile due to longer half-life, in the clearance level was sufficiently higher than the minimum detectable count rate of NaI(Tl) scintillation survey-meter with a simple shielding for environmental radiation.

Key Words: LHD, gamma-ray, survey meter, HPGe, PHITS

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1. Introduction

The deuterium plasma experiments begun in March 2017 in the Large Helical Device (LHD), which is one of the world’s largest superconducting fusion machine, have been successfully operating to achieve high temperature plasma, high density plasma and high beta plasma, and to reveal the physics in such high-performance plasmas\(^{1-4}\). The deuterium-deuterium fusion reaction in the plasma produces neutrons and tritons. Therefore, the comprehensive radiation control system has been developed in LHD. The detail of this system can be found elsewhere\(^{5,6}\).

The neutron generation in the vacuum vessel of LHD produced radioactivated components in the torus hall. In the LHD vacuum vessel, more than 4,000 armor tiles are covering the inner wall and have been irradiated by high flux fast neutron\(^{7,8}\). These armor tiles can be damaged by the high heat and particle fluxes of high temperature plasma, which are normally confined by the magnetic field but can be fluctuated by the experimental conditions. Also, the investigation of tritium retention in the vacuum vessel is significantly important in the deuterium experiments from the radiation control point...
of view. Therefore, the armor tiles have been replaced frequently due to damage or for analyses. Also, it is planned that all armor tiles will be removed from the vacuum vessel to evaluate the in-vessel tritium retention after the end of deuterium experiments in LHD.

Because there exists the huge number of the armor tiles, the radiation safety management for the storage of these tiles will be necessary. For the radiation safety on tritium, the release of tritium during storage should be mitigated. It is well known that tritium adsorbed on the surface of materials can easily desorb by the interaction with water vapor in the air, resulting in the internal radiation exposure through inhalation. To prevent the tritium release, hydrogen plasma discharge to promote the isotope exchange reaction has been adopted in LHD. After the deuterium plasma experiments in each campaign, hydrogen plasma experiments were conducted to remove tritium retained in the armor tiles so that the workers can enter the vacuum vessel of LHD in the maintenance period after the experiment campaign. By this process and with an appropriate ventilation, the internal radiation exposure by tritium can be sufficiently mitigated.

On the contrary, the external radiation exposure by gamma-ray due to the accumulated radioactive nuclides in the armor tiles is another issue. Therefore, the mitigation for external radiation exposure is focused in this study. The installation of thick radiation shield is considered so that the occupational external radiation dose can be mitigated. For designing an effective shielding component, it is necessary to sort the radioactivated armor tiles with respect to their activity. This work can be easily performed using conventional survey meters such as NaI(Tl) scintillation survey-meter. However, such a conventional survey-meter is not capable of a gamma-ray spectroscopy to discriminate the inspecting peaks from the background signals and of adjusting the acquisition time. Accordingly, the reliable measurement for specimen with low radioactivity would be difficult.

Therefore, in this study, the gamma-ray detection capability of NaI(Tl) scintillation survey-meter for armor tiles activated by neutrons during the deuterium plasma experiments in LHD was evaluated quantitatively. First, the kinds of radioactive nuclides which exist in the armor tiles were attributed from the gamma-ray spectrum measured by high-purity germanium detector (HPGe). The activity concentrations of each gamma-ray emitting nuclide were evaluated using the count rate for each photo-peak measured by HPGe and the detection efficiencies of each peak estimated by PHITS (Particle and Heavy Ion Transport code System). The measurement of armor tiles using the NaI(Tl) scintillation survey-meter was also carried out. The gamma-ray detection capability of NaI(Tl) scintillation survey-meter for the armor tiles with very low radioactivity (comparable to the clearance level) was evaluated from the detection efficiency estimated by PHITS.

2. Experimental

2.1 Detectors

A portable high-purity germanium detector (P-HPGe), Falcon-5000 of Mirion Technologies Canberra, was used in this work. P-HPGe equips the Ge crystal cooled by electromechanical cooling system. The voltage of $-3500 \text{ kV}$ is applied on a surface of Ge crystal for the measurement. The geometry of P-HPGe in the measurement set-up modeled in PHITS can be found in Fig. 1. The size of Ge crystal is $6 \text{ cm}^3 \approx 3 \text{ cm}^3$. The back surface of the crystal has grooves for the electrode contact. The crystal is placed inside the vacuum chamber to avoid the exposure to the air. The vacuum chamber is in the outside of the detector housing containing the electric components. The collimator is also used in this work. The collimator composed with $8 \text{ mm}$-thick tungsten polymer, $1 \text{ mm}$-thick tin and $1.5 \text{ mm}$-thick copper, forming a cylinder shape to reduce the gamma-ray flux into the side surface of Ge crystal.

![Fig. 1. Geometry of P-HPGe modeled in PHITS.](image-url)
The NaI(Tl) scintillation survey-meter used in this work is TCS-172 of Hitachi Ltd. The size of NaI(Tl) crystal is 2.54 cm$^2 \times 2.54$ cm$^2$. The crystal is installed in a detector head which is connected to the indicator. The distance between the front detector head to the crystal surface is 0.73 cm. The indicator of this survey-meter can display the dose rate and the count rate in the units of $\mu$Sv h$^{-1}$ and s$^{-1}$, respectively.

2.2 Benchmark experiment of radiation transport model using sealed gamma-ray sources

Before measuring the radioactivated armor tiles, the benchmark measurements of gamma-rays from sealed gamma-ray sources were carried out to validate the radiation transport models of P-HPGe and NaI(Tl) scintillation survey-meter in PHITS.

For P-HPGe, the sealed gamma-ray sources of $^{137}$Cs and $^{60}$Co, with the respective radioactivities of 1.0 MBq and 0.64 MBq, were used. In the measurement using each sealed gamma-ray source, the distance between the front surface of Ge crystal and the gamma-ray source was 95.6 cm. The height position of the gamma-ray source was 10 cm from the floor, which is equivalent to the center position of Ge crystal in P-HPGe. The measurements were conducted for 1000 s or more for each gamma-ray source. Then, the count rates of each gamma-ray peak, 0.66 MeV for $^{137}$Cs, 1.17 and 1.33 MeV for $^{60}$Co, were evaluated. In PHITS, the experimental set-up was modeled, and the gamma-ray transport from the gamma-ray source was calculated. The transport and interaction of photon and electron were also evaluated by EGS5 in PHITS. For evaluating count rate, the t-deposit tally was applied, and the energy deposition event into NaI(Tl) crystal above 50 keV was integrated for taking an event trigger into consideration. On the other hand, the dose rate was estimated in PHITS as follows. For calculating the dose rate at the position of NaI(Tl) crystal, the composition of the crystal was replaced to the air. Then, the gamma-ray flux and energy distribution at this position were evaluated by t-track tally which is a track-length tally in PHITS. Thereafter, the dose rate was estimated from the flux and the energy of gamma-ray by the conversion factors provided in ICRP Publication 116.

2.3 Measurement of the armor tiles and the detection capability estimation by NaI(Tl) scintillation survey-meter

Figure 2 is the photographs of the front surface of an armor tile. The armor tile is composed as a layered structure consisting of stainless steel (front surface) and copper (back surface). The thicknesses of each layer were 0.5 cm. There are four bolt-holes and grooves. The armor tiles are stuck on the inner surface of the LHD vacuum vessel by bolts through these bolt-holes. The grooves can accept bolt-heads so that the flat surface of the armor tile with bolt-heads can be achieved. The copper layer of the back surface contacts to the coolant channel passing on the inner surface of LHD vacuum vessel to cool down the armor tile against the heat flux from the high temperature plasma. The geometry of the armor tiles can be found in Fig. 2(b).

The armor tiles used in this study were removed from the LHD vacuum vessel in the maintenance period after elapsing 5 months from the end of the third campaign of the deuterium plasma experiment. Note that, these armor tiles have been placed in the LHD vacuum vessel in the previous campaigns of deuterium experiments. Therefore, the radioactivity in these armor tiles have piled up. The typical weight of an armor tile is 1.5 kg. The armor tiles were placed in front of P-HPGe. The distance between the front surface of the armor tile and that of the Ge crystal was 3.6 cm as shown in Fig. 3. The armor tile...
was placed on the floor in this measurement, therefore, the center positions of the armor tile and the Ge crystal were not equivalent. The measurement was conducted for several armor tiles for 10000 s or more, and the average count rates for each gamma-ray peak were obtained. Note that the count rates in each gamma-ray peak were subtracted by those in the background measurement. The radioactivities of gamma-ray emitting nuclides in the armor tiles were estimated according to the count rates of each photo-peak measured by P-HPGe and those estimated by PHITS.

In the measurement with NaI(Tl) scintillation survey-meter, the detector head of the survey-meter was contacted on the
center position of the front surface of the armor tiles. Then, the
dose rate was measured with the time constant of 10 s. The
background dose rate was also measured. The dose rate for the
armor tile displayed in the following section is already
subtracted with the background dose rate.

### 3. Results and discussion

Tables 1 show the results of gamma-ray measurements for
sealed gamma-ray sources using P-HPGe and NaI(Tl)
scintillation survey-meter. In both cases, the estimated count
rate and dose rate were almost consistent with those measured
by the detectors. Here, it is possible that the model in this work
is not valid for gamma-rays with much lower energy or higher
energy. In this study, however, the gamma-ray energy range
detected in the measurement of the armor tiles were covered by
those of gamma-ray sources (see the results below). Therefore,
one can reasonably judge that the radiation transport model
here is sufficiently appropriate in this work.

The gamma-ray energy spectrum for the armor tile
measured by P-HPGe is displayed in Fig. 4. There are six
dominant gamma-ray peaks located at 0.51, 0.81, 0.83, 1.17,
1.33, and 1.46 MeV. The gamma-ray at 1.46 MeV was assigned
to the $^{40}$K. Unlike a conventional HPGe measurement using
thick lead box, the measurement with P-HPGe in this work was
carried out without such shielding components around the
system. Therefore, the gamma-ray emitting nuclides in the
concrete wall and floor can be observed significantly. $^{40}$K is
naturally contained in the concrete, and is detected significantly
in this measurement. Also, other gamma-ray emitting nuclides
such as $^{214}$Pb, $^{214}$Bi, $^{208}$Tl, and so on were observed as small
peaks in this spectrum. The peaks at 0.81 and 0.83 were attributed
to the $^{58}$Co and $^{54}$Mn, respectively, and the peaks at
1.17 and 1.33 were assigned to $^{60}$Co. $^{60}$Co is a typical gamma-
ray emitting nuclide in the field of nuclear engineering. $^{60}$Co is

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**Table 1** The results of the benchmark experiment for the measurement of gamma-rays from the sealed sources using P-HPGe and NaI(Tl) scintillation survey-meter. The error in the actual measurement was estimated by 1$\sigma$. The statistic error of the calculation is also displayed.

**Detector: P-HPGe**

| Gamma-ray source | Activity [MBq] | Energy [MeV] | Count rate [cps] | Estimated count rate by PHITS [cps] |
|-----------------|---------------|--------------|-----------------|----------------------------------|
| $^{137}$Cs      | 1.0           | 0.66         | 32.7 ± 0.2      | 34.3 ± 0.5                      |
| $^{60}$Co       | 0.64          | 1.17         | 14.4 ± 0.2      | 14.9 ± 0.3                      |

**Detector: NaI(Tl) scintillation survey-meter**

| Gamma-ray source | Activity [MBq] | Dose rate [$\mu$Sv/h] | Count rate [cps] | Estimated dose rate [$\mu$Sv/h] | Estimated count rate [cps] |
|-----------------|---------------|------------------------|-----------------|-------------------------------|--------------------------|
| $^{137}$Cs      | $1.6 \times 10^{-2}$ | 3.7 ± 0.1             | 781 ± 30        | 3.5 ± 0.1                     | 772 ± 28                 |
| $^{60}$Co       | $3.3 \times 10^{-2}$ | 25.9 ± 0.5            | 2539 ± 50       | 26.7 ± 0.5                    | 2670 ± 52                |

* The threshold countable energy was 50 keV

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Fig. 4. The gamma-ray energy spectrum for the armor tile measured by P-HPGe.
generated by (n, γ) reaction of 59Co with thermal neutron. The cobalt is not a nominal component of stainless steel which consists of iron, nickel, chromium, and others. The cobalt is an impurity in iron contaminated during the fabrication processes. 58Co and 54Mn were caused by the (n, p) reaction of 58Ni and 54Fe as the main constituent atoms of stainless steel, respectively. These nuclear reactions can be occurred when the neutron energy is sufficiently high 21). The effective threshold energies for (n, p) reaction of 58Ni and 54Fe are around 0.6 MeV and 1.0 MeV, respectively. In LHD, the major energy of neutron generated by deuterium-deuterium fusion reaction is around 2.45 MeV22,23). This high energy of neutron can overcome the threshold energies to proceed with these reactions. The peak at 0.51 MeV was caused by the annihilation gamma-ray of electron-positron pair. 59Co emits positron when it decays, and the emitted positron should recombine with an electron in the system. Finally, according to these assignments, one could find that the major artificial radioactive nuclides of 58Co, 54Mn, and 60Co were generated in the armor tiles in LHD vacuum vessel.

Table 2 summarizes the results of PHITS simulating the gamma-ray detection from the armor tile by P-HPGe. The error in the actual measurement was estimated by 1σ. The statistic error of the calculation is also displayed.

| Nuclide | Energy [MeV] | Count rate [cps] | Estimated count rate by PHITS [Bq⁻¹] | Evaluated activity [kBq] |
|---------|-------------|-----------------|-----------------------------------|--------------------------|
| 58Co    | 0.81        | 12.6 ± 0.1      | (4.0 ± 0.1) × 10⁻³                  | 3.2 ± 0.1                |
| 54Mn    | 0.83        | 10.3 ± 0.1      | (4.1 ± 0.1) × 10⁻³                  | 2.5 ± 0.1                |
| 60Co    | 1.17        | 5.2 ± 0.1       | (3.0 ± 0.1) × 10⁻³                  | 1.7 ± 0.1                |
|         | 1.33        | 4.7 ± 0.1       | (2.7 ± 0.1) × 10⁻³                  | 1.8 ± 0.1                |

Table 3 The estimated dose rates induced by each gamma-ray emitting nuclides in the radioactivated armor tiles by the NaI(Tl) scintillation survey-meter. The error in the actual measurement was estimated by 1σ. The statistic error of the calculation is also displayed.

| Nuclide | Activity measured by P-HPGe [kBq] | Estimated dose rate by PHITS [μSv Bq⁻¹] | Estimated dose rate [μSv h⁻¹] |
|---------|----------------------------------|----------------------------------------|-----------------------------|
| 58Co    | 3.2 ± 0.1                        | (2.1 ± 0.1) × 10⁻⁶                    | 0.24 ± 0.1                  |
| 54Mn    | 2.5 ± 0.1                        | (1.8 ± 0.1) × 10⁻⁶                    | 0.16 ± 0.1                  |
| 60Co    | 1.7 ± 0.1                        | (5.2 ± 0.2) × 10⁻⁶                    | 0.32 ± 0.1                  |

activities of 59Co, 54Mn, and 60Co were estimated to be about 3.2, 2.5, 1.7 kBq, respectively. It can be found that the radioactive nuclides of 59Co and 54Mn, which were generated by the fast neutron, were the major components in the armor tile used in this work. Next, the dose rate at the position of NaI(Tl) scintillation survey-meter was estimated. In this estimation, the activities of nuclides in the armor tile were the same as evaluated in Table 2. The results are summarized in Table 3. The activity of 60Co was set as the average of peaks at 1.17 and 1.33 MeV in Table 2. As found in Table 3, the influence of 60Co on the dose rate was more than two times larger than those of others because 60Co emits two gamma-ray with higher energy. Each estimated dose rate indicated that the total dose rate at the position of NaI(Tl) scintillation survey-meter would be 0.72 ± 0.2 μSv h⁻¹. The dose rate of 0.71 ± 0.2 μSv h⁻¹ was obtained in the actual measurement for the armor tile using NaI(Tl) scintillation survey-meter. This consistency should indicate the validity of the series of measurements and calculation in this study.

Thereafter, the detection capability of NaI(Tl) scintillation survey-meter for gamma-ray emitting nuclides was evaluated using the model developed in this work. Table 4 summarized
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The predicted count rate for $^{58}\text{Co}$, $^{54}\text{Mn}$, and $^{60}\text{Co}$. The activity concentrations of these nuclides were set to be in the clearance level of these nuclides as provided in ref. 24. The gamma-ray flux from the nuclides in the clearance level can cause the occupational external dose below 10 $\mu$Sv in a year. Such a low dose rate indicates that the strict radiation shielding of the armor tiles in the clearance level can be no longer necessary. In this condition, the predicted count rates of $^{58}\text{Co}$, $^{54}\text{Mn}$, and $^{60}\text{Co}$ are $24.7 \pm 0.7$, $1.9 \pm 0.2$, and $3.4 \pm 0.3$ s$^{-1}$, respectively. The count rates of $^{54}\text{Mn}$ and $^{60}\text{Co}$ are quite lower than that of $^{58}\text{Co}$, because their activity concentrations in the clearance level are significantly low.

For the predicted count rates for each nuclide in Table 4, the minimum detectable count rate was evaluated by the following equation:

$$n_N = \frac{k}{2} \left\{ \frac{k}{t} + \sqrt{\left(\frac{k}{t}\right)^2 + 4n_B \left(\frac{1}{t} + \frac{1}{t_B}\right)} \right\}$$

Here, $n_N$ is the minimum detectable count rate, $n_B$ is the background count rate, $k$ is a constant which is 3, $t$ and $t_B$ are the measurement durations for sample and background, respectively. In the case of the measurement with the time constant of 30 s, the measurement duration is 60 s. The background count rate in a conventional workspace was 25 s$^{-1}$. The background count rate can easily be reduced when using the shielding box as shown in Fig. 5. The shielding box used in this photograph is of 3 cm-thick lead. The count rate was 3 s$^{-1}$ when the detector head of NaI(Tl) scintillation survey-meter was inserted into this box while a side of the box completely opened as shown in Fig. 5. In these background measurement results, the minimum detectable count rate in the conventional workspace is $2.8 \pm 0.1$ s$^{-1}$. By the reduced background level, the minimum detectable count rate in the lead shielding box is $1.0 \pm 0.1$ s$^{-1}$. The minimum detectable count rate in the conventional workspace was slightly lower than the predicted count rate for the clearance level concentration of $^{60}\text{Co}$ which will be the deterministic radioactive nuclide after passing about 10 years because of a much longer half-life compared to those of $^{58}\text{Co}$ and $^{54}\text{Mn}$20). However, it would be difficult to certainly detect the $^{60}\text{Co}$ in the clearance level because the background level in the conventional workspace is sometimes fluctuated by the environment radiation. On the other hand, the measurements in the lead shielding box can certainly detect the gamma-rays from the radioactive nuclides in the armor tiles with the clearance level although the work efficiency can be decreased.

4. Summary

In this study, the application of simple measurement method using NaI(Tl) scintillation survey-meter to detect the gamma-ray from the armor tiles of LHD vacuum vessel exposed to fast neutron during deuterium plasma experiment.
was evaluated to control the occupational exposure for the storage of huge numbers of the armor tile. The gamma-ray spectrometry using HPGe showed the gamma-ray peaks from $^{58}$Co, $^{54}$Mn and $^{60}$Co. The activity concentrations of these nuclides were estimated by the detection efficiencies evaluated by PHITS code. Then, the detection efficiencies of these nuclides in NaI(Tl) scintillation survey-meter were also evaluated, and the predicted dose rate was consistent with the actual measurement. The predicted count rate in NaI(Tl) scintillation survey-meter for $^{60}$Co, which will be a deterministic nuclide in the armor tile due to longer half-life, in the clearance level was sufficiently higher than the minimum detectable count rate of NaI(Tl) scintillation survey-meter with a simple shielding for environmental radiation. This result indicates that the radiation control for the radioactivated armor tiles using NaI(Tl) scintillation survey-meter is reasonably possible.

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