INTRODUCTION

There are a variety of survey meters for personal and environmental monitoring of radiation, such as ionisation chambers, Geiger-Müller counters, and scintillation counters. There is no radiation survey meter that can discriminate among alpha particles, beta particles, and gamma-rays with one material. Previously, undoped poly(ethylene terephthalate) (PET) has been shown to be an effective material for beta particle and gamma-ray detection. Here, we demonstrate a prototype survey meter for alpha particles based on undoped PET. A 140 × 72 × 1-mm PET substrate was fabricated with mirrored surfaces. It was incorporated in a unique detection section of the survey meter that directly detects alpha particles. The prototype exhibited an unambiguous response to alpha particles from a 241Am radioactive source. These results demonstrate that undoped PET can perform well in survey meters for alpha particle detection. Overall, the PET-based survey meter has the potential to detect multiple types of radiation, and will spawn an unprecedented type of radiation survey meter based on undoped aromatic ring polymers.

MATERIALS AND METHODS

There is no radiation survey meter that can discriminate among alpha particles, beta particles, and gamma-rays with one material. Previously, undoped poly(ethylene terephthalate) (PET) has been shown to be an effective material for beta particle and gamma-ray detection. Here, we demonstrate a prototype survey meter for alpha particles based on undoped PET. A 140 × 72 × 1-mm PET substrate was fabricated with mirrored surfaces. It was incorporated in a unique detection section of the survey meter that directly detects alpha particles. The prototype exhibited an unambiguous response to alpha particles from a 241Am radioactive source. These results demonstrate that undoped PET can perform well in survey meters for alpha particle detection. Overall, the PET-based survey meter has the potential to detect multiple types of radiation, and will spawn an unprecedented type of radiation survey meter based on undoped aromatic ring polymers.

KEY WORDS: poly(ethylene terephthalate), aromatic ring polymer, radiation survey meter, alpha particle, count rate, plateau.

I INTRODUCTION

There are a variety of survey meters for personal and environmental monitoring of radiation, such as ionisation chambers, Geiger-Müller counters, and scintillation counters. An appropriate survey meter must be selected for the type of radiation source. For example, in scintillation counters, ZnS(Ag) works for alpha particles, plastic for beta particles, and NaI(Tl) for gamma-rays. However, there are no radiation survey meters based on only one material that can discriminate among alpha particles, beta particles, and gamma rays.

Plastic scintillation materials have been the subject of considerable interest. This was triggered by the existence of wavelength conversion processes having unknown mechanisms. Recent reports provided a considerable understanding of radiation detection, and created a new category of scintillation materials made from aromatic ring polymers that do not require doped fluorescent guest molecules. Undoped poly(ethylene terephthalate) (PET) has been used to detect both beta particles and gamma-rays. Because it is a common material used in plastic bottles, PET has certain advantages for radiation detection.

Alpha Particle Response for a Prototype Radiation Survey Meter Based on Poly(ethylene terephthalate) with Un-doping Fluorescent Guest Molecules

Philip NGUYEN,*1 Hidehito NAKAMURA,*1,2 Hisashi KITAMURA,*2 Nobuhiro SATO,*1 Tomoyuki TAKAHASHI,*1 Daisuke MAKI,*1 Masaya KANAYAMA,*1 Yoshiyuki SHIRAKAWA*3 and Sentaro TAKAHASHI*1

(Received on December 18, 2015) (Accepted on February 4, 2016)

For example, commercially available plastic bottles have been used to detect beta particles and gamma-rays from the naturally occurring radionuclide 40K, and have been performed well for radiation education in elementary schools. Alpha particle detection will expand the application range for PET-based radiation monitoring. In this context, we have developed a prototype survey meter that has a unique section for PET-based detection of alpha particles. The response to alpha particles demonstrates that a PET-based survey meter has the potential to detect various radiation sources.

II MATERIALS AND METHODS

The structure of PET is:

A 140 × 72 × 1-mm plate with a density of 1.33 g/cm³ was machined from PET resin (Teijin Co., Ltd.). Both large surfaces were polished with a succession of six waterproof sandpapers (~320, ~400, ~600, ~800, ~1000, ~1500; Kohnan Shoji Co., Ltd.). Mirrored surfaces were created by buffing with four abrasive soaps (501MC-16, 506MC-16, 5605S-16AU; Sankei Co., Ltd. & Acrysunday; Acrysunday Co., Ltd.). A photograph of the transparent plate is shown in Fig. 1; it emits pale-blue light with a 385-nm emission maximum.

Figure 2 depicts a unique detection section that allows samples to be directly placed on the PET plate. The 23 × 39.5 × 14.5-cm frame is made of polyvinyl chloride. Light from the plate induced by the radioactive sample is detected with a photomultiplier tube (PMT, R7373A-01; Hamamatsu.
Photonics Co., Ltd.) that has a 25-mm-diameter hemispherical window. A shielding pad prevents light leakage. Here, the source was radioactive $^{241}$Am (AMRB5862; Nuclitec GmbH), which primarily emits 5,486-keV alpha particles and 60-keV gamma-rays. To isolate the response to alpha particles, the threshold of the meter was adjusted to be above 60 keV. The centre of the source was placed at coordinates on the plate that were located above the apex of the PMT window.

Signals from the PMT are processed by a meter (SPS-210Z; Ohyo Koken Kogyo Co., Ltd.) with a 30-s time constant, and then monitored with a data logger (MR-8870; Hioki Co., Ltd.). The count rates for the $^{241}$Am radioactive source and background were each acquired ten times and averaged, while controlling the PMT supply voltages in the dynamic range. To verify alpha particle detection, a 40-μm thick aluminium foil (Yisu Trading Co., Ltd) was held between the PET plate and the $^{241}$Am radioactive source. The count rate was again obtained ten times under this condition and averaged.

**III RESULTS AND DISCUSSION**

The dependences on PMT supply voltages of all the count rates obtained by the PET survey meter are shown in Fig. 3.

Each data set exhibited a plateau over the dynamic range of the supply voltage. The count rates for the $^{241}$Am radioactive source, after passing through the aluminium foil, are indistinguishable from that of the background. Thus, the count rate does not include the 60-keV gamma-rays. Hence, when the count rates detected through the aluminium foil are subtracted from those of the unimpeded $^{241}$Am radioactive source, the net result is the alpha particle count rate, as displayed in Fig. 4. The extracted alpha particle rates (182 ± 10 cpm) were obtained with a linear fit. These results demonstrate that undoped PET can perform well in survey meters for alpha particle detection. Optimisation of the PET plate and the PMT configuration improves the detection efficiency. Surface treatments of the PET plate can also lead to improvements.20–22) The detection section with an optimised geometry and light shielding enables evaluation of radioactive samples with variable thicknesses. In addition, it is effective to design an entrance window for transmitted alpha particles. This will expand the application range of the PET survey meter because various types of radiation can be detected by selecting suitable PET thicknesses. There is great interest in undoped PET responses that will enable discrimination among alpha particles, beta particles, and gamma-rays. Next, it will be important to demonstrate the PET response to neutrons.

**IV CONCLUSION**

We have developed a prototype survey meter that has a unique PET-based detection section for alpha particles. The characteristics of undoped PET and the unique detector design...
enable alpha particle detection. The alpha particle response exhibited a plateau over the dynamic range of the PMT supply voltage. More detailed optical characteristics of undoped PET for alpha particle detection will be reported elsewhere. A PET survey meter has the potential to detect multiple types of radiation, and will stimulate development of an unprecedented type of radiation survey meter based on aromatic ring polymer undoped with fluorescence guest molecules, makes a significant contribution to radiation education.

ACKNOWLEDGEMENTS

This research was supported by the Kyoto University and the National Institute of Radiological Sciences. The authors thank the KUR Research Program for the Scientific Basis of Nuclear Safety for partial support at this work. The authors express gratitude to Mr. T. Kamata for valuable discussions. The authors are grateful to Dr. T. Murata, Ms. M. Nakatani, and Ms. M. Yasaku for their cooperation.

REFERENCES

1) G. Knoll; “Radiation Detection and Measurement”, 4th edition (2010), Wiley, New York.
2) W. R. Leo; “Techniques for Nuclear and Particle Physics Experiments: A How-to Approach”, 2nd edition (1992), Springer-Verlag, Berlin and Heidelberg.
3) J. Beringer et al. (Particle data group); Review of particle physics, Phys. Rev. D, 86, 010001 (2012).
4) G. H. V. Bertrand, M. Hamel and F. Guerra; Current status on plastic scintillators modifications, Chem. Eur. J., 20 (48), 15660–15685 (2014).

Fig. 3 Dependence of count rates on PMT supply voltages. Count rates for the $^{241}$Am radioactive source, the same source after passage through the aluminium foil, and the background are indicated with open squares, open triangles and open circles, respectively.

Fig. 4 Count rates for alpha particles extracted from Fig. 3. The straight line indicates a linear fit.

5) H. Nakamura, Y. Shirakawa, H. Kitamura, N. Sato, O. Shinji, K. Saito and S. Takahashi; Mechanism of wavelength conversion in polystyrene doped with benzoazethene: emergence of a complex, Sci. Rep., 3, 2502 (2013).
6) H. Nakamura, H. Kitamura, O. Shinji, K. Saito, Y. Shirakawa and S. Takahashi; Development of polystyrene-based scintillation materials and its mechanisms, Appl. Phys. Lett., 101, 261110 (2012).
7) H. Nakamura, Y. Shirakawa, H. Kitamura, N. Sato, O. Shinji, K. Saito and S. Takahashi; Light propagation characteristics of high-purity polystyrene, Appl. Phys. Lett., 103, 161111 (2013).
8) I. Sen, M. Ureff er, D. Penumadu, S. A. Young, L. F. Miller and A. N. Mabe; Polyester composite thermal neutron scintillation films, IEEE Trans. Nucl. Sci., NS59 (4), 1781–1786 (2012).
9) R. Uppal, I. Sen, D. Penumadu, S. Young, M. J. Ureff er and L. F. Miller; 6Li embedded biaxially stretched scintillation films for thermal neutron detection and neutron/gamma discrimination, Adv. Eng. Mater., 16, 196–201 (2013).
10) H. Nakamura, Y. Shirakawa, H. Kitamura, N. Sato, O. Shinji, K. Saito and S. Takahashi; Optical characteristics of pure poly (vinyltoluene) for scintillation applications. Nucl. Instrum. Methods A, 770, 131–134 (2015).
11) D. Flöhs, A. Flöhs, M. Ebenau and M. Eichmann; Polyethylene naphthalate scintillator: a novel detector for the dosimetry of radioactive ophthalmic applicators, Ocul. Oncol. Pathol., 2 (1), 5–12 (2016).
12) H. Nakamura, Y. Shirakawa, H. Kitamura, N. Sato and S. Takahashi; Detection of alpha particles with undoped poly(ethylene naphthalate). Nucl. Instrum. Methods A, 739, 6–9 (2014).
13) S. Nagata, M. Mitsuzuka, S. Onodera, T. Yaegashi, K. Hoshi, M. Zhao and T. Shikama; Damage and recovery processes for the luminescence of irradiated PEN films, *Nucl. Instrum. Methods. B*, **315**, 157–160 (2013).

14) H. Nakamura, H. Kitamura and R. Hazama; Radiation measurements with heat-proof polyethylene terephthalate bottles, *Proc. R. Soc. A*, **466**, 2847–2856 (2010).

15) S. Nagata, H. Katsui, K. Hoshi, B. Tsuchiya, K. Toh, M. Zhao, T. Shikama and E. R. Hodgson; Recent research activities on functional ceramics for insulator, breeder and optical sensing systems in fusion reactors, *J. Nucl. Mater.*, **442**, Supplement 1, S501–S507 (2013).

16) H. Nakamura, Y. Shirakawa, S. Takahashi, T. Yamano, Y. Kobayashi, R. Hazama, C. Takagi and O. Hasebe; Cheap educational materials for understanding radiation, *Phys. Educ.*, **47**, 17–18 (2012).

17) V. Kumar, Y. Ali, R. G. Sonkawade and A. S. Dhaliwal; Effect of gamma irradiation on the properties of plastic bottle sheet, *Nucl. Instrum. Methods. B*, **287**, 10–14 (2012).

18) H. Nakamura, Y. Shirakawa, H. Kitamura, T. Yamada, Z. Shidara, T. Yokozuka, P. Nguyen, T. Takahashi and S. Takahashi; Blended polyethylene terephthalate and polyethylene naphthalate polymers for scintillation base substrates, *Radiat. Meas.*, **59**, 172–175 (2013).

19) H. Nakamura, Y. Shirakawa, N. Sato, H. Kitamura and S. Takahashi; Undoped polycarbonate for detection of environmental radiation, *Jpn. J. Health Phys.*, **49** (2), 98–101 (2014).

20) Y. Shirakawa, H. Nakamura, T. Kamata, K. Watai, M. Mitsunaga, Z. Shidara and F. Murakawa; Radiation counting characteristics on surface-modified polyethylene naphthalate scintillators, *Radioisotopes*, **62**, 879–884 (2013).

21) H. Nakamura, Y. Shirakawa, M. Kanayama, N. Sato, H. Kitamura and S. Takahashi; A model survey meter using undoped poly (ether sulfone), *Nucl. Instrum. Methods. A*, **780**, 127–130 (2015).

22) Y. Shirakawa, H. Nakamura, T. Kamata and K. Watai; A fast response radiation detector based on a response prediction method for decontamination, *Radiat. Meas.*, **49**, 115–119 (2013).