**One-year Measurements of Gamma-ray Background Using a High-purity Germanium Detector**

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Many studies of background levels in gamma-ray measurements using a high-purity germanium detector have been reported from various aspects such as its reduction and variation. In the present work, natural gamma-ray background was thoroughly measured in a year (283.5 days in total, \( n = 271 \)) One measurement time was almost all either 86,400 sec (1 day) or 100,000 sec. The data was first discussed in relation to radon concentrations in the laboratory. No correlations were found between the gamma-ray count rates from \(^{214}\)Pb and \(^{214}\)Bi and radon concentrations, meaning that radon just around the germanium detector was reduced to the negligible level by the introduction of nitrogen gas. Also, the count rates of major nuclides appeared to fluctuate with the normal distribution or its similar distribution, without seasonal variations. The coefficient of variance of a few up to several tens of percent was seen, which were larger than those calculated from counting statistics alone. Furthermore, summing of all gamma-ray spectra allowed us to see neutron-induced peaks that cannot be detected in usual short-term measurements. All data obtained here would be the knowledge useful for the practice of gamma-ray measurements.

**KEY WORDS:** gamma ray, background, high-purity germanium detector, variation, natural radionuclides, radon, radon progeny, evaporating nitrogen, neutron-induced gamma ray.

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**I INTRODUCTION**

Proper background subtraction is essential for determining the activity concentrations of radionuclides in an environmental sample by gamma-ray spectrometry, since gamma-ray background is subject to variation. In general, the background measurement time is days, weeks or months, depending on the required accuracy of measured data on a test sample. Many studies of background levels have been reported from various aspects such as its reduction,1–8) its long-term variation9, 10) and radioactivity in common materials used for the construction of detection systems.1, 11–14) Of these aspects, the background reduction was most intensively investigated and various approaches were presented depending on the nature of background sources (e.g. radionuclide in materials used for the detector and shield, cosmic-ray induced background, and radon and its progeny).15–17)

After radon was pointed out as one of the main background sources, its reduction technique was proposed to purge radon from the free volume between the detector and shield – the introduction of the boil-off nitrogen gas from the liquid nitrogen dewar used for cooling a high-purity germanium (HPGe) detector. This cost-free and effortless technique was demonstrated to be effective for reducing the radon-induced background and has been commonly utilized in many laboratories.3–6) While the great effect of the evaporating nitrogen was clearly observed, discussion in relation to radon concentration has been missing so far.

The aim of the present study was to acquire fundamental information on the background in the practice of gamma-ray spectrometry. The organized statistical data on this topic would be valuable, especially for the quantification of low-level natural radioactivity, because of few publications.9 First, a correlation was examined between radon concentrations in the laboratory and radon-induced background counts measured using a HPGe detector, based on one-year measurements. The statistics of gamma-ray background counts for major natural radionuclides were then summarized to discuss the monthly variation, the fluctuation and its normality. In addition, all gamma-ray spectra collected in the year were summed up so that many peaks that cannot not be observed in common short-term background measurements were identified.

**II MATERIALS AND METHODS**

The research facility, built for the radon exposure to animals, is located in Misasa, Tottori, Japan. The ventilation and air-conditioning systems are always working in the facility, as mentioned earlier in detail.18) The laboratory in which the present measurements were performed is on the
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ground level and is corresponding to the “measurement room” called in the previous paper.18)

A well-type HPGe detector (GWL-120-15, ORTEC) was used with 10-cm lead shielding and 5-mm oxygen-free copper lining. Gamma-ray background measurements were repeatedly made for a year between April 2015 and March 2016, when it was available. Evaporating nitrogen gas was constantly introduced from the liquid nitrogen dewar to the free volume in the immediate vicinity of the detector. One measurement time was almost all either 86,400 sec (1 day) or 100,000 sec.

Table 1 summarizes the total number and counting time of the measurements. The analyzed photopeaks were 47 ($^{210}$Pb), 63 ($^{234}$Th), 186 ($^{226}$Ra/$^{235}$U), 239 ($^{212}$Pb), 352 ($^{214}$Pb), 583 ($^{208}$Tl), 609 ($^{214}$Bi), 911 ($^{228}$Ac) and 1,461 keV ($^{40}$K). These nine peaks were selected because they can be significantly detected in our usual routine background measurements as shown in Fig. 1 (a).

In parallel, radon concentration was also measured and recorded hourly using a passive radon monitor (Radim3A, Jiri Plch, Czech Republic), placed near the HPGe detector in the same room. The total number of 8,784 readings was obtained in the year.

| Year | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Total |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
|      | 22  | 11  | 18  | 23  | 20  | 21  | 26  | 28  | 13  | 31  | 28  | 30  | 271   |
| Time (days) | 22  | 11  | 17.9| 22.7| 23  | 24.3| 30.1| 30.6| 12.8| 31  | 28  | 30  | 283.5 |

Table 1 Number and counting time of gamma-ray background measurements.

![Fig 1](https://example.com/image1.png) Gamma-ray background spectra. In the figure (a), “Sum” represents the summed spectrum of 271 data collected in the year (corresponding to 283.5 days) and “1 day” represents the typical spectrum measured for one day. The sign “°” stands for the peak used for the analysis. The peaks derived from interactions between the detector or shield and neutrons can be found in the figures (b) and (c), which cannot usually be seen in short-term measurements.
III RESULTS AND DISCUSSION

Figure 2 shows the monthly arithmetic means and standard deviations of radon concentrations in the laboratory. The radon concentrations in April and May 2015 were a little lower, but no noticeable trend was seen in the year. The annual arithmetic mean (± standard deviation) was 23.7 ± 13.5 Bq m⁻³, which was similar to the value of 25 Bq m⁻³ given by the short-term test at the different room of the same facility¹⁰ (see Group E (background) in Fig. 4 of this paper). The diurnal variation that was indicated in this paper, namely higher radon concentrations during daytime hours, was obviously found in the present study as well (data not shown).

Figure 3 shows the background count rates of gamma rays emitted by radon progeny (²¹⁴Pb and ²¹⁴Bi) as a function of radon concentration. The x-axis corresponds to the radon concentration averaged over the time during which gamma-ray measurement was carried out. Since both $R^2$ values were quite low, radon-induced gamma-ray background count rates can be regarded in practice as being independent of radon concentrations in the condition of our gamma-ray detection system. No correlations shown in Fig. 3 are completely different from the data of MAURING et al.¹⁹ that indicated a significant linear correlation between radon concentrations and gamma-ray background count rates. This can be explained by the fact that gamma-ray measurements of MAURING et al.¹⁹ were done without an effort for the reduction of airborne radon from the free volume between the HPGe detector and shield. In our system, the liquid nitrogen for cooling the HPGe detector was consumed at a rate of about 1.8 l d⁻¹ and its boil-off gas was introduced into the free volume of 0.8 l in the immediate vicinity of the detector at the corresponding rate of 0.9 l min⁻¹. It is concluded that with a ventilation rate of at least 1 min⁻¹, gamma-ray background due to airborne radon (certainly, thoron as well) can be satisfactorily suppressed in a common laboratory.

Figures 4 shows the monthly arithmetic means and standard deviations of the gamma-ray background count rates. No specific variations were seen for all nuclides in the year. This result seems reasonable, since they are included in earth’s surface and materials used for the detector, ancillary equipment, supports, shields and building construction and are supposed to be constantly emitting gamma rays.¹⁶ It is also noted that the changes in ²¹⁴Pb and ²¹⁴Bi counts (Fig. 4) did not follow that in radon concentrations (Fig. 2), which was due to the success of our reduction measure against airborne radon. Here, it should be better to touch on measurement environment (temperature), which has a possibility to affect the electronics used and then to result in the occurrence of variation in gamma-ray background. Our laboratory was air-conditioned to keep temperature around 20°C through the year. Nevertheless, in fact, the seasonal variation in temperature was slightly observed that it was higher in summer and lower in winter. Since any nuclide did not indicate such variation as temperature (Fig. 4), temperature was not considered to be a key factor for explaining the variation in the gamma-ray background if controlled well.

The statistics of the gamma-ray background count rates averaged over the year ($n = 271$) are summarized in Table 2. The coefficients of variance (CV) were found to be larger by a factor of 2 up to 4 than those calculated from counting statistics alone, although the background count rates resulting from the radioactivity of the detection system and building construction are expected to be virtually constant in time.¹⁶ In the case of ²¹⁴Pb (352 keV), for example, around 300 counts in a single measurement (86,400 or 100,000 sec in the present study) can be acquired and the standard deviation (i.e. the square root of the counts) is 17 counts, yielding the CV of 6%. The CV value (20%) presented in Table 2 is about three times
higher than that calculated above. BOSEW (2005) reported that based on 16-year background monitoring, the CV values were in the range of 14–62% for several major gamma lines, excluding the extra-high value of 128% in 214Pb (352 keV): this significantly higher CV appeared due to the dynamics of radon in the laboratory where no radon reduction was implemented during the long monitoring. In conclusion, it is stated that the gamma-ray background counts may commonly fluctuate by several tens of percent, depending on counting time.

To check the normality of distribution of gamma-ray background count rates obtained for each nuclide in the year \( n = 271 \), quantile-quantile plots were depicted in Fig. 5. Apparently, the linearity of the plots can be seen for almost all nuclides, leading to an idea that the fluctuations of the count rates were based on normal distributions. The Shapiro-Wilk test was then performed to statistically evaluate the normality of data. As a result, the normality was not rejected for all nuclides \( (p < 0.01) \), whereas rejected for 234Th, 212Pb, 214Bi and 40K \( (p < 0.05) \). Considering the origin of gamma rays of interest here (as discussed above), it might be practically reasonable to interpret all presented data as normal distributions. According to the data of BOSEW (2005), many of natural gamma lines interested there could also be approximated roughly as normal distributions, while only radon progeny \((214Pb)\) indicated the log-normality maybe because of the influence of radon in the laboratory (see the previous paragraph).

Lastly, Fig. 1 shows the summed gamma-ray spectrum of 271 data collected through the year (corresponding to 283.5 days) and the typical spectrum measured for one day. Obviously, the summed spectrum had more peaks than the one-day spectrum (Fig. 1 (a)). In addition to natural radionuclides with low gamma-emission probabilities, a variety of interactions between the detector or shield and neutrons from cosmic rays \((e.g., (n,\gamma)\) and \((n,n')\)) contributed to making such peaks \((Figs. 1 (b) and (c))\). In the present study, the peaks were detected at the following energies and identified as neutron-induced gamma rays: 67 (73mGe), 140 (75mGe), 160 (77mGe), 199 (76*Ge), 563 (76*Ge), 570 (76*Ge, 207*Pb), 596 (76*Ge, 208*Pb), 670 (76*Ge, 209*Pb), 691 (76*Ge) and 803 keV \((206*Pb)\). Here, the sign \\

### Table 2 Statistics of gamma-ray background net count rates averaged over the year \( (n = 271) \).

| \( ^{210}\)Pb | \( ^{232}\)Th | \( ^{226}\)Ra/\( ^{235}\)U | \( ^{214}\)Pb | \( ^{208}\)Tl | \( ^{214}\)Bi | \( ^{228}\)Ac | \( ^{40}\)K |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| (47 keV)       | (63 keV)       | (186 keV)      | (239 keV)      | (352 keV)      | (583 keV)      | (609 keV)      | (1,461 keV)    |
| Arithmetic mean (cps) | 0.0037 | 0.0050 | 0.0088 | 0.0056 | 0.0030 | 0.0040 | 0.0042 | 0.0043 | 0.043 |
| Standard deviation (cps) | 0.0009 | 0.0008 | 0.0009 | 0.0007 | 0.0006 | 0.0005 | 0.0005 | 0.0004 | 0.001 |
| Coefficient of variance (%) | (15 – 31) | (12 – 21) | (8 – 12) | (9 – 17) | (15 – 27) | (8 – 17) | (7 – 17) | (5 – 12) | (3 – 4) |

Note: The values in parentheses represent the range of the coefficient of variance in one month.
evaporating nitrogen was introduced into the free volume around the HPGe detector with a ventilation rate of about 1 min⁻¹. Secondly, no seasonal variations in gamma-ray count rates of the major natural nuclides were observed. Also, these count rates appeared to generally fluctuate with the normal distribution or its similar distribution with the CV of a few up to several tens of percent through the year, which were larger than those calculated from counting statistics alone. Finally, summing of all individual gamma-ray spectra, corresponding to 283.5-day measurement, manifested many unusual peaks that were produced by interactions especially between the germanium crystal and neutrons.

The present paper provided the fundamental information on the statistics of background counts in the practice of gamma-ray spectrometry. The organized data shown here is believed to be useful knowledge, even to other laboratories, for the quantification of low-level natural radioactivity.

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