An alpha particle detector based on a GPS mosaic scintillator plate for continuous air
monitoring in plutonium handling facilities

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ABSTRACT

An alpha particle detector was developed for continuous air monitoring of radioactive contamination in working chambers at plutonium handling facilities. A 5-cm-square $\text{Gd}_2\text{Si}_2\text{O}_7\text{:Ce}$ (cerium-doped gadolinium pyro-silicate, GPS:Ce) mosaic scintillator plate for alpha particle measurements was fabricated from GPS single-crystal grains of around 550 μm diameter; the GPS grains were made of a GPS polycrystalline body grown using a top seeded solution method. The scintillator layer thickness was approximately 100 μm . The surface filling rate of the GPS grains was ca. 62%. To suppress the influence of non-uniformity of pulse heights of a photomultiplier tube, a central part of $\varnothing$ 40 mm of a 76-mm-diameter photomultiplier tube was used. In addition, 3 mm thick high-transmission glass was used as a substrate of the scintillator plate. The detector achieved energy resolution of 13% for 5.5 MeV alpha particles, detection efficiency of 61% and a radon progeny nuclide reduction ratio of 64.5%. A new alpha particle detector was developed to achieve a high radon progeny nuclide reduction ratio approaching that of a silicon semiconductor detector, with high resistance to electromagnetic noise and corrosion.

Highlights

- An alpha particle detector was developed for continuous air monitoring.
- The detector comprises a mosaic scintillator plate and a photomultiplier tube.
- A 5-cm-square GPS mosaic scintillator plate was fabricated.
- Its respective energy resolution and detection efficiency were 13 and 61%.

- The radon progeny nuclide reduction ratio of the developed detector was 64.5%.

Keywords:

continuous air monitoring
plutonium handling facility
alpha particle detector
mosaic scintillator plate
Gd₂Si₂O₇:Ce (GPS)

1. Introduction

In nuclear fuel reprocessing plants and mixed plutonium–uranium oxide (MOX) fuel plants, contamination control for plutonium and related radioactive nuclides is conducted according to legal restrictions. The relevant law prevents internal and external exposure of workers and also prevents the release of radioactive nuclides to the environment. As presented in the table, plutonium and nuclear-fuel-related nuclides emit alpha particles. Thereby contamination control has been conducted based on alpha particle measurements. A continuous air monitor (CAM), an important early warning instrument, measures alpha particles continuously from dust in the air of working chambers or from exhaust air using a dust collection filter [1–3].

A CAM for exhaust air from a facility measures exhaust air through decontamination filters set in an exhaust air system. Thereby, it is possible to ignore the influence of natural radon progeny nuclides. For this CAM, a ZnS:Ag scintillation detector is used at plutonium handling facilities of the Japan Atomic Energy Agency (JAEA). Although the ZnS:Ag scintillator has no capability of energy discrimination, it is not strongly influenced by gamma and beta rays because of its low thickness. In addition, the ZnS:Ag scintillator is sufficiently robust against humid and acidic atmosphere conditions. It uses a photomultiplier tube. For that reason, a ZnS:Ag scintillator is less susceptible to electromagnetic noise than a silicon semiconductor detector.

However, a CAM for a working chamber must identify 5.1 and 5.5 MeV alpha particles from plutonium in background alpha particles from radon progeny nuclides such as 7.7 MeV alpha particles from ²¹⁴Po. Consequently, an ion implanted silicon semiconductor detector with high energy resolution is used for this purpose. As shown in the table [4], although there are other radon progeny nuclides such as ²¹²Bi, ²¹²Po and ²¹⁶Po belonging to the ²²⁰Rn progeny, their influence is attributed to their short lifetimes.

A silicon semiconductor detector has high energy resolution, but it is weak against external

electromagnetic noise. Furthermore, conventional silicon surface barrier semiconductor detectors for CAM at working chambers were adopted several decades ago in JAEA to obtain high energy resolution. Consequently, they sometimes showed corrosion on surface electrodes in a weak nitric acid atmosphere and high humidity at plutonium handling facilities. In truth, evacuation orders have been issued because of conditions in the working chamber in JAEA. Such orders were attributed to external electromagnetic noise from high-frequency sealing machines that are used widely in the working chambers and to increased leakage current caused by corrosion on the surface electrode. Although some parts of these silicon surface barrier detectors have been replaced, and although the latest silicon semiconductor detectors for CAM have a thick surface electrode and/or a protective film, the vulnerability of semiconductor detectors to electromagnetic noise persists.

Izaki et al. applied an improved ZnS:Ag scintillator for a CAM to alleviate these difficulties related to silicon semiconductor detectors. They succeeded in measurement of alpha particles from plutonium in the presence of radon progeny nuclides by optimizing the ZnS:Ag scintillator thickness[5]. Nevertheless, some room for improvement remains in energy discrimination capability compared to that of a silicon semiconductor detector because it consists of semi-transparent powders.

As another approach for alpha particle measurement using a powder scintillator, Usuda et al. reported a phoswich detector composed of powder YAlO_3 (YAP) and $\text{Y}_3\text{Al}_5\text{O}_{12}$ (YAG) single-crystal scintillators [6, 7]. In their development, a YAP scintillator was adopted because of its short decay time of 27 ns. A single-crystal YAP scintillator had high energy resolution of 5.7% for 662 keV gamma rays [8]. However, the powder YAP scintillator had a similarly poor energy resolution for alpha particles compared to that of a conventional ZnS:Ag scintillator.

As a conjecture from the YAP powder scintillator application, a key to improving the energy resolution for alpha particles is how to suppress scattering and absorption at the grain boundary, and collecting scintillation light effectively into a light detector, e.g., a photomultiplier tube. One method is the use of a large grain size scintillator instead of a conventional powder scintillator. Janecek et al. reported correlation between the increased grain size of scintillator and increased collected light yield for X-rays using several scintillators: Lu_2SiO_5 , $\text{Bi}_4\text{Ge}_3\text{O}_{12}$, YAlO_3 , and CsBa_2I_5 [9]. Fukabori et al. reported similar results achieved with the increased grain size of a Y_2O_3 ceramic scintillator for alpha particles [10].

The authors have developed an alpha particle detector based on a $\text{Gd}_2\text{Si}_2\text{O}_7\text{:Ce}$ (cerium-doped gadolinium pyro-silicate, GPS:Ce) scintillator [11–15] with high light yield instead of the ZnS:Ag scintillator[16]. The GPS scintillator achieved energy resolution of 4.6% and 1.4 times the light yield of a conventional NaI:Tl scintillator for 662 keV gamma rays [17]. For 5.5 MeV alpha particles, light yields of 4.4 and 2.0 times compared with those of BGO [18] and YAP

scintillator [16] were reported, respectively. The central wavelength of scintillation light from a GPS was 395 nm. Actually, GPS:Ce has decay time of 50–120 ns, with no deliquescence or intrinsic-radioactivity. Moreover, it works under a high temperature environment of 300 °C [18]. In addition, GPS:Ce is expected to function for a neutron scintillator [20–22] because gadolinium has the maximum absorption cross section for thermal neutrons. After absorption, it predominantly emits a gamma-ray of 79 keV or an internal conversion electron of 29.3 keV and subsequent a KX-ray of 44 keV [23].

For alpha particle measurement and for suppression of beta and gamma-ray background noise, the scintillator must be less than 100 µm thick. Fabricating a large scintillator plate, i.e., a 5-cm-square with 100 µm thick from a GPS single crystal is difficult. To solve this difficulty, a mosaic scintillator plate made of GPS single crystal grains of around 550 µm was developed [16]. These grains were made by smashing a GPS polycrystal grown by a top seeded solution growth method. The size of the developed GPS mosaic scintillator plate was only ø 15 mm, but it had high energy resolution compared with the ZnS:Ag scintillator. It suppressed the influence from beta and gamma-rays. For this study, a 5-cm-square GPS mosaic scintillator plate was fabricated. Then energy resolution, uniformity, detection efficiency, and the radon progeny reduction ratio were evaluated, aiming at production of a continuous air monitor.

2. Experimental

2.1 Non-uniformity of pulse heights of a photomultiplier tube depending on the entrance window position

A conventional ZnS:Ag scintillator has poor energy resolution for alpha particles. Thereby, non-uniformity of pulse heights of a photomultiplier tube dependence on the position on an entrance window has no meaningful effect on a detector's performance. However, a GPS scintillator plate is expected to have energy resolution of around 10%. Therefore, the non-uniformity of pulse heights of a photomultiplier tube must be suppressed.

A solid line depicted in Fig. 1a) shows typical non-uniformity of the pulse heights of a photomultiplier tube (H7159; Hamamatsu Photonics KK) of 51 mm diameter. The data were obtained with a GPS single crystal of 5 × 5 × 5 mm that had been coupled directly on the entrance window of the photomultiplier tube by an optical compound. Alpha particles of 5.5 MeV from ²⁴¹Am were injected into the upper side of the scintillator through a copper collimator of ø 1 mm and 0.1 mm thickness. The pulse height at the center of the entrance window, i.e., $r = 0$, was normalized as 100%. It was decreased until 82% at $r = 16$ mm. Its

145 relative variation was 18%.

146 To suppress the influence of non-uniformity of pulse heights of a photomultiplier tube, a
147 high-transmission glass or an acrylic plastic was interleaved between the scintillator and the
148 entrance window. These plates were expected to diffuse the scintillation light and irradiate a
149 wider area of the photon-electron conversion layer. The dashed line and dashed-dotted line in
150 Fig. 1a) show pulse height distributions obtained with 3-mm-thick high-transmission glass or
151 the 5-mm-thick acrylic plate. Pulse heights respectively decreased until ca. 80% and 27.5% at r
152 $= 0$ for the high-transmission glass and the acrylic plate. Relative variations of pulse heights
153 between $r = 0$ and $r = 16$ were, respectively, 7% and 25%. The high-transmission glass
154 moderated the non-uniformity of pulse heights with acceptable light loss.

155 Then the same measurements were conducted with a 76 mm diameter photomultiplier tube
156 (H6559; Hamamatsu Photonics KK); higher uniformity of pulse heights was expected at around
157 a 40-mm-diameter central area. The solid line and dashed line in Fig. 1b) respectively show
158 pulse height distributions obtained with the direct coupling and the high-transmission glass.
159 Pulse heights were decreased to 93.4% at $r = 15$ mm for direct coupling. The relative variation
160 was moderated compared with that obtained using the smaller photomultiplier tube presented in
161 Fig. 1a). Moreover, the relative variation of pulse heights was suppressed until ca. 2% between r
162 $= 0$ and $r = 20$ mm by the high-transmission glass.

163 From this point forward, all measurements described herein were conducted with the
164 central part of $\varnothing 40$ mm region of the 76 mm diameter photomultiplier tube. As a substrate of a
165 scintillator plate, 3-mm-thick high-transmission glass was adopted.

166

167 2.2. Fabrication of a 5-cm-square GPS mosaic scintillator plate

168

169 A GPS polycrystalline body was grown using top-seeded solution growth method at
170 Hokkaido University. As the starting material, powders of Gd_2O_3 , SiO_2 , and CeO_2 were prepared
171 with respective purity of 4 nines, 5 nines, and 4 nines. These powders were mixed in
172 composition of $(\text{Gd}_{0.975}\text{Ce}_{0.025})_2\text{Si}_2\text{O}_7$. They were then sintered at 1650 °C for 6 hr in air.
173 Subsequently, a GPS polycrystalline body was grown using a high-radio-frequency furnace and
174 an iridium crucible [16]. The obtained GPS polycrystalline body was annealed in a N_2
175 environment for 12 hr.

176 The GPS polycrystal was mashed using an agate mortar and a muddler; then it was sorted
177 into particle size around 550 μm using screens. To improve the scintillator plate energy
178 resolution, fine powders were rinsed out using ethanol. The relation between grain size and
179 energy resolution and influence of fine powders was explained in an earlier report [18]. First,
180 the GPS grains were laid in the nearest proximity possible, with close packing on the

glass substrate. The GPS grains were fixed the glass substrate using epoxy adhesive (Crystal resin; Nissin Resin Co. Ltd.). Then they were polished mechanically until the GPS grain surface increased. The scintillator layer was removed from the glass substrate. Then the polished surface was turned over and fixed on the high-transmission glass substrate of $5\text{ cm} \times 5\text{ cm} \times 3\text{ mm}$. Finally, the scintillator layer was polished mechanically to $100\text{ }\mu\text{m}$. The respective ranges of 5.5 and 7.7 MeV alpha particles in GPS were 16 and $26\text{ }\mu\text{m}$. Consequently, the necessary thickness of the GPS scintillator layer was at least $30\text{ }\mu\text{m}$. However, an adhesive layer was present between the scintillator layer and the substrate. To suppress exfoliation of GPS grains during mechanical polishing, $100\text{ }\mu\text{m}$ thickness was adopted.

Fig. 2a) presents an optical overview of the fabricated GPS mosaic scintillator plate. In addition, Fig. 2b) shows an optical microscopic image of the surface: the white part was GPS; the filling rate of GPS on the surface was 62%.

2.3. Experimental setup

As described in subsection 2.1, a 76 mm diameter photomultiplier tube (H6559; Hamamatsu Photonics KK) was used. The GPS mosaic scintillator plate was fixed on the photomultiplier tube using optical compound. Output signals from the last dynode of the photomultiplier tube were sent into a measurement circuit composed of a delay line amplifier (460; Ortec), a stretcher (542; Ortec), and a multi-channel analyzer (WE7562; Yokogawa Analytical Systems Inc.).

Instead of alpha particles from ^{238}Pu , 5.5 MeV alpha particles from ^{241}Am surface source of $\varnothing 5\text{ cm}$ were used. Air dust collected on a HE40T dust collection filter in an airtight room enclosed within concrete walls was used as the radon progeny nuclide source. A HE40T dust collecting filter has cellulose fibers and fine glass fibers. The dust accumulation inside of the filter worsens the energy resolution over time. Although a membrane filter gives superior energy resolution, the HE40T filter was chosen for daily dust sampling operations in nuclear fuel plants.

In the measurement, a paper collimator with 0.26 mm thickness, the same as the conventional CAM system based on ZnS:Ag scintillator (RD-361Z; Toshiba Corp.) was set between the alpha particle source and the scintillator plate. Only the central part of $\varnothing 40\text{ mm}$ region of the scintillator was used. All measurements were conducted in air at room temperature.

3. Experimental results

3.1. Evaluation of uniformity of a GPS mosaic scintillator plate

Fig. 3a) shows response functions for 5.5 MeV alpha particles from the ^{241}Am source injected into the center part of the GPS mosaic scintillator plate through a collimator of $\varnothing$ 1 mm and 0.1 mm thickness in air. Energy resolution of 9.3% was achieved. Fig. 3b) shows a response function with energy resolution of 4.9% obtained using a GPS single crystal for comparison. The ratio between full width at half maximum of the peak and peak centroid channel was adopted as the energy resolution for these analyses. Total counts of these two spectra were almost identical.

Fig. 4 presents uniformity of a) collected light yield and b) count rate of the GPS mosaic scintillator plate. To avoid getting the influence of non-uniformity of pulse heights on the position of the entrance window, all five measurement points were set at the center of the entrance window of the photomultiplier tube by moving the scintillator plate. The collected light yield at the center, $r = 0$ mm, was normalized as 100%. Error bars respectively show FWHM for the collected light yield and square root counts for the count rate. Non-uniformities were smaller than $\pm 1\%$ and $\pm 3\%$ for the former and the latter.

3.2. Comparison of response functions between the GPS mosaic scintillator plate and ZnS:Ag scintillator for alpha particles

Fig. 5 presents response functions for 5.5 MeV alpha particles obtained by a) GPS mosaic scintillator plate, b) ZnS:Ag scintillator. Alpha particles of 5.5 MeV from the ^{241}Am surface source and radon progeny nuclides collected on the HE40T dust collection filter were used. The optimized ZnS:Ag scintillator in an earlier report [4] was used for energy discrimination. It was not a conventional ZnS:Ag scintillator used for an alpha survey meter.

The collection time of radon progeny nuclides on the HE40T dust collection filter was longer than 3 hr. This collection time was chosen assuming continuous air monitoring operations. Each uranium series radon progeny nuclide from ^{218}Po to ^{214}Po reaches an equilibrium state. Measurements were started within 5 min after collection. The measurement duration was approximately 60 min. The half-life of ^{218}Po , which emits 6.0 MeV alpha particle, is 3.1 min. Consequently, 6.0 MeV alpha particles from ^{218}Po mainly produce a spectrum within the first several minutes. In fact, 7.7 MeV alpha particles from ^{214}Po mainly produce the spectrum. The semblance half-life of ^{214}Po on the dust collection filter, considering the decay chain, is approximately 35 min.

Energy resolution of the scintillation detector for alpha particles is governed mainly by a combination of original energy resolution of the GPS mosaic scintillator plate, as portrayed in

Fig. 3a) and by the non-uniformity of pulse heights on the entrance window position, as presented in Fig. 1b). Although the ZnS:Ag scintillator was able to discriminate 5.5 MeV alpha particles from these from radon progeny nuclides, the GPS mosaic scintillator plate achieved higher energy resolution of 13% for 5.5 MeV alpha particles. In addition, the influence of beta and gamma-rays can be avoided by setting a lower level of discrimination.

The detection efficiency of the GPS mosaic scintillator plate was ca. 61% compared with a GPS single crystal; it was almost identical to the surface filling ratio of 62% measured by the optical microscope in subsection 2.2. The detection efficiency is expected to increase up to 70% by improvement of the fabrication process.

Related to detection sensitivity of the developed detector, the effective detection area was 778.2 mm² and 40 mm diameter. It has sufficient detection sensitivity for CAMS. Moreover, a 5-cm-square GPS scintillator plate was fabricated. It will be possible to achieve almost identical detection sensitivity to that of the largest passivated implanted planar silicon (PIPS) detector by combination with a larger photomultiplier tube.

3.3. Evaluation of radon progeny nuclide reduction ratio

To evaluate radon progeny nuclide reduction ability quantitatively for CAM, an evaluation index of $S_{\text{high}}/S_{\text{low}}$ was defined: the radon progeny nuclide reduction ratio. In that expression, S_{high} denotes the count of alpha particles from radon progeny nuclides in channels higher than the upper discrimination level. Also S_{low} represents the count of alpha particles from radon progeny nuclides in channels higher than the lower discrimination level. As depicted in Figs. 5a) and 5b), the upper discrimination levels were set at channels where 99% of 5.5 MeV alpha particles were measured. The lower discrimination levels were set at channels where the influence of beta and gamma-rays was avoidable. From Fig. 5a) and 5b), the radon progeny nuclide reduction ratio of the GPS mosaic scintillator plate and the ZnS:Ag scintillator were, respectively, 64.5 and 40.1%. However, the value for a silicon surface barrier semiconductor detector was ca. 68% [4]. The alpha particle detector based on the GPS mosaic scintillator plate achieved a high radon progeny nuclide reduction ratio near that of a semiconductor detector, with high resistance to electromagnetic noise and corrosion.

The developed GPS mosaic scintillator plate had an approximately 100 μm thick scintillator layer. Consequently, the lower discrimination level was set at a higher channel than that of the ZnS:Ag scintillator. It is possible to produce scintillator layer thickness of down to 50 μm. In this case, the lower discrimination level is expected to be half.

3.4. Influence of pulse-height non-uniformity of the entrance window position on the energy

290
291 Fig. 6 shows changes of energy resolution and radon progeny nuclide reduction ratio on a
292 sensitive area that was controlled by changing the paper collimator diameter. The energy
293 resolution and radon progeny nuclide reduction ratio improved with the decrease of the sensitive
294 area. Finally, the former became 10.9%. The latter became 67.6% at $\varnothing$ 10 mm. Those were
295 almost identical levels to those of a silicon surface barrier semiconductor detector. This result
296 shows that even using the 76 mm diameter photomultiplier tube and the high-transmission glass
297 substrate, some room for improvement remains.

298 This experimentally obtained result, i.e., change of energy resolution, was worse than
299 expected results shown in Fig. 1 and described in section 2.1. The change was probably
300 attributable to the difference between the GPS scintillator thicknesses used for the respective
301 measurements. For the measurement portrayed in Fig. 1, a GPS single-crystal scintillator with 5
302 mm thickness was used. Scintillation light diffused in the GPS single crystal. It moderated the
303 difference of pulse height on the position. Therefore, the possibility exists that it improves
304 energy resolution by increasing the thickness of the high-transmission glass substrate by around
305 8 mm with the balance of the passing rate. Another sophisticated choice would be adoption of a
306 position-sensitive photomultiplier tube or a multi-pixel photon counter that can achieve a
307 uniform pulse height distribution by calibration.

311 Conclusion

312
313 For alpha particle measurements, a 5-cm-square GPS mosaic scintillator plate was
314 fabricated from GPS single-crystal grains of around 550 μm . The scintillator layer thickness
315 was approximately 100 μm . The surface filling rate was ca. 62%. To suppress the influence of
316 non-uniformity of pulse heights of a photomultiplier tube, the central $\varnothing$ 40 mm part of the 76-
317 mm-diameter photomultiplier tube and the high-transmission glass substrate were adopted.
318 Energy resolution of 13%, detection efficiency of 61%, and a radon progeny nuclide reduction
319 ratio of 64.5% were achieved using the developed detector. The new alpha particle detector
320 fulfills a high reduction ratio of radon progeny nuclides approaching that of a silicon
321 semiconductor detector. High resistance to electromagnetic noise and corrosion were achieved.

322 For this study, a 5-cm-square scintillator plate with high energy resolution was developed.
323 The detector performance was limited by non-uniformity of pulse heights of a photomultiplier
324 tube. As future work, a scintillation detector having the same radon progeny reduction ratio and

325 [reliability](#) as a silicon semiconductor detector [is possible](#) by combination of the GPS mosaic
326 scintillation plate and a position sensitive photomultiplier tube or similar technique. The
327 detection efficiency may be improved up to 70% by extension of the fabrication method
328 developed for this study. For further improvement, adoption of a ceramic growth process [23] or
329 other technique will be required.

330

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394 Table and Figure captions

395

396

397 Table **Characteristic energy** of alpha particles from nuclear fuel related nuclides in plutonium
 398 handling facilities and radon progeny nuclides. Energy and decay time were extracted
 399 from [Ref. 4](#). Alpha particles of 7.7 MeV from ^{214}Po belonging to the uranium–radium
 400 series are the most important background for continuous air monitoring for working
 401 chambers.

402

Characteristic energy of alpha particles (MeV)	Nuclides	Half-life	
4.2	^{238}U	$4.47 \times 10^9 \text{ y}$	Nuclear fuel related nuclides
4.4	^{235}U	$7.04 \times 10^8 \text{ y}$	
4.9	^{242}Pu	$3.75 \times 10^5 \text{ y}$	
5.2	^{239}Pu	$2.41 \times 10^4 \text{ y}$	
	^{240}Pu	$6.56 \times 10^3 \text{ y}$	
5.5	^{238}Pu	87.7 y	
	^{241}Am	$4.32 \times 10^2 \text{ y}$	
6.0	^{218}Po	3.10 m	Natural radioactive nuclides (Radon progeny nuclides)
6.1	^{212}Bi	60.6 m	
6.8	^{216}Po	0.145 s	
7.7	^{214}Po	$1.64 \times 10^{-4} \text{ s}$	
8.8	^{212}Po	$2.99 \times 10^{-7} \text{ s}$	

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408 Fig. 1

409 Non-uniformities of pulse heights of photomultiplier tubes: a) H7159 ($\varnothing$ 51 mm) and b) H6659
410 ($\varnothing$ 76 mm). The distance from the center of the entrance window was r . A GPS single-crystal
411 scintillator of $5 \times 5 \times 5$ mm was used. Alpha particles of 5.5 MeV were injected into the GPS
412 scintillator from the upper side through a copper collimator. The pulse height obtained with
413 direct coupling of the scintillator and the entrance window at $r = 0$ was normalized as 100%.
414 Dashed lines in a) and b) were obtained with 3-mm-thick high-transmission glass. A dashed–
415 dotted line in a) was obtained with a 5-mm-thick acrylic plate.

416

417 Fig. 2

418 a) Optical image of a fabricated 5-cm-square GPS mosaic scintillator plate. b) Optical
419 microscopic image of the surface of the GPS mosaic scintillator plate (white part, GPS grains;
420 gray part, epoxy resin). The surface filling rate of the GPS obtained from b) was 62%.

421

422 Fig. 3

423 Examples of response function obtained by a) A 5-cm-square GPS mosaic scintillator plate and
424 b) a GPS single crystal scintillator for 5.5 MeV alpha particles. Alpha particles were injected
425 into scintillators through a copper collimator of $\varnothing$ 1 mm and 0.1 mm thickness in air. Energy
426 resolutions of the scintillators were, respectively, 9.3% and 4.9%.

427

428 Fig. 4

429 Uniformities of a) the collected light yield and b) count rate of the GPS mosaic scintillator plate.

430

431 Fig. 5

432 Examples of response function obtained using a) GPS mosaic scintillator plate and b) ZnS:Ag
433 scintillator for alpha particles of 5.5 MeV and from radon progeny nuclides. Irradiated areas
434 were central parts of $\varnothing$ 40 mm for each scintillator. Radon progeny nuclides collected on the
435 HE40T dust collection filter were used. Upper and lower discrimination levels are shown in
436 each figure. Radon progeny reduction ratios were 64.5% and 41% for the GPS mosaic
437 scintillator and ZnS:Ag scintillator.

438

439 Fig. 6

440 Changes of the energy resolution and radon progeny nuclide reduction ratio on a sensitive area
441 were controlled by changing the paper collimator diameter.

442

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6