

Development of a Multi Radiation Type Survey Meter
Using Aromatic Ring Polymers Undoped with Fluorescent
Molecules

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Abstract

There are numerous types of survey meters. They are essential to radiation management in various public and private sectors worldwide, from nuclear power to research to medicine. They were needed in response to the Fukushima Daiichi Nuclear Power Plant disaster that followed the 2011 Great East Japan earthquake.

Plastic scintillation materials, which are a main component in a survey meter, require the doping of fluorescent guest molecules and are useful for beta particle detection. However, we have shown that common polymers that possess aromatic rings in their structure such as polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and polyethersulfone (PES) do not require the special doping process for radiation detection.

The objective of this research is to develop a new type of radiation survey meter that has two unique features in the detection section with 140 mm x 72 mm x 1 mm PET, PEN, and PES sheets and demonstrate its unique feature for alpha particle, beta particle and low energy gamma ray detection. This study should provide basic knowledge to generate multi-radiation detectors with undoped aromatic ring polymers.

Keywords: Undoped aromatic ring polymer, Radiation survey meter, Detection section,, Multi-radiation (alpha particles, beta particles, gamma rays, and neutrons), basic performance

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1. Introduction

1.1 Purpose

Because we cannot see, taste, or smell ionizing radiation produced by radioactive materials, we depend on instruments to indicate their presence. Radioactive materials can exist in different physical states and be indistinguishable from non-radioactive materials without the use of special markings. Therefore, numerous types of radiation detectors exist, from scintillation detectors to gas filled detectors, and are needed to detect ionizing events produced by ionizing radiation.

i. Massive accident at Japan's Fukushima Daiichi Nuclear Power Plant

On March 11, 2011, a magnitude 9.0 earthquake and tsunami occurred off the Pacific coast of Tohoku in northeastern Japan [1]. The tsunami resulted in meltdowns at three reactors, causing the release of large amounts of radioactive materials. Radiation measurements were crucial in the aftermath of the disaster to provide reliable information for dose assessment and decision-making. Radiation detectors with long-term stability are needed to monitor high dose rate environments.

ii. Environmental Monitoring System

Various systems for environmental monitoring and contamination surveying were established by the Japanese government immediately after the earthquake. On March 12th, nationwide environmental monitoring was started by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) with assistance from universities and other organizations. The Nuclear Regulatory Authority and United States Department of Energy also supported monitoring, which consisted of measurements of air dose rates, radioactivity in fallout, tap water, soil, seawater, ocean sediment, and air dust. The Ministry of Health, Labor, and Welfare provided measurements for foodstuffs, and the Ministry of Agriculture, Forestry, and Fisheries provided measurements of farmland soil and fertilizers.

These radiation detectors are used at about 3600 monitoring posts in the Fukushima prefecture after the disaster to show measurement data in real time. These monitoring posts are set up in schools, parks, and other public areas, operate 24 hours, and transmit collected data to the server every 10 minutes. These readings are performed by Japan Atomic Energy Agency (JAEA), MEXT, and other organizations.

iii. Demand for New Radiation Detectors

The enormous damaged area in Fukushima requires extensive surveying and investigation for contamination, which requires an increase in the number and types of detectors [2][3][4][5][6][7]. Radiation detectors are used for personal monitoring, with the most common detectors being ZnS for alpha particle detection and plastic scintillation detectors for beta particle detection. In addition, NaI(Tl) scintillation detectors and ionization chambers are commonly used for environmental monitoring and are still in use both in and out of the 20 km zone around the Fukushima Daiichi Nuclear Power Plant.

There is currently no radiation detector for multi-radiation detection. Various types of detectors are used to detect specific radiation types due to the high performance of specialized detectors. In addition, these various types of detectors are costly, further reducing their availability. A multi-type high-performance radiation detector that is low cost is needed for personal and environmental monitoring.

iv. Outline of the Chapters

Chapter 1 introduces the basic concepts of radiation and radiation detection. It provides an overview of radiation detectors and includes a list of current detectors available. It also introduces scintillation survey meters. It finally provides a summary of the Fukushima Nuclear Power Plant accident and how such detectors were used in the aftermath of the event.

Chapter 2 introduces the main scintillation materials used for this research, undoped aromatic ring polymers PET, PEN, and PES. It reviews their characteristics and properties as scintillation materials.

Chapter 3 shows the developed unique detection section of a survey using the produced PET, PEN, and PES sheets, and demonstrates their performance for beta particle detection from a radioactive source.

Chapter 4 demonstrates the performance of the multi-radiation detector for alpha particles from a radioactive source. It shows that the undoped aromatic ring polymer survey meter is able to detect multiple types of radiation, including alpha, beta, and gamma radiation.

Chapter 5 indicates the advantages of using aromatic ring polymers for radiation detection. It compares the developed survey meter with typical survey meters, and discusses the current and future applications of such survey meters and aromatic ring polymers.

1.2 Introduction to Radiation

Radioactivity occurs as a result of nuclear instability, meaning that the nucleus has either too many or not enough neutrons. These are radioisotopes that emit radiation (alpha, beta, gamma-ray, x-ray, neutron) due to their instability.

An alpha particle contains two protons and two neutrons. It carries a +2 charge and strongly interacts with matter. They travel a few centimeters through air and can be easily stopped by a thin sheet of paper.

A beta particle is a subatomic particle that is equivalent to an electron. It carries a -1 charge. Beta particles travel a few meters and can be stopped by a sheet of aluminum foil.

Gamma rays and X-rays are forms of electromagnetic radiation. They have no mass and no charge. Both gamma rays and X-rays are highly penetrating and can travel straight through matter.

Neutrons exist during nuclear fission and fusion. Neutron particles lack charge and travel hundreds to thousands of meters in the air.

1.3 Survey Meters

Numerous types of instruments exist to detect the presence of ionizing radiation. Although, the main focus of this research is on plastic-type scintillation survey meters, the other types of detectors will be briefly discussed.

1.3.1 Why Radiation Survey Meters are Needed

Survey meters are useful radiation management in the nuclear power industry, as well as in scientific research, medicine, and other public and private sectors globally. These were essential devices in the response to the Fukushima Daiichi Nuclear Power Plant disaster that followed the 2011 Great East Japan earthquake.

Radiation detectors allow us to understand and determine the level of risk or contamination in case of an accident. Since there are many sources of radiation, and many different radioisotopes have their own characteristics and energies, several types of detection instruments are required to match the specific radiation types for efficient detection.

1.3.2 Scintillation Survey Meters

Scintillation survey meters consist of a scintillation material, photomultiplier tube, and an electronic measuring device. When radiation interacts with the scintillation materials, the materials are excited and emit photons [8][9]. Photomultiplier tubes (PMT), a type of photosensor, detect the external light using a photocathode and generate electrons proportional to the light intensity as shown in Figure 1.

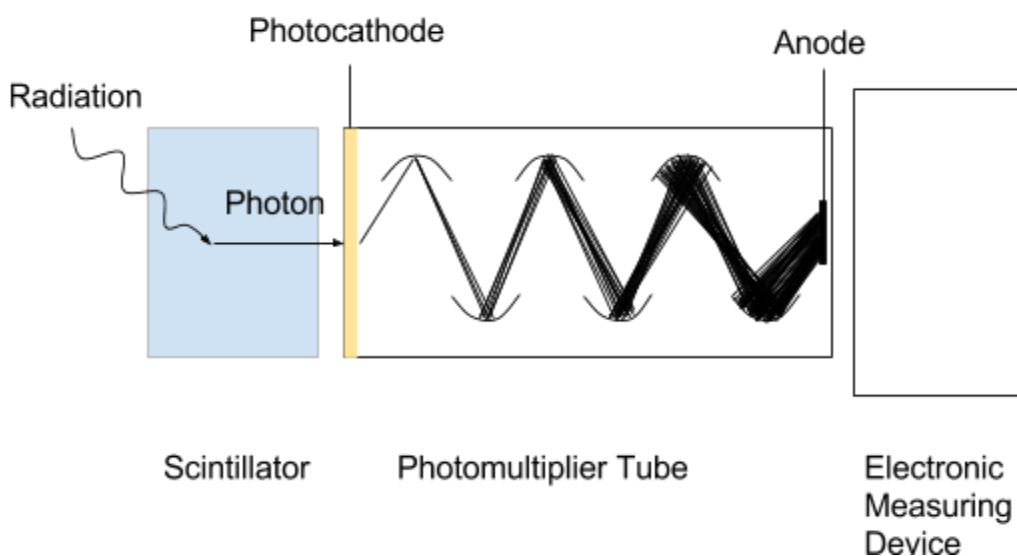


Figure 1. Schematic of a typical scintillation survey meter. More details can be seen in reference [10][11].

For targeted radiation, the type of scintillation survey meter must be considered [12].

Organic materials used in scintillation survey meters are efficient with beta detection. On the other hand, while inorganics are good for gamma detection, they cannot detect alpha or beta due to their need for shielding.

Plastic scintillation survey meters are used for detecting beta particles, as shown in Figure 2.



Figure 2. Photograph of a plastic scintillation survey meter (Ohyo Koken Kogyo Co. Ltd.).

Zinc Sulfide detectors are widely used for alpha detection but they may become unusable due to the effects of its own luminescence. A zinc sulfide detector is shown in Figure 3.



Figure 3. Photograph of a ZnS Detector (Hitachi Aloka).

NaI(Tl) counters are used widely for gamma ray detection. The crystals absorb moisture easily, so they are sealed before being placed on the entry window. A sodium iodide counter is shown in Figure 4.



Figure 4. Photograph of a NaI detector (Hitachi Aloka).

1.3.3 Other Counters

Geiger-Mueller (GM) counters are used to measure beta, and gamma radiation, as shown in Figure 5.



Figure 5. Photograph of a GM counter (Hitachi Aloka).

Neutron rem counters, shown in Figure 6, are used to measure real-time neutron radiation dose rates from the environment. Although there are also gas types, typical neutron counters are scintillation neutron detectors.



Figure 6. Photograph of a neutron rem counter (Hitachi Aloka).

Ionization chambers, shown in Figure 7, are used to measure large amounts of radiation and are more commonly used to measure gamma radiation intensity and gamma dose measurements in radiation protection. They commonly use air as the fill gas and operate at low voltages so no multiplication of ionization events occur.



Figure 7. Photograph of an ionization chamber (Hitachi Aloka).

2. Undoped Scintillation Materials

2.1 Brief History and Recent Work

Plastic scintillation materials were first produced in the early 1940s with the development of the photomultiplier tube [13][14]. They consist of a base material doped with a few fluorescent molecules (fluors) and can emit light when exposed to radiation. The base materials contain aromatic hydrocarbons [13]. The fluors are used to shift the light into a detectable range due to the low sensitivity of the photosensors. Recent improvements in photosensor technology have increased their light sensitivity and detection at short wavelengths (~300 nm regions) and allowed for other readily available and better performing plastic scintillators to be developed that do not require fluors [15].

2.1.1 Base Substrates in Common Plastic Scintillation Materials

Polystyrene (PS) and polyvinyl toluene (PVT) are typically used as the base substrates in plastic scintillation materials [16].

PS is a widely used and common plastic found in regular everyday items such as CD cases, containers, and bottles. The structure is shown in Figure 8. A polystyrene-based scintillator has a density of 1.05 g/cm³, and a refractive index of 1.59 [17]. The optical characteristics of high purity PS were recently reported [18]. The high purity PS emits light at an emission maximum of 310 nm [18].

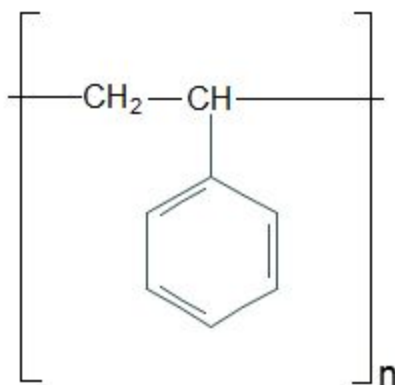


Figure 8. Molecular structure of PS, $(\text{C}_8\text{H}_8)_n$.

PVT is used as a plastic scintillator after doping it with fluors. The structure of PVT is shown in Figure 9. A polyvinyl toluene based scintillator has a density of 1.03 g/cm³, and a refractive index of 1.58 (Saint-Gobain Co., Ltd.) [19]. The optical characteristics of high purity PVT, consisting of a para and meta mixture, were reported [20]. The high purity PVT emits light at an emission maximum of 315 nm [20].

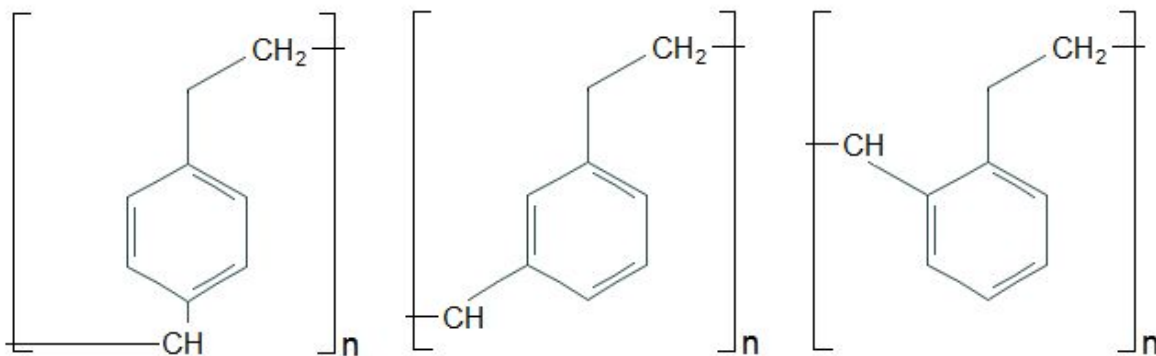


Figure 9. Molecular structures of PVT (C₉H₁₀)_n.

The characteristics of PS and PVT are summarized in Table 1. PS and PVT need the doping of fluorescent molecules, because they emit undetectable short wavelength light for radiation detection. In addition, their densities are relatively low, which results in low interaction in the material for gamma detection [13]. To remove these problems, our group started to research other aromatic ring polymers as alternatives to the plastic scintillation material.

Table 1. PS and PVT characteristics [17][19].

Substrate	Formula	Density (g/cm ³)	Refractive Index	Maximum emission (nm)
PS	(C ₈ H ₈) _n	1.05	1.59	310
PVT	(C ₉ H ₁₀) _n	1.02	1.58	315

2.1.2 Undoped Aromatic Ring Polymers as Scintillation Materials

We previously demonstrated that aromatic ring polymers without fluorescent guest molecules, such as polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and polyethersulfone (PES) do not require doping with fluors to detect light induced by radiation [18][20][21][22][23][24]. These studies provided a deeper understanding for radiation detection [25][26][27][28][29]. Moreover, the applications have drawn interest and have been studied globally [30][31][32][33][34].

The undoped aromatic ring polymers are easily available, their production process is simple, and they can be easily shaped and produced on a large scale. PET resin is widely used in the production of bottles, containers, packaging, and personal care products. PEN resin is especially increasing in popularity worldwide, and is becoming more available in Japan for tableware, packaging material, and containers [35][36][37]. PES resin is used to manufacture various items from cookware to medical products.

These features have excellent advantages in the field of radiation detection. Their optical characteristics as scintillation materials are demonstrated and covered in the next section.

2.2 Materials and Methods

To estimate the optical characteristics (refractive index, and excitation and emission spectra), sample plates of PET, PEN, and PES were prepared. The PET, and PEN plates (31 x 31 x 5 mm) were manufactured by Teijin Co., Ltd. The PES plate (31 x 31 x 5 mm) was manufactured by Sumitomo Heavy Industries Co., Ltd. The densities of PET and PEN are both 1.33 g/cm³ [32]. The density of PES is 1.37 g/cm³, higher than that of both PET and PEN [32]. They have similar structures, containing aromatic rings in the repeat unit, as seen in Figures 10, 11, and 12.

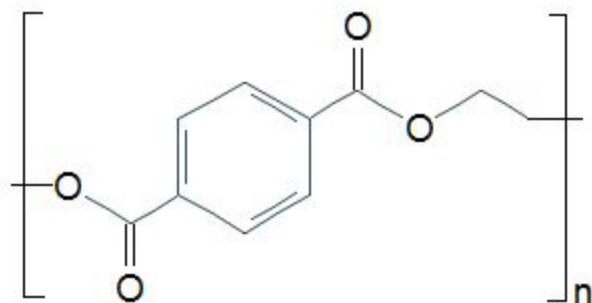


Figure 10. Molecular structure of PET, (C₁₀H₈O₄)_n. It consists of one benzene ring in the repeat unit.

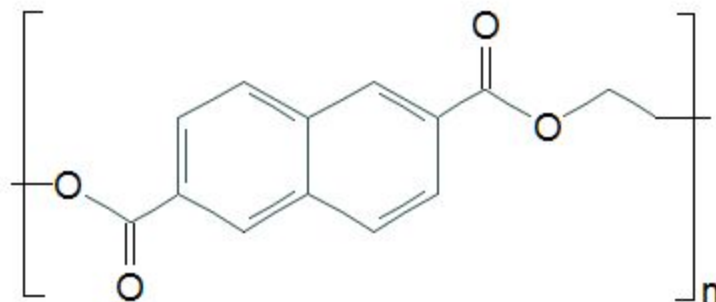


Figure 11. Molecular structure of PEN, $(C_{14}H_{12}O_4)_n$. It consists of a naphthalate ring in the repeat unit.

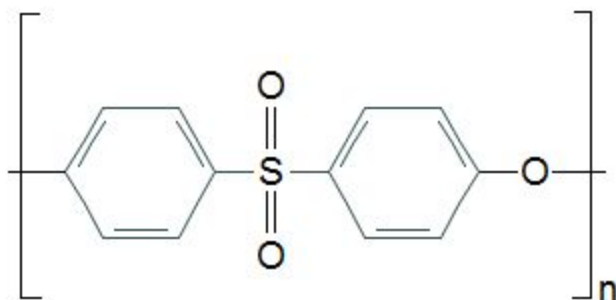


Figure 12. Molecular structure of PES, $(C_{12}H_{12}O_3S)_n$. It consists of two benzene rings in the repeat unit.

The refractive indices were determined using a refractometer (PR-2; Carl Zeiss, Jena, Germany) at the sodium D line of 589 nm.

For the emission and excitation spectra, three plates were placed in a fluorescence spectrophotometer (F-2700; Hitachi High-Technologies Co.) as shown in Figure 13. The fluorescence spectrophotometer, using a xenon lamp, emits light directed and focused towards the plates. The emitted light from the plates is then read by a mounted photomultiplier tube as shown in Figure 14. The data are obtained by FL Solutions 4.1 (Hitachi High-Technologies Co.).

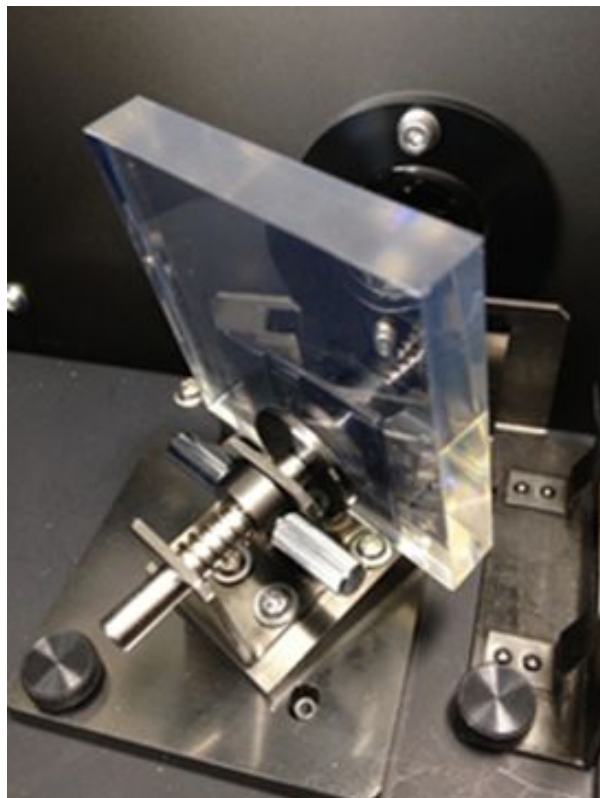


Figure 13. View of a sample plate in the fluorescence spectrophotometer (F-2700; Hitachi High-Technologies Co.).

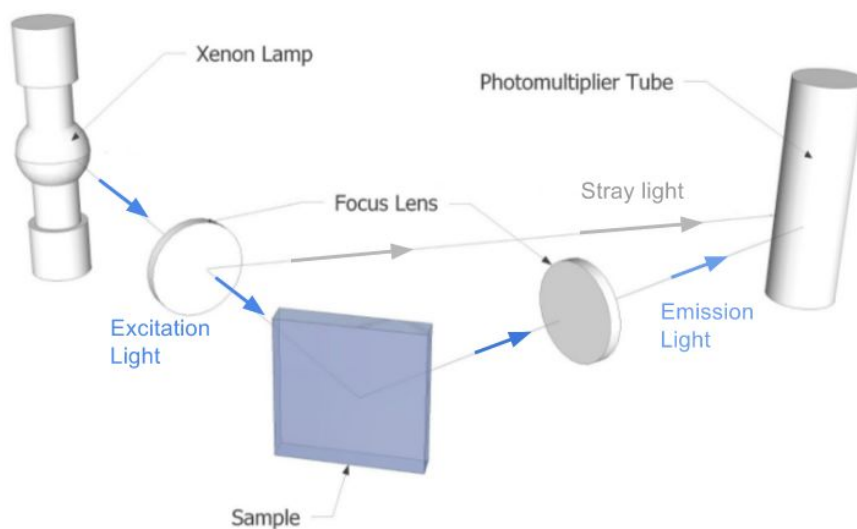


Figure 14. Schematic of the fluorescence spectrophotometer.

2.3 Results

The refractive index of the PET plate was 1.57 for the sodium D-line. Figure 15 shows the fluorescence from the PET plate [38]. The x-axis is the emission wavelength (nm) and the y-axis is the excitation wavelength (nm). The figure shows that the fluorescent peak is at the intersection of the 340 nm excitation wavelength and the 385 nm emission wavelength. This result demonstrates that PET emits detectable light in the short wavelength region.

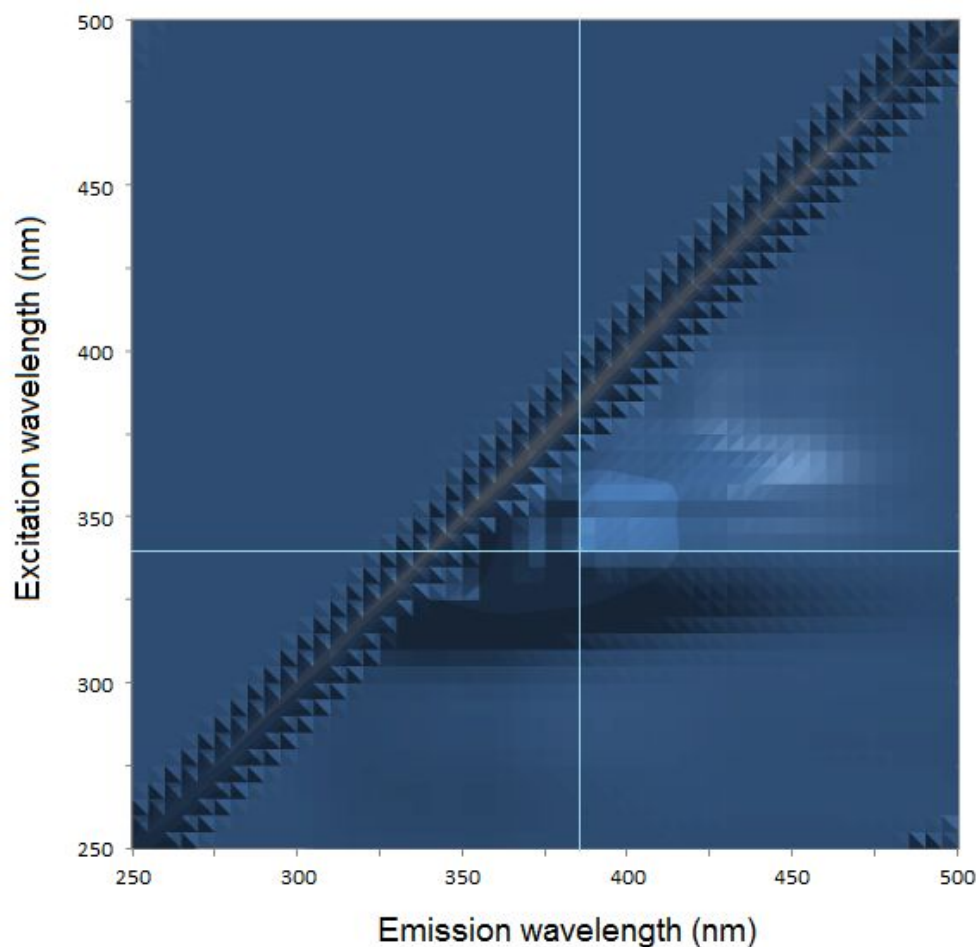


Figure 15. Correlation between the emission and excitation wavelengths in the PET fluorescence. The emission maximum and the excitation maximum are shown by light blue lines. The diagonal line is generated by stray light generated in the UV-Vis spectrometer.

The refractive index of the PEN plate was 1.65 for the sodium D-line. Figure 16 shows the fluorescence from the PEN plate [38]. The figure shows that the fluorescent peak is at the intersection of the 370 nm excitation wavelength and the 425 nm emission wavelength. This result demonstrates that PEN emits visible light in the violet to blue region.

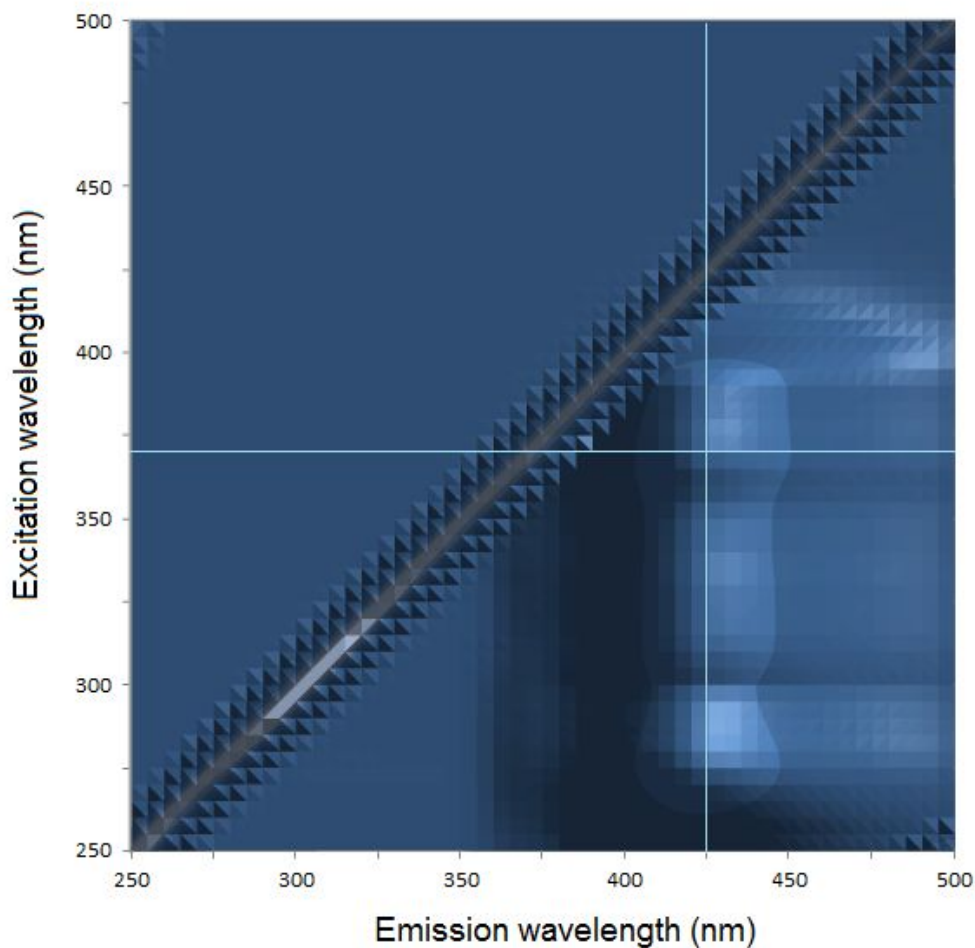


Figure 16. Correlation between the emission and excitation wavelengths in the PEN fluorescence. The emission maximum and the excitation maximum are shown by light blue lines. The diagonal line is generated by stray light generated in the UV-Vis spectrometer.

The refractive index of the PES plate was 1.65 for the sodium D-line, which is the same value for the PEN plate. Figure 17 shows the fluorescence from the PES plate [32]. The figure shows that the fluorescent peak is at the intersection of the 315 nm excitation wavelength and the 350 nm emission wavelength. This result demonstrates that PES emits detectable light in the short wavelength region. Additionally, its wavelength is shorter than that of PEN and PET.

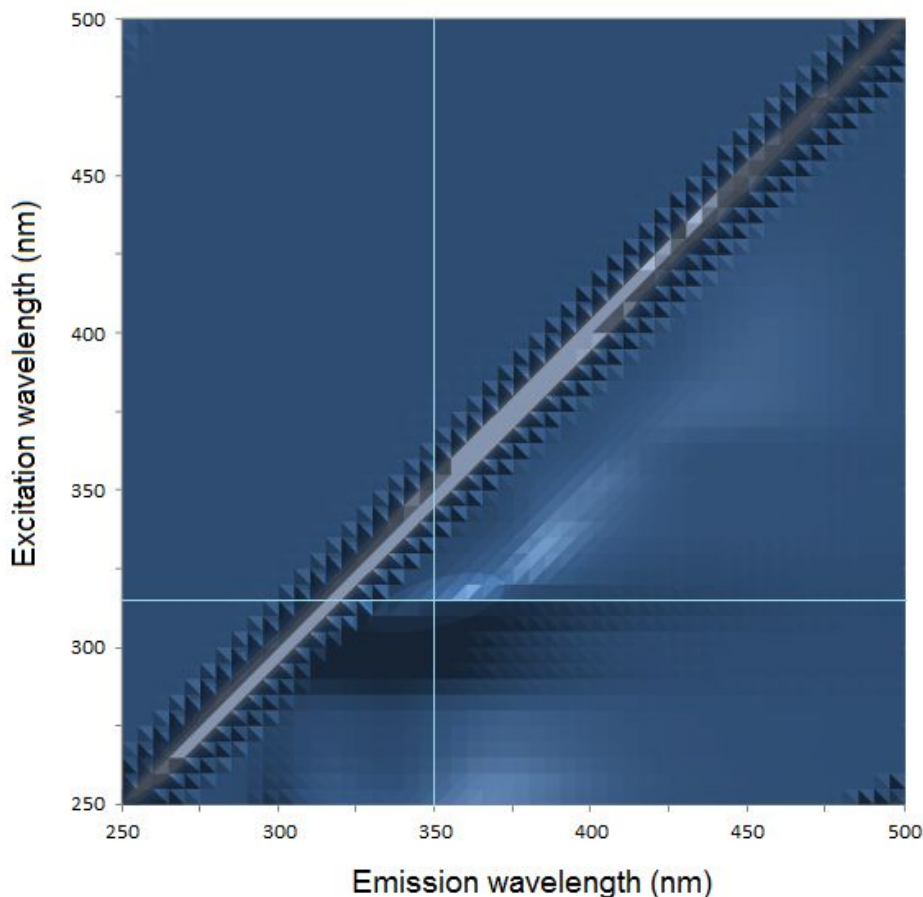


Figure 17. Correlation between the emission and excitation wavelengths in the PES fluorescence. The emission maximum and the excitation maximum are shown by light blue lines. The diagonal line is generated by stray light generated in the UV-Vis spectrometer.

2.4 Discussion

The characteristics of PET, PEN, and PES are summarized in Table 2. Their chemical structures are relatively complicated in comparison to PS and PVT. Additionally, they include heavy elements, such as oxygen or sulfur. Their densities are higher than those of PS and PVT, which leads to more interactions with radiation [13]. The emission maximums of light from PET, PEN, and PES are higher than those from PS and PVT, and are in the detectable wavelength regions

for typical photosensors. It demonstrates that these aromatic ring polymers require no doping with fluors. Thus, we have revealed that PET, PEN, and PES have excellent optical characteristics for radiation detection.

They have potential to be more advantageous. In the next chapter, we show one application using these materials.

Table 2. PET, PEN, PES characteristics [30][32][38].

Substrate	Formula	Density (g/cm ³)	Refractive Index	Maximum Emission (nm)
PET	C ₁₀ H ₈ O ₄	1.33	1.57	385
PEN	C ₁₄ H ₁₂ O ₄	1.33	1.65	425
PES	C ₁₂ H ₁₂ O ₃ S	1.37	1.65	350

3. Development of a Unique Detection Section

3.1 Purpose

There is a large variety of survey meters for personal and environmental monitoring of radiation. However, there is currently no radiation survey meter that can differentiate among alpha particles, beta particles, and gamma rays in a single scintillation material. Thus, we have developed a survey meter detection section using the fabricated sheets of undoped aromatic ring polymers PEN, PET, and PES and determined their radiation counting efficiencies.

Plastic scintillation survey meters are used for beta particle detection [10]. In a previous study, PEN has been used to demonstrate beta response [22]. Initially, to compare the performance of the developed survey meter with those of typical plastic scintillation surveys, beta particle response with the developed detection section are demonstrated in this chapter.

3.2 Materials and Methods

3.2.1 Development of Thin Undoped Aromatic Ring Polymer Sheets

To develop the detection section of a survey meter, sheets were produced from PET, PEN, and PES resins. The sizes were $72 \times 140 \times 1$ mm. The surfaces of the sheets were polished using common sandpapers (#320, #400, #600, #800, #1000, #1500; Kohnan Shoji Co., Ltd.). Then, the mirrored surfaces were created by buffing with common soaps (501MC-16, 506MC-16, 5605S-16AU; Sankei Co., Ltd. & Acrysunday; Acrysunday Co., Ltd.).

The photographs of the plates can be seen in Figures 18 through 23 . The PET sheet is transparent. It emits blue light when exposed to UV, as seen in Figure 19. The PEN sheet is also transparent. It also emits blue light when exposed to UV, as seen in Figure 21. The PES sheet has an amber-colored transparency. However, it can confirm blue light when exposed to UV, as seen in Figure 23.

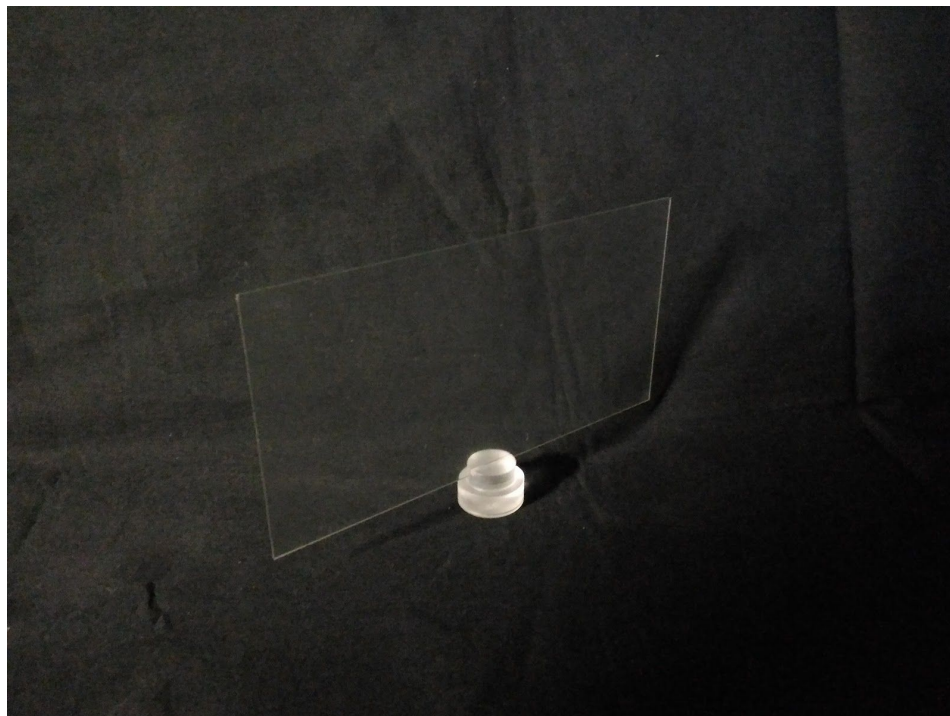


Figure 18. Photograph of the PET sheet.

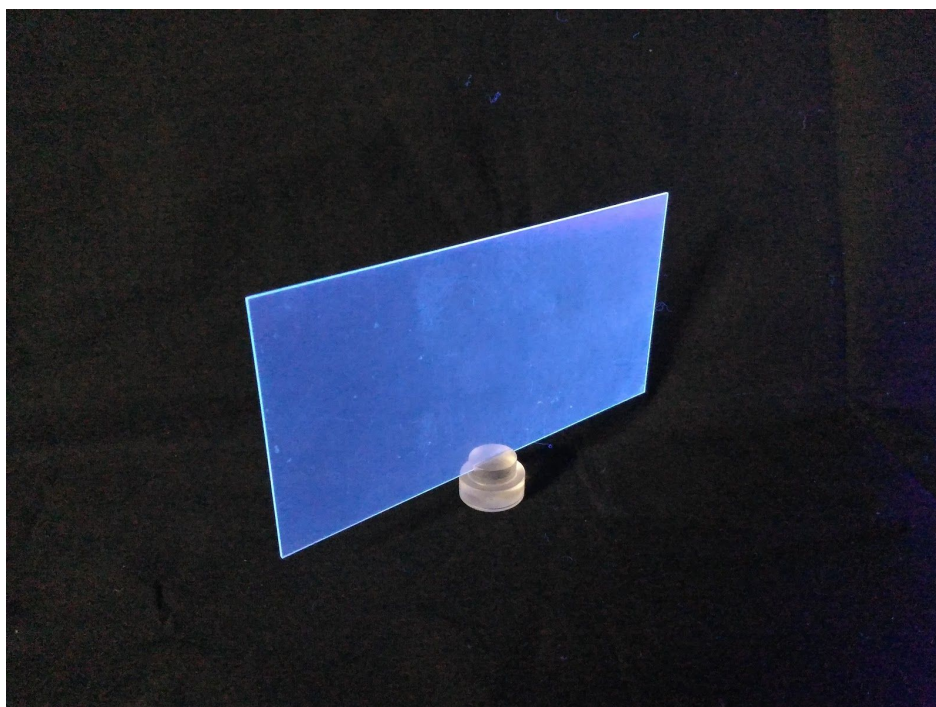


Figure 19. Photograph of the PET sheet excited by ultraviolet light.

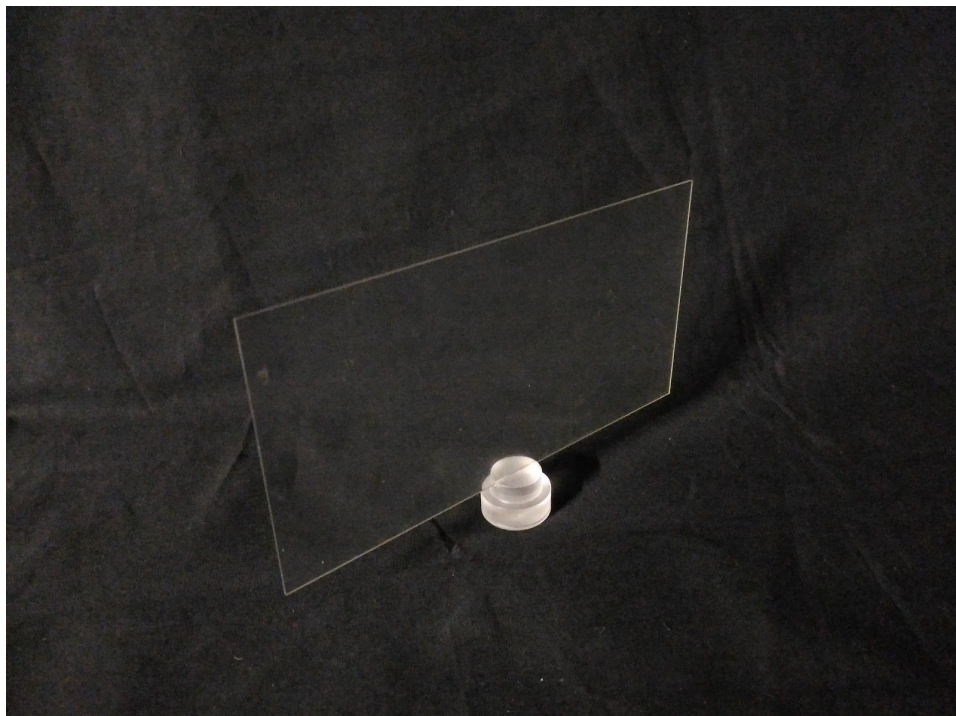


Figure 20. Photograph of the PEN sheet.

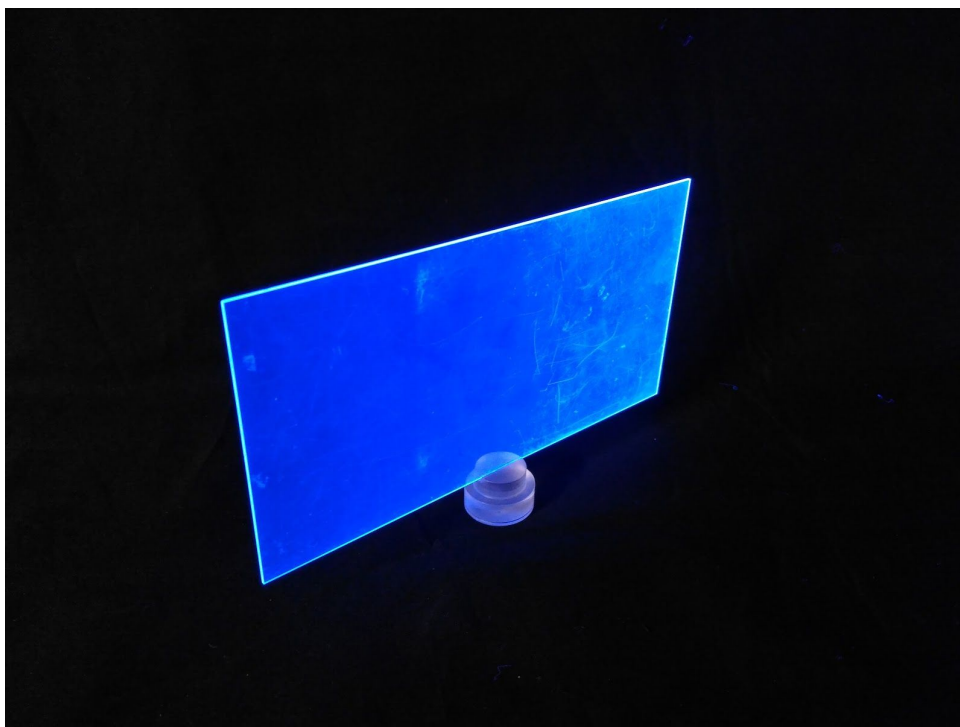


Figure 21. Photograph of the PEN sheet excited by ultraviolet light.

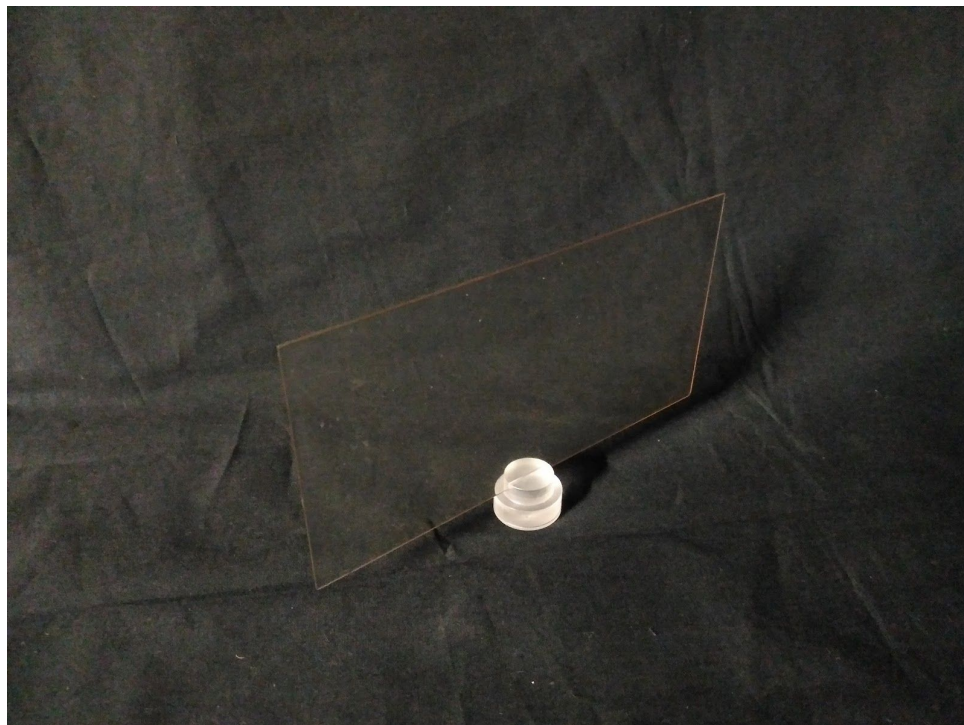


Figure 22. Photograph of the PES sheet.

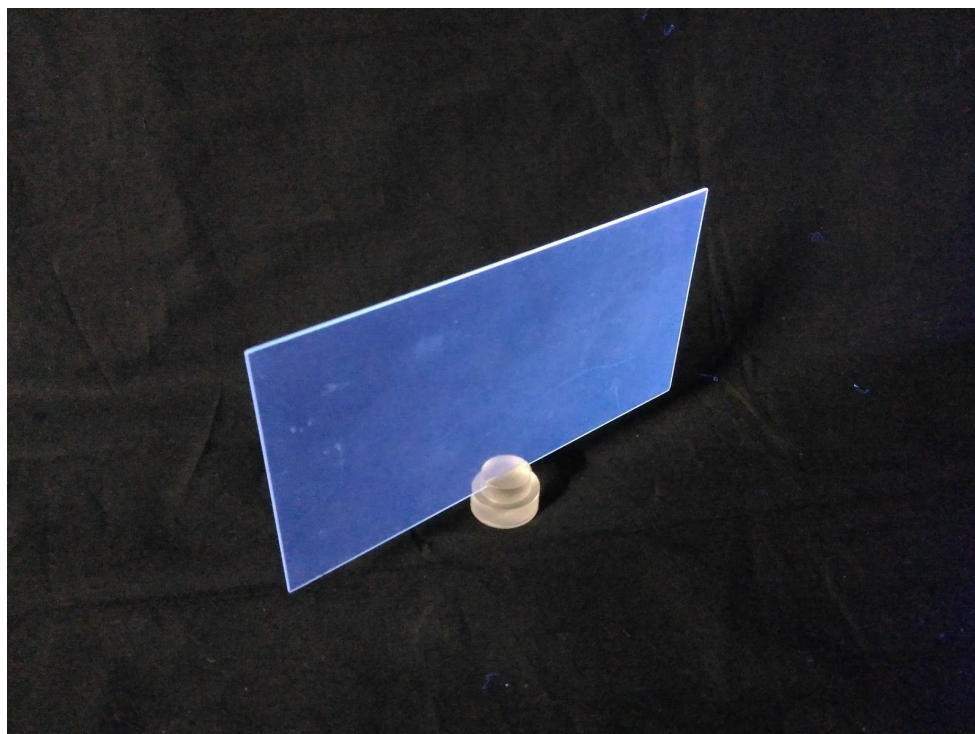


Figure 23. Photograph of the PES sheet excited by ultraviolet light.

3.2.2 Geometrical Configuration of the Detection Section

We have designed the detection section of a survey meter with the produced aromatic ring sheets. It simply consists of a sheet, a photomultiplier tube (PMT) as a photosensor, and a light shield pad to prevent light leakage. The photo and schematic are shown in Figure 24 and 25, respectively. The frame is made from polyvinyl chloride (PVC), and its outer size is 224 x 380 x 140 mm. The output signals from the PMT are transferred to a meter with a cable. Thus, there is a cable drain.

There are two unique features in this detection section. One is that the radioactive samples can be directly placed on the sheets. Alpha particles are short ranged and rapidly lose their energy in matter [13]. Thus, it is difficult to detect alpha particles from radioactive samples. However, this geometry provides a potential to allow alpha particle penetration. Second, there is no acrylic frame to support the sheets. For typical detection sections, acrylic frames are used to support the sheets. We previously reported the optical characteristics of acrylics [39]. The absorption spectrum shows the maximum peak in the 340 nm region. The absorbance prevents light from the sheets from being transferred efficiently. Thus, there is no acrylic frame to support the sheet in this detection section.

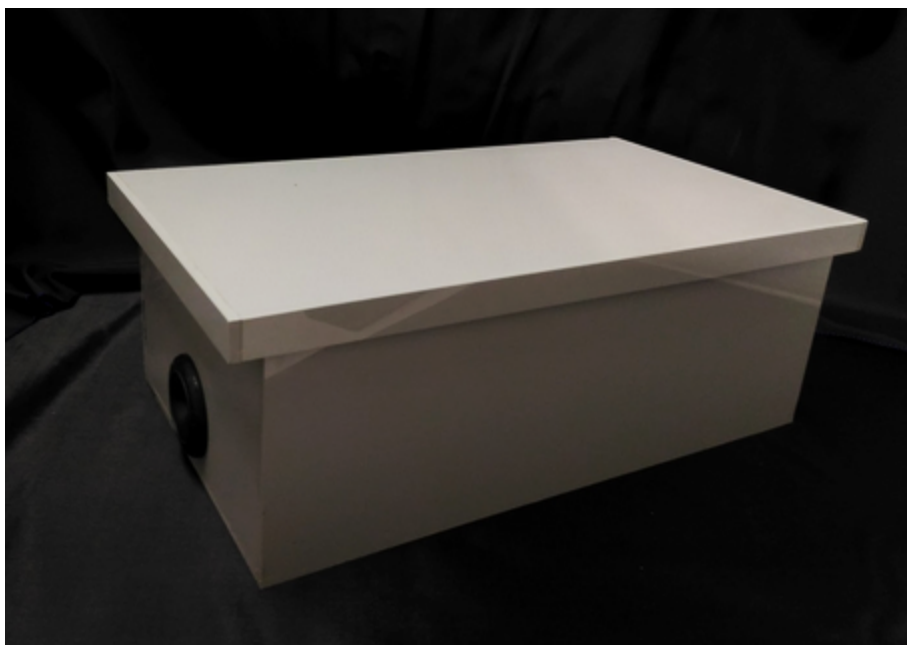


Figure 24. Photo of the detection section.

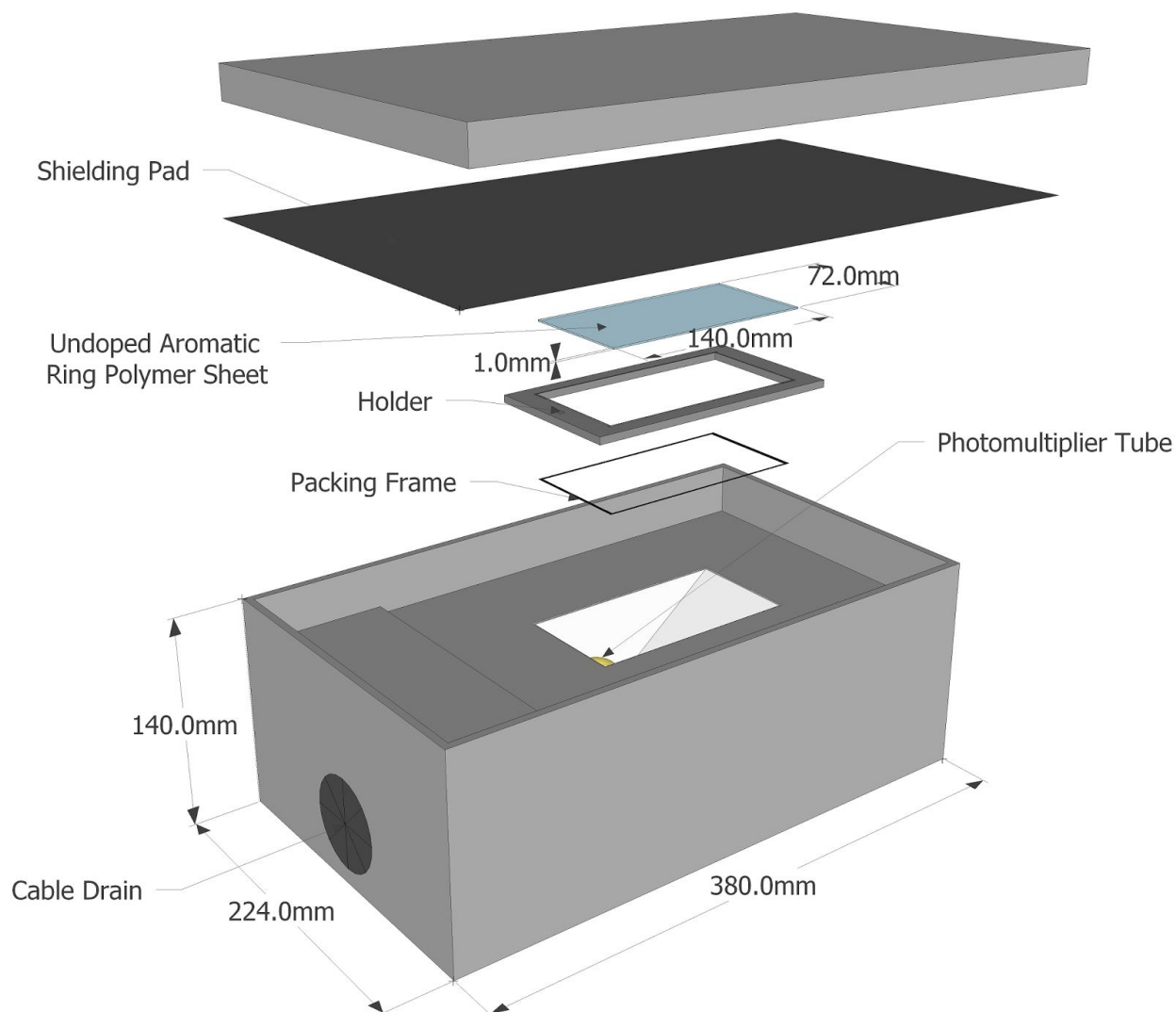


Figure 25. Schematic of the detection section of the survey meter showing components.

Light from the sheets produced by the radioactive sample is detected by the PMT (R7373A-01, Hamamatsu Photonics Co. Ltd.) which has a 25 mm diameter hemispherical window shown in Figure 26. The characteristics for the PMT are summarized in Table 3.

Table 3. Characteristics of the PMT (R7373A-01; Hamamatsu Photonics Co. Ltd.) The information is provided by Hamamatsu Photonics Co. Ltd [40].

Parameter	Description / Value	Unit
Spectral Response	300-650	nm
Maximum Quantum Efficiency	380-400	nm
Wavelength of Maximum Response	420	nm
Window material	Borosilicate glass	--
Maximum supply voltage	1250	V



Figure 26. Photo of the PMT showing the sensitive region (R7373A-01; Hamamatsu Photonics Co. Ltd.).

3.2.3 Setting

The performance of the detection section for beta particles was estimated from a radioactive source. Moreover, the stability of the detection section was observed by controlling the supply voltage (700–1000 V) in the PMT dynamic range. The experimental setup is shown in Figure 27. A Strontium-90 radioactive source (SIRB5870, Nuclitec GmbH), which has a half-life of about 28.8 years, was used. It emits beta particles with the maximum ending energies of 546 keV and 2.28 MeV (from daughter Y-90).

Additionally, to discriminate beta particle counts from background counts, a 5 mm thick PVC plate was used. The signals from the PMT were received by a meter (SPS-210Z; Ohyo Koken Kogyo Co. Ltd.). The time constant of the meter was set to 30 s.

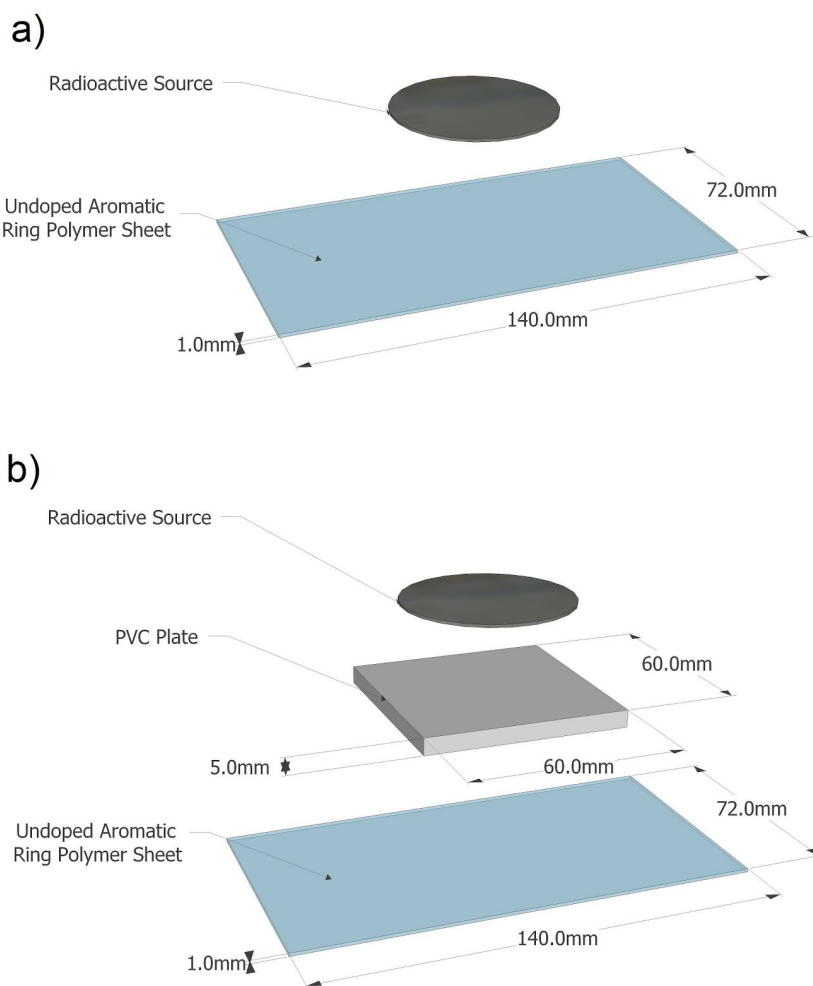


Figure 27. Schematic of the experimental setup for detecting beta particles. (a) The Sr-90 source is directly placed on each aromatic ring polymer sheet. (b) The 5 mm thick PVC plate is used to prevent beta particle penetration.

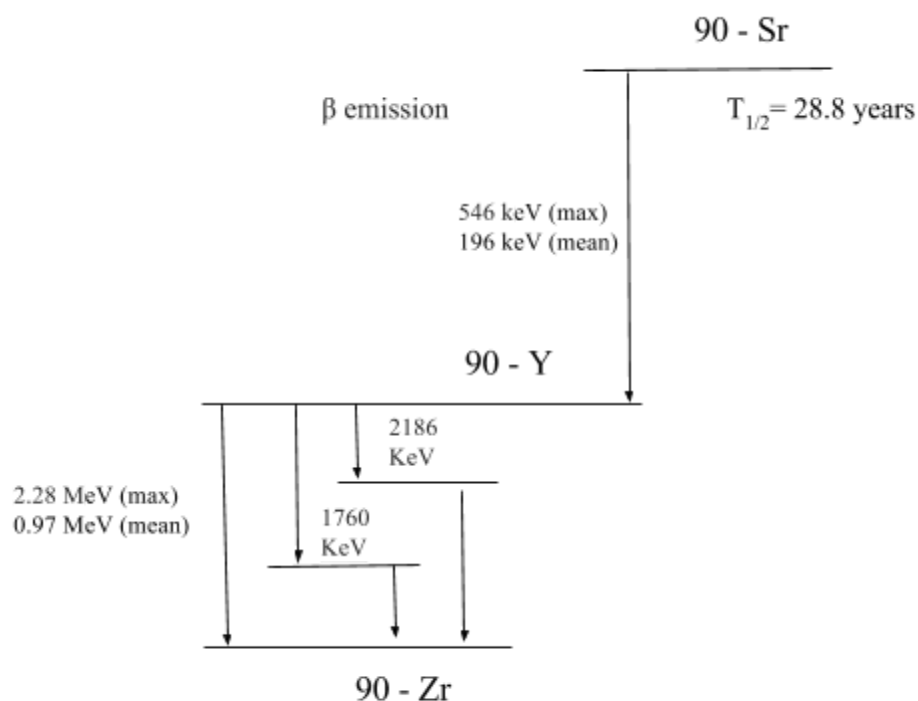


Figure 28. Sr-90 decay scheme.

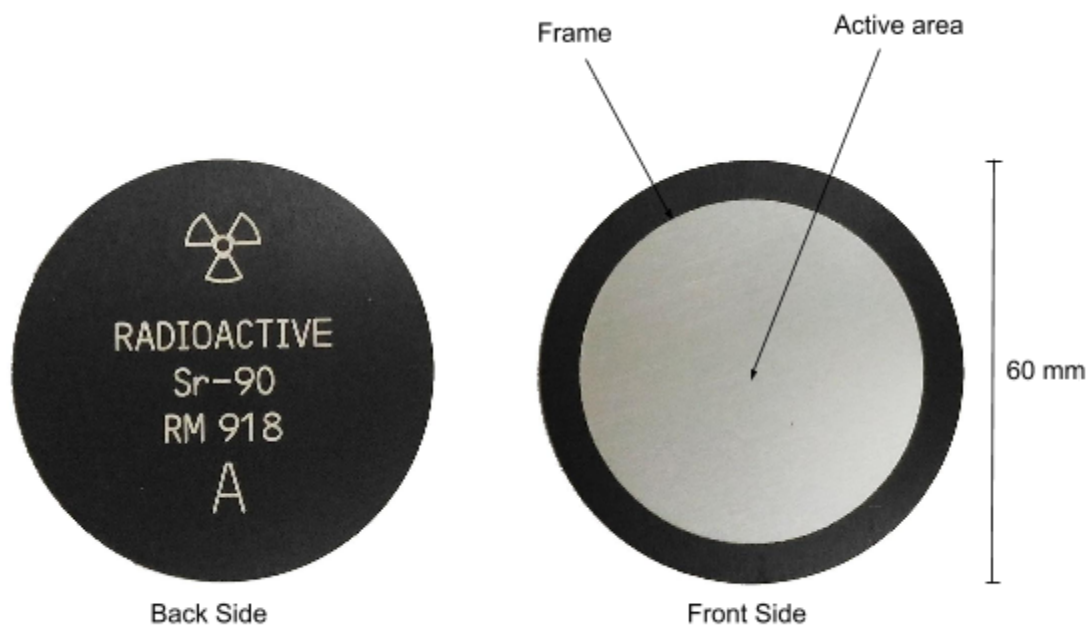


Figure 29. Photograph of the Sr-90 source (SIRB5870, Nuclitec GmbH) showing the front and back sides. The front side contains the active surface.

Table 4 shows the characteristics of the Sr-90 source (SIRB5870, Nuclitec GmbH).

Table 4. Characteristics of the Sr-90 source (SIRB5870, Nuclitec GmbH).

Parameter	Description / Value	Unit
Activity	149	Bq
Beta surface emission rate	190	S ⁻¹ in 2 π steradian
Active surface dimension	40.6	mm
Dimension	50 x 0.8	mm
Calibration date	9 October 2008	--
Relative uncertainty of activity	5	%
Relative uncertainty of beta surface emission	3	%

The data acquisition system (DAQ) was configured for measuring count rates and its diagram are shown in Figure 30 and 31. The developed detection section is monitored by a meter. The output signals from the meter (SPS-210Z; OKEN) are recorded on a compact flash card (Hioki 9830, Hioki e.e. Co.) by a data logger (MR-8870; Hioki e.e. Co.). The data is transferred to the PC and analyzed by the computer software Physics Analysis Workstation (PAW, V. 2.12/22) [41].

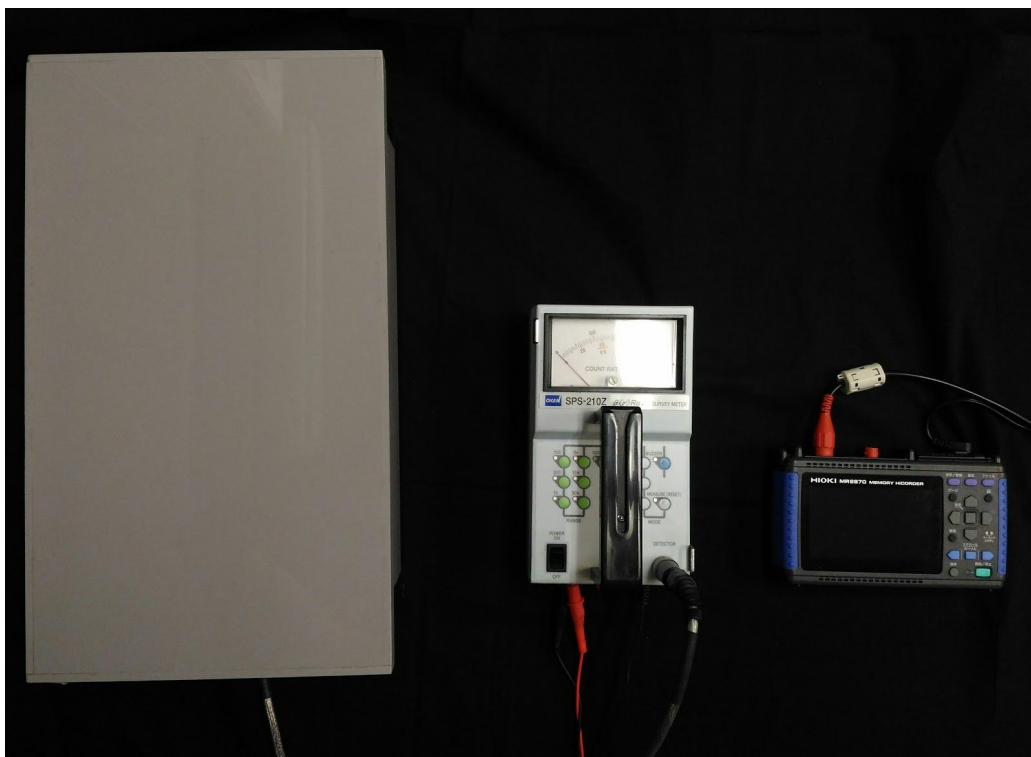


Figure 30. Photo of the data acquisition system showing the developed detection section, meter, and data logger (from left to right).

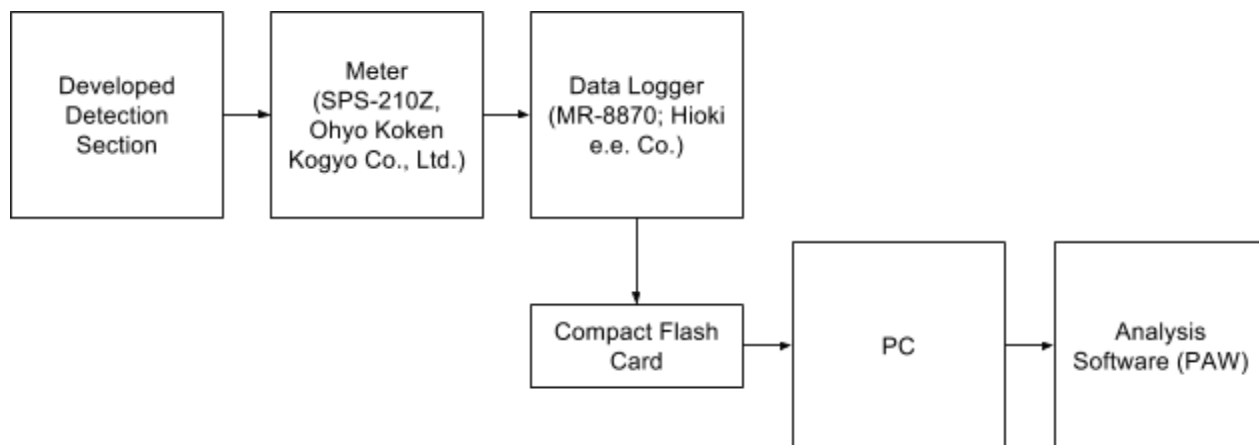


Figure 31. Diagram of the data acquisition system. The time constant of the meter was set to a 30 s.

Figures 32–34 show sample data on the data logger taken for the background count rates, source with the PVC plate, and source directly on top of the surface of an undoped aromatic ring polymer sheet. The x-axis represents the time (s), and the y-axis represents the voltage (mV). The signals are stabilized in the region from 90 s (time constant $\times 3$) to 120 s (time constant $\times 4$) as highlighted in the blue area. The average in the region was defined as its count rate. The count rates were obtained ten times for each condition and were averaged.

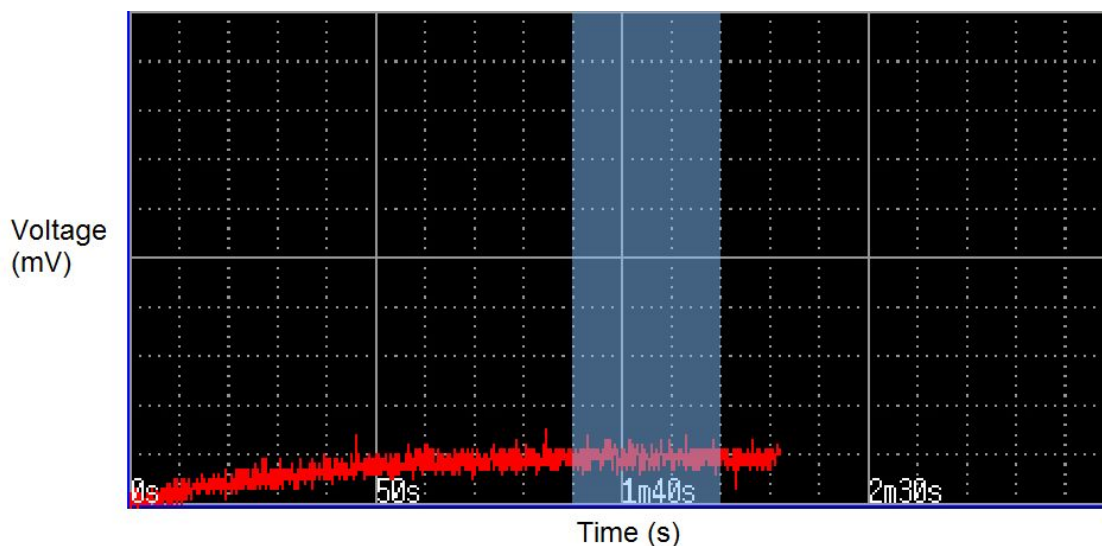


Figure 32. Sample data on the data logger taken for the background count rates. Here, the PET sheet is used. The 90–120 s region is highlighted.

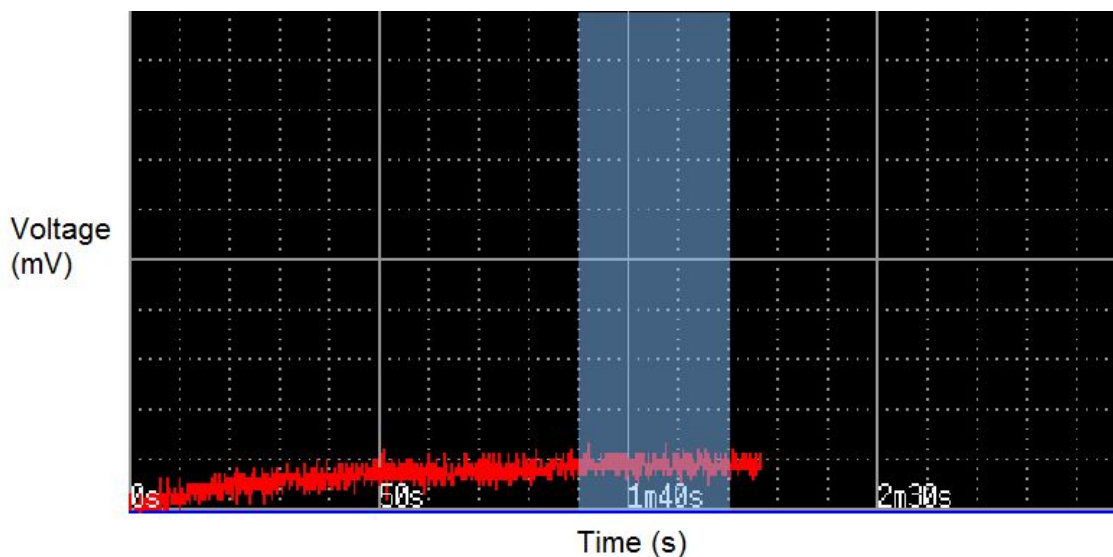


Figure 33. Sample data on the data logger taken for the count rates for the source with the PVC plate. Here, the PET sheet is used. The 90–120 s region is highlighted.

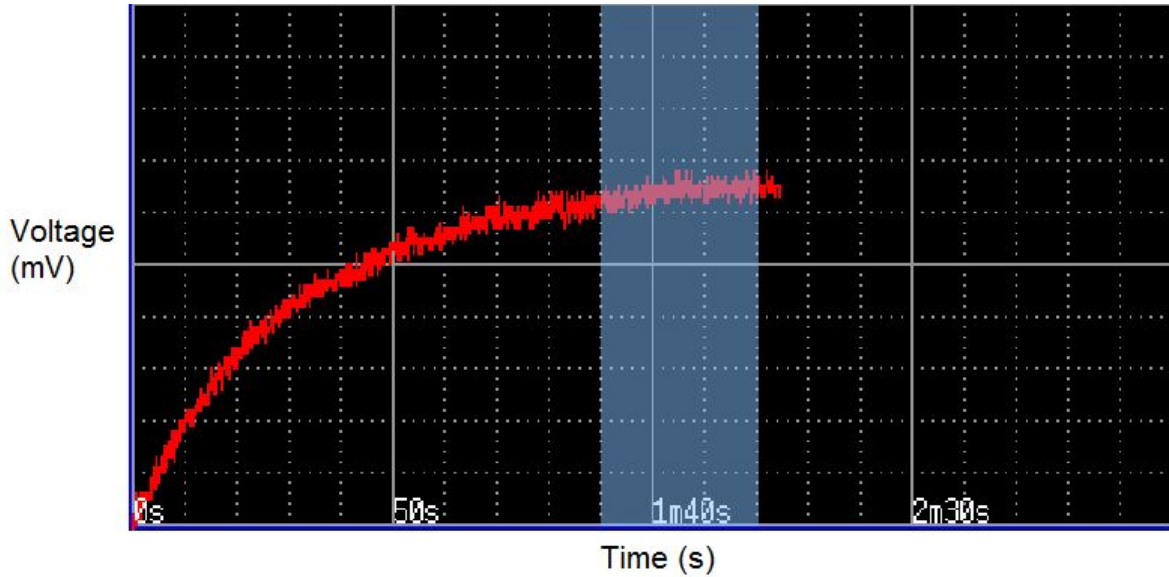


Figure 34. Sample data on the data logger taken for the count rates for the source. Here, the PET sheet is used. The 90–120s region is highlighted.

3.3 Results

Figure 35 shows the beta response for PET as a function of the PMT supply voltage using the Sr-90 radioactive source at the location ($x=0$ mm and $y=70$ mm). The x-axis represents the supply voltage (V) and the y-axis represents the count rate (counts per min). The solid triangles represent the count rates obtained through the unimpeded Sr-90 source. The solid squares represent the count rates for the source after passage through the PVC plate, and the open squares show the background count rates.

The count rates for the source with the PVC plate are not consistent with the count rates for the background. This was caused by several beta particles with high energies passing through the 5 mm thick PVC plate. However, the results show that almost all beta particles were cut by the PVC plate. Thus, the count rates for pure beta particles can be extracted from these results.

Additionally, there is no supply voltage dependence for each count rate. It demonstrates that the detection section that mounts the PET sheet is stable.

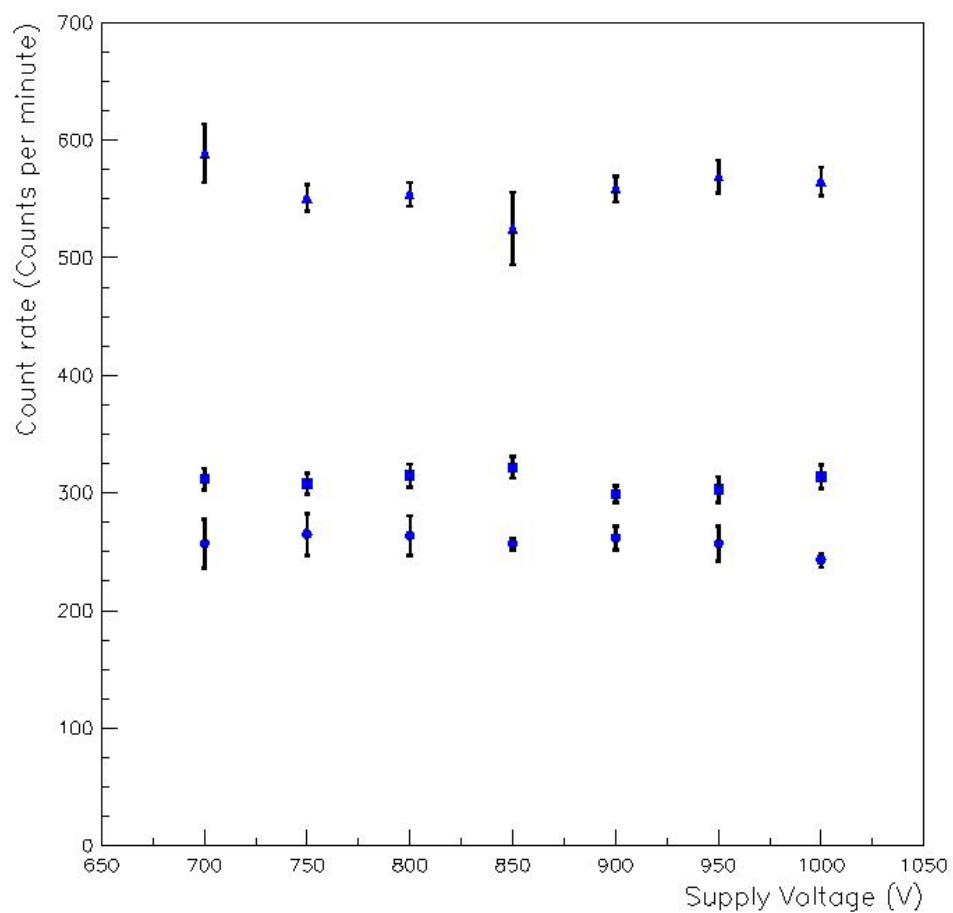


Figure 35. Relationship between PET count rates and PMT supply voltages. Triangles represent the count rates obtained through the unimpeded Sr-90 source. Squares represent the count rates for the same source after passage through the PVC plate, and circles show background count rates.

Figure 36 shows the beta response for PEN as a function of the PMT supply voltage using a Sr-90 radioactive source at the location ($x=0$ mm and $y=70$ mm). The results show that almost all beta particles are cut when using the PVC plate and pure beta particles can be extracted. There is no supply voltage dependence for the count rates, showing the stability of the detection section that mounts the PEN sheet. The PEN sheet shows a higher beta response compared to the PET sheet.

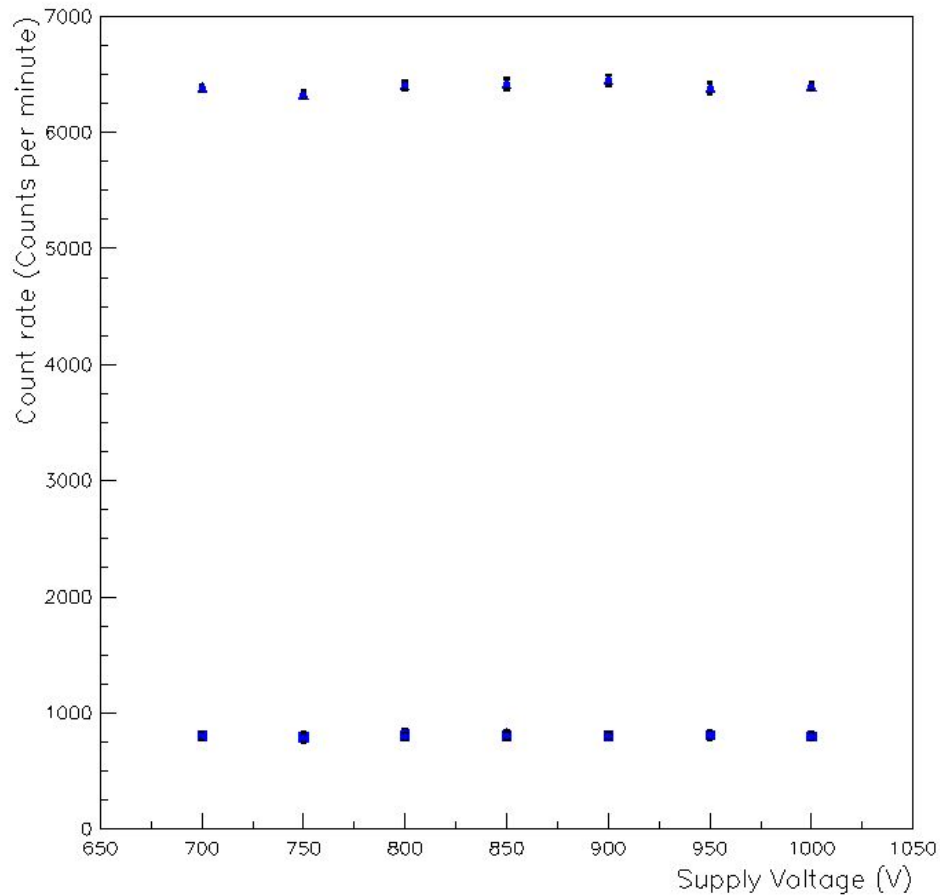


Figure 36. Relationship between PEN count rates and PMT supply voltages. Triangles represent the count rates obtained through the unimpeded Sr-90 source. Squares represent the count rates for the same source after passage through the PVC plate, and circles show background count rates.

Figure 37 shows the beta response for PES as a function of the PMT supply voltage using a Sr-90 radioactive source at the location ($x=0$ mm and $y=70$ mm). The results show that almost all beta particles are cut when using the PVC plate and pure beta particles can be extracted. There is no supply voltage dependence for the count rates, showing the stability of the detection section mounting the PES sheet. The PES sheet shows a higher beta response compared to the PEN sheet, but a lower beta response compared to the PET sheet.

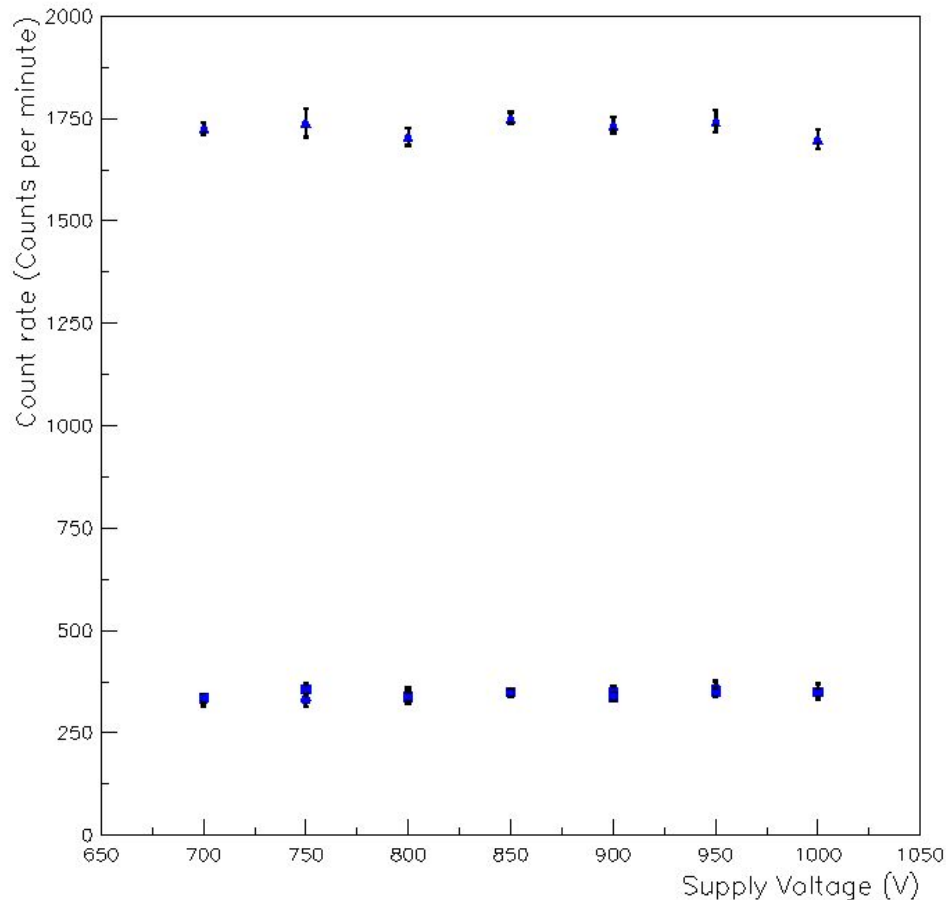


Figure 37. Relationship between PES count rates and PMT supply voltages. Triangles represent the count rates obtained through the unimpeded Sr-90 source. Squares represent the count rates for the same source after passage through the PVC plate, and circles show background count rates.

For each sheet, the pure beta count rates were extracted by subtracting the count rates for the source by the count rates for the source with the PVC plate. The results are shown in Figure 39. The x-axis represents the supply voltage (V) and the y-axis represents the count rate (counts per minute). The open squares, solid triangles, and solid squares represent the beta count rates for the PET, PEN, and PES sheet, respectively. Each count rate shows a plateau over the supply voltage in the PMT dynamic range, and is then linearly fit.

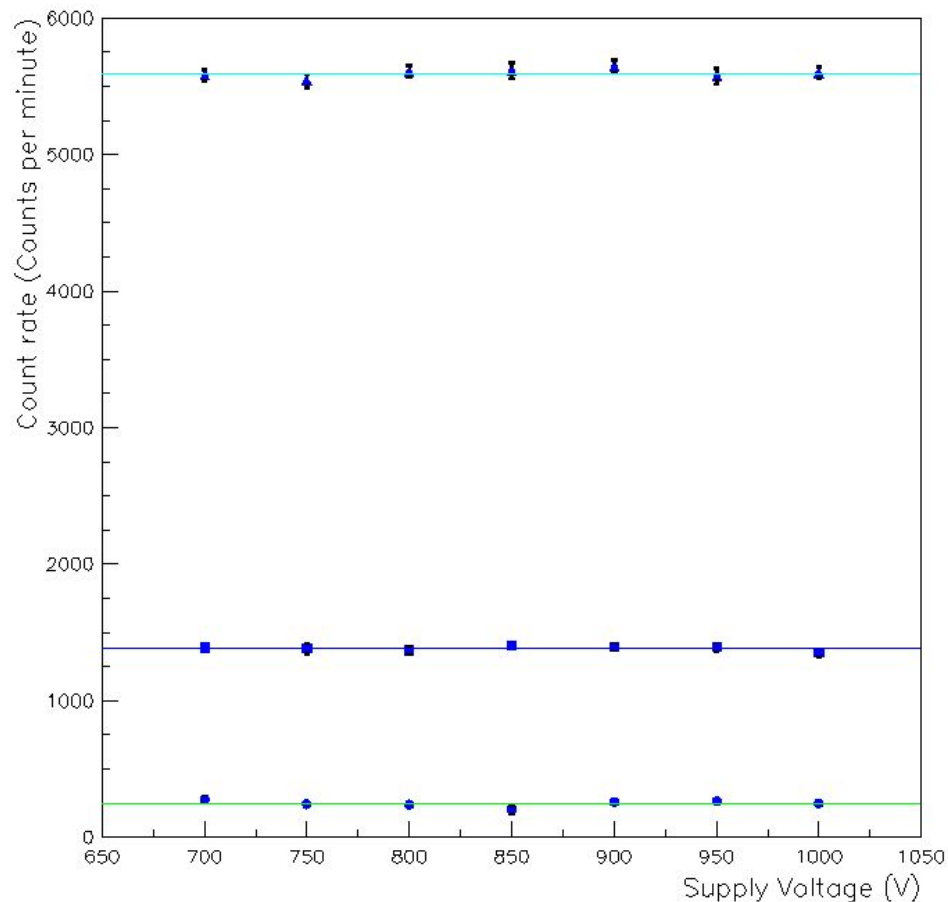


Figure 38. Pure beta particle count rates for PET (circles), PEN (triangles), and PES (squares). The straight lines indicate linear fits for PET (green line), PEN (light blue line, and PES (blue line).

3.4 Discussion

We have produced the PET, PEN, and PES sheets and have developed a new detection section for a survey meter using these sheets. From their performances for beta detection using a Sr-90 source, we conclude that the detection section can be used for detecting beta particles. This is consistent with our preliminary study [22].

The pure beta count rates for each sheet were extracted. The beta particle count rates for PET (248 ± 53 CPM), PEN (5595 ± 130 CPM), and PES (1384 ± 68 CPM) were obtained.

The light yields from the PEN sheet outperforms PET and PES by 22.5x, and 4x, respectively. These results are useful for designing a radiation detector based on PET, PEN, and PES sheets.

4. Alpha Particle Detection

4.1 Purpose

The developed detection section with the mounted PET, PEN, or PES sheet has been shown to perform well in survey meters and is sensitive to beta particles. Preliminary research has been carried out on the alpha particle response of PET [42]. Here, we show the performance of the detection section using PET, PEN, and PES sheets for alpha particles and demonstrate its capability in detecting multiple types of radiation. Alpha particle detection with aromatic ring polymer sheets will significantly expand its application range.

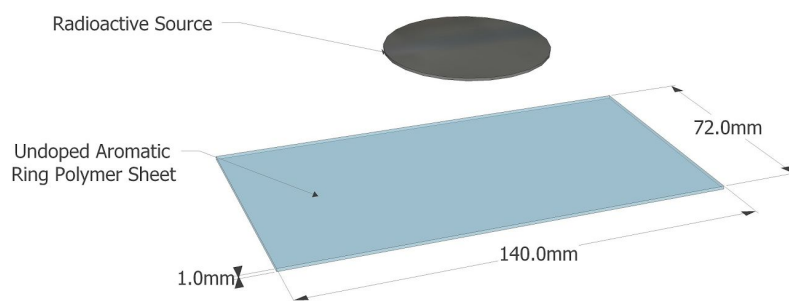
4.2 Materials and Methods

4.2.1 Settings

The performances (count rate and position dependence for the sheet) of the detection section for alpha particle detection were estimated by a radioactive source. Moreover, the stability of the detection section was observed by controlling the supply voltage (700 - 1000 V) in the PMT dynamic range.

The experimental setup for detecting alpha particles is shown in Figure 39. An Americium 241 radioactive source (AMRB5862; Nuclitec GmbH), which has a half-life of about 432.2 years, was used. It mainly emits alpha particles which are 5.48 MeV and gamma rays which are 59.5 keV. Additionally, to discriminate just alpha particles counts from the background counts, four 12- μm thick aluminum foils (Toyo Aluminum Ekco Products Co. Ltd.) were used. The signals from the PMT were received by the meter (SPS-210Z; OKEN). To confirm the responses of alpha particles and the low energy gamma rays, the threshold was set to minimum value (7 mV). The time constant of the meter was set to 30 sec. Here the average of the 90 - 120 seconds signals on the meter was defined as its count rate. The count rates were obtained ten times for each condition and were averaged.

a)



b)

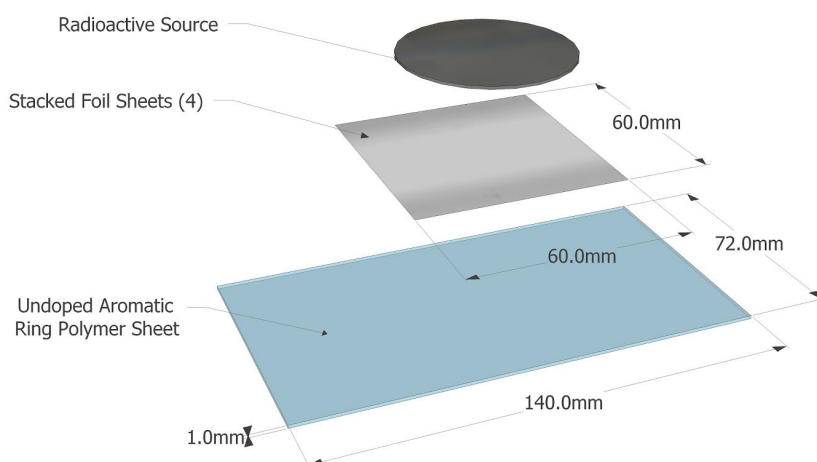


Figure 39. Schematic of the experimental setup for detecting alpha particles. (a) The Am-241 source is placed directly on each aromatic ring polymer sheet. (b) Four 12- μm -thick aluminum foils with a total thickness of 48 μm were used to prevent alpha particle penetration.

The experimental setup to obtain the position dependence of the count rates is shown in Figure 40. Figure 41 shows a photograph of the detection window in the detection section. The coordinates (X, Y, Z) on the detection window in the detection section are defined in Figure 42. The sheets are 30 mm above the head of the PMT. Each sheet was irradiated with alpha particles from the Am-241 source at a 9×23 array of points along sample the detection window. A 20 mm x 20 mm square hole collimator made from four 12- μ m thick aluminum foil sheets (Toyo Aluminum Ekco Products Co. Ltd.) was used to force the irradiated location. For the count rate distribution along the x-axis and y-axis, the data points were taken ten times.

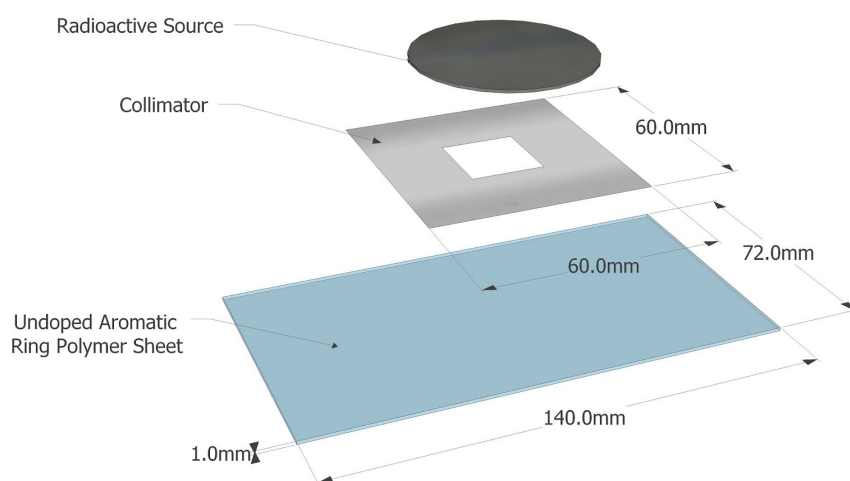


Figure 40. Schematic of the experimental setup to obtain the position dependence for the alpha particle count rates.



Figure 41. Photograph of the detection window.

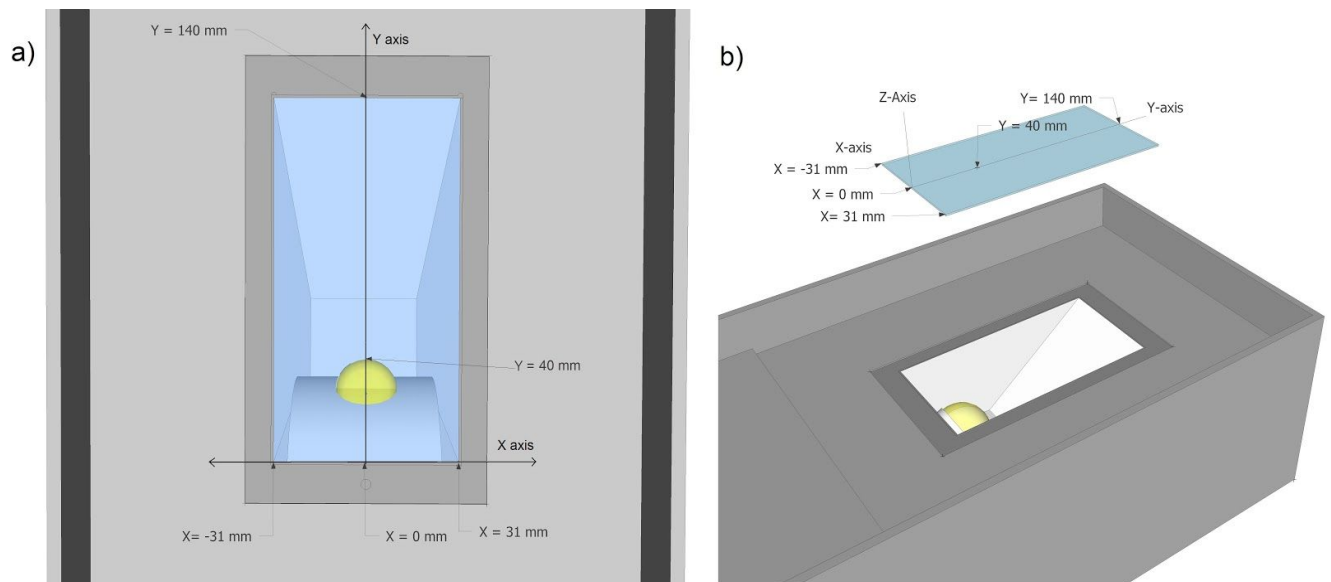


Figure 42. Schematic of the detection window and defined coordinates, a) top down view, b) at an angle.

An Am-241 radioactive source (AMRB5862; Nuclitec GmbH) was used. Its decay chain and characteristics are shown in Figure 43 and Table 5, respectively. The isotope decays into its daughter element, Neptunium-237. Alpha particles (5.49 MeV) and low energy gamma rays (59.5 keV) are produced. The final decay of the series is Bismuth-209.

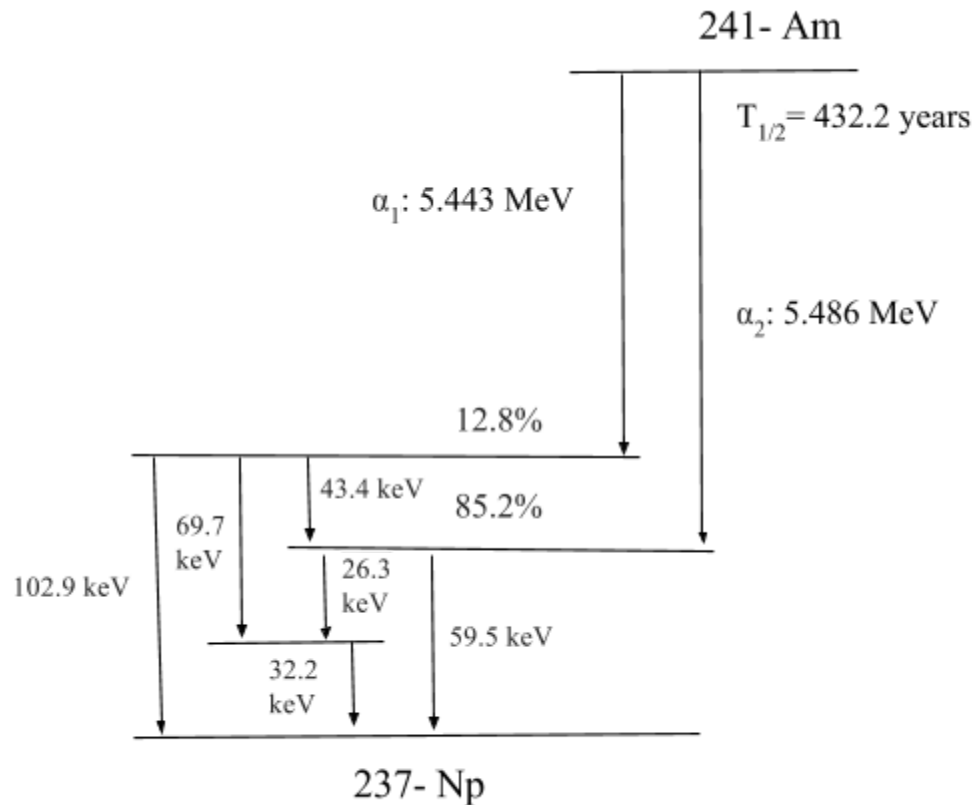


Figure 43. Am-241 decay chain to Np-237.

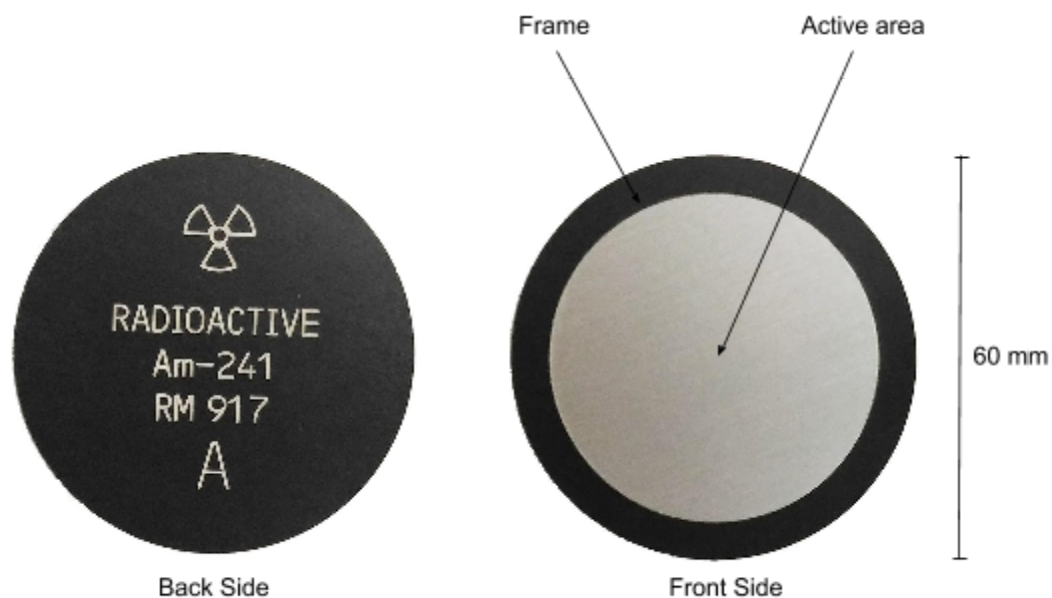


Figure 44. Photograph of the Am-241 source (AMRB5862; Nuclitec GmbH) showing the front and back sides. The front side contains the active surface.

Table 5 shows the characteristics of the Am-241 source (AMRB5862; Nuclitec GmbH).

Table 5. Characteristics of the Am-241 source (AMRB5862; Nuclitec GmbH).

Parameter	Description / Value	Unit
Activity	211	Bq
Alpha surface emission rate	190	S^{-1} in 2π steradian
Active surface dimension	40.6	mm
Dimension	50 x 0.8	mm
Calibration date	9 October 2008	--
Relative uncertainty of activity	3	%
Relative uncertainty of beta surface emission	3	%

4.3 Results

4.3.1 Count rate

Figure 45 shows the alpha response for PET as a function of the PMT supply voltage using the Am-241 radioactive source. The x-axis represents the supply voltage (V) and the y-axis represents the count rate (counts per min). The solid triangles represent the count rates obtained through the unimpeded Am-241 source. The solid squares represent the count rates for the same source after passage through the aluminum foil sheets, and the open squares show the background count rates.

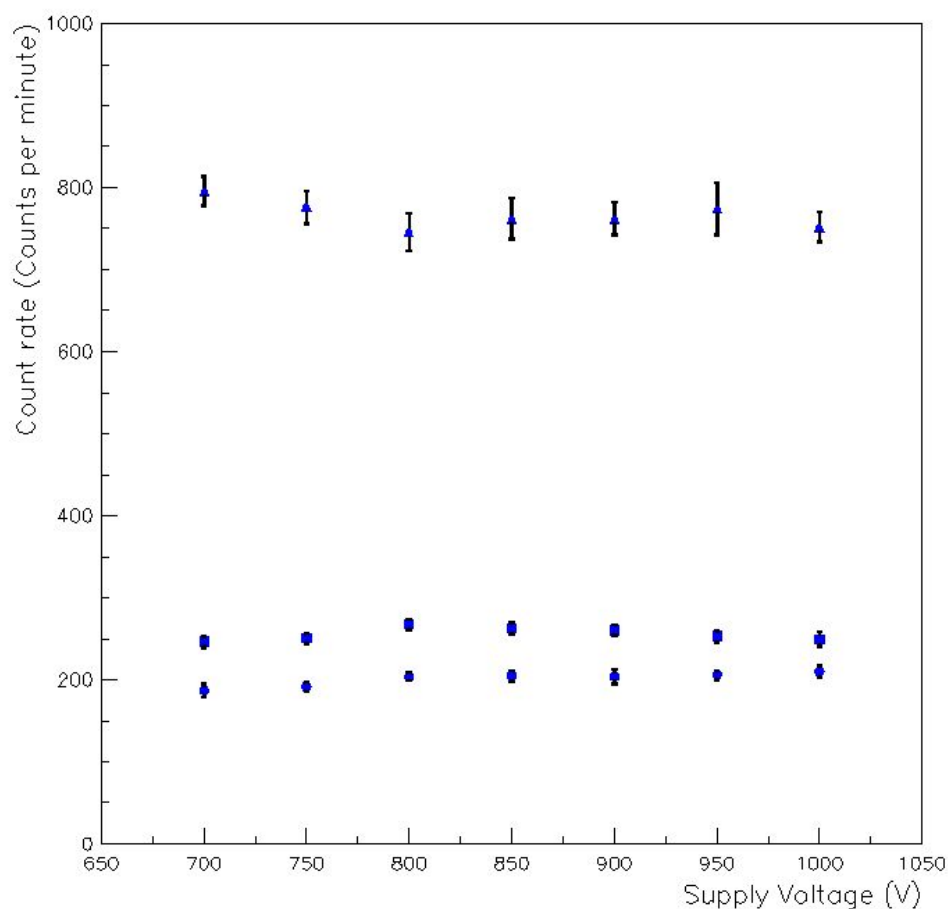


Figure 45. Relationship between PET count rates and PMT supply voltages. Triangles represent the count rates obtained through the unimpeded Am-241 source. Squares represent the count rates for the same source after passage through the aluminum foils, and circles show background count rates.

The count rates for the source with the aluminum foils are isolated from the count rates for the background. The aluminum foils block all alpha particles from the Am-241 source. Thus, the isolated count rates were induced by low energy gamma rays. From these results, the pure alpha particle events and the low energy gamma ray events can be extracted. In addition, there is no supply voltage dependence for each count rate. It demonstrates that the detection section that mounted the PET sheet is stabilized for alpha particles and low energy gamma rays.

Figure 46 shows the alpha response for PEN as a function of the PMT supply voltage using the Am-241 source. The count rates for the source with the aluminum foils are isolated from the count rates for the background. The aluminum foils block all alpha particles from the Am-241

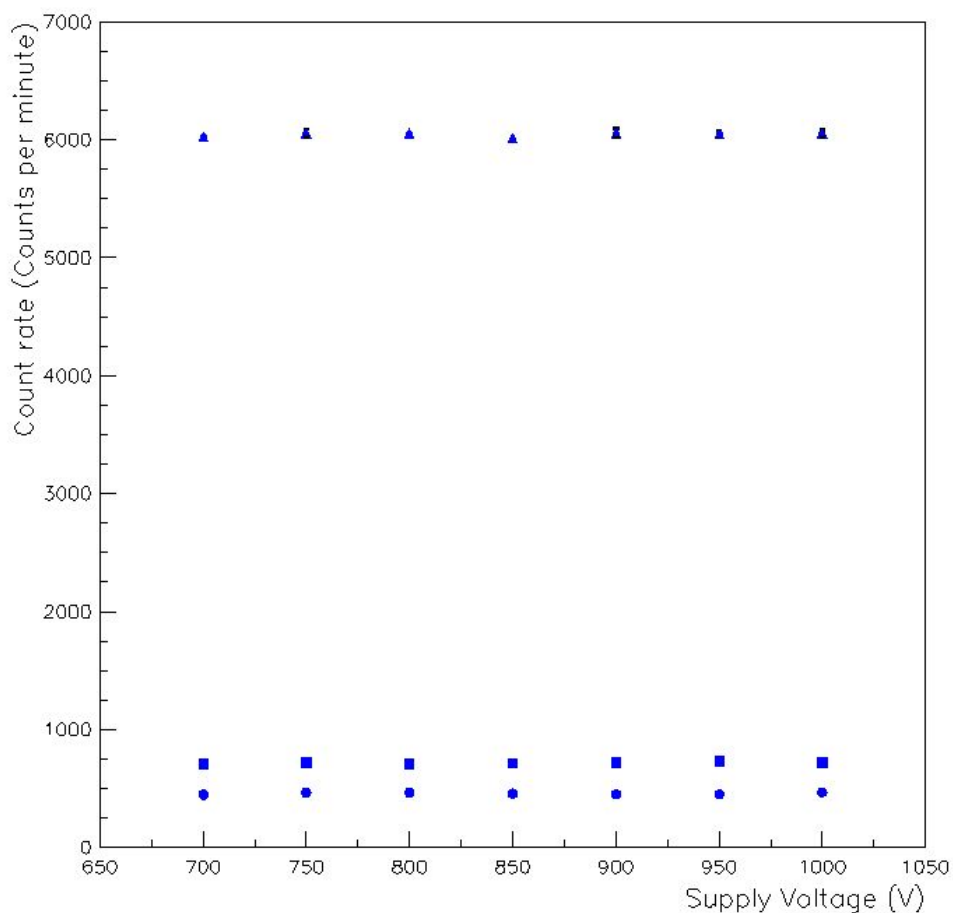


Figure 46. Relationship between PEN count rates and PMT supply voltages. Triangles represent the count rates obtained through the unimpeded Am-241 source. Squares represent the count rates for the same source after passage through the aluminum foils, and circles show background count rates.

source. Thus, the isolated count rates were induced by low energy gamma rays. From these results, the pure alpha particle events and the low energy gamma ray events can be extracted. In addition, there is no supply voltage dependence for each count rate. It demonstrates that the detection section mounting the PEN sheet is stabilized for alpha particles and low energy gamma rays. The PEN sheet shows a higher alpha response compared to the PET sheet.

Figure 47 shows the alpha response for PES as a function of the PMT supply voltage using the Am-241 source. The count rates for the source with the aluminum foils are isolated from the count rates for the background. The aluminum foils block all alpha particles from the Am-241

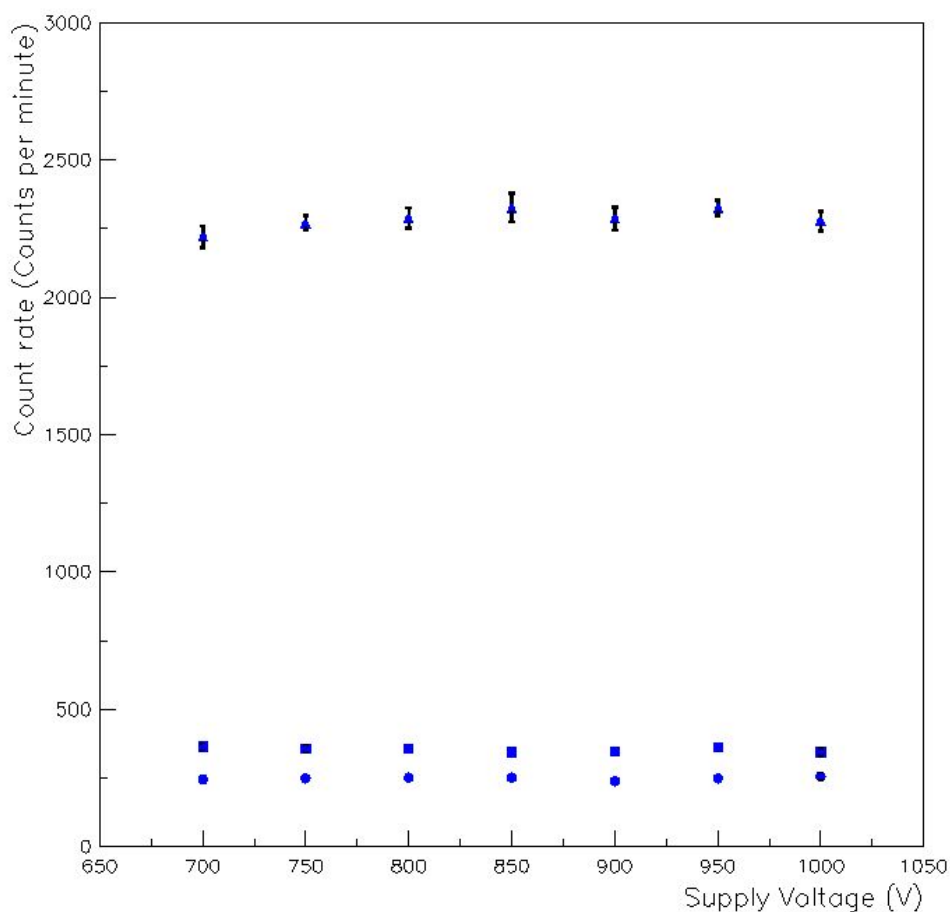


Figure 47. Relationship between PES count rates and PMT supply voltages. Triangles represent the count rates obtained through the unimpeded Am-241 source. Squares represent the count rates for the same source after passage through the aluminum foils, and circles show background count rates.

source. Thus, the isolated count rates were induced by low energy gamma rays. From these results, the pure alpha particle events and the low energy gamma ray events can be extracted. In addition, there is no supply voltage dependence for each count rate. It demonstrates that the detection section that mounted the PES sheet is stabilized for alpha particles and low energy gamma rays. The PES sheet shows a higher alpha response compared to the PET sheet, but a lower alpha response compared to the PEN sheet.

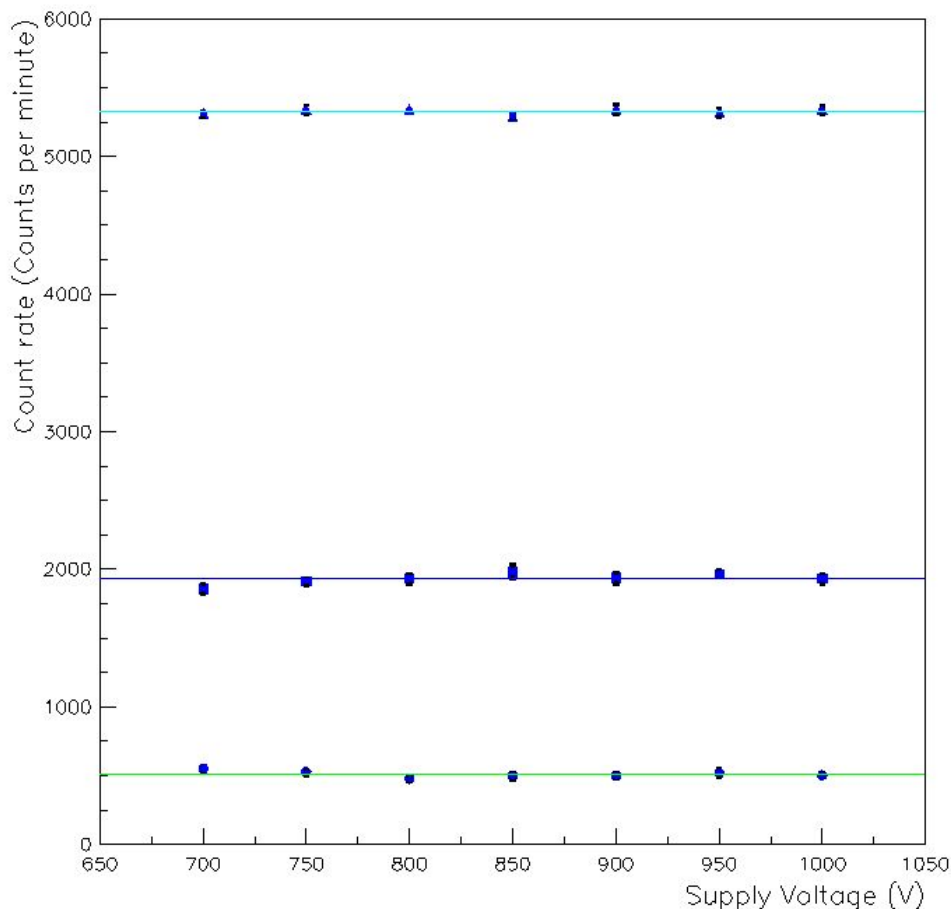


Figure 48. Pure alpha particle count rates for PET (circles), PEN (triangles), and PES (squares). The straight lines indicate linear fits for PET (green line), PEN (light blue line), and PES (blue line).

For each sheet, the pure alpha count rates were extracted by subtracting the count rates for the source by the count rates for the source with the aluminum foils. The results are shown in Figure 48. The x-axis represents the supply voltage (V) and the y-axis represents the count rate (counts per min). The open squares, solid triangles, and solid squares represent the alpha count rates for the PET, PEN, and PES sheets, respectively. Each count rate shows a plateau over the supply voltage in the PMT dynamic range and is displayed with a linear fit.

4.3.2 Position Dependence

Figure 49 shows the Am-241 count rate distribution along the locations of the PET sheet. The x-axis (mm) and y-axis (mm) represent the x and y coordinates on the sheet as seen in Figure 42. The z-axis represents the count rate (counts per min).

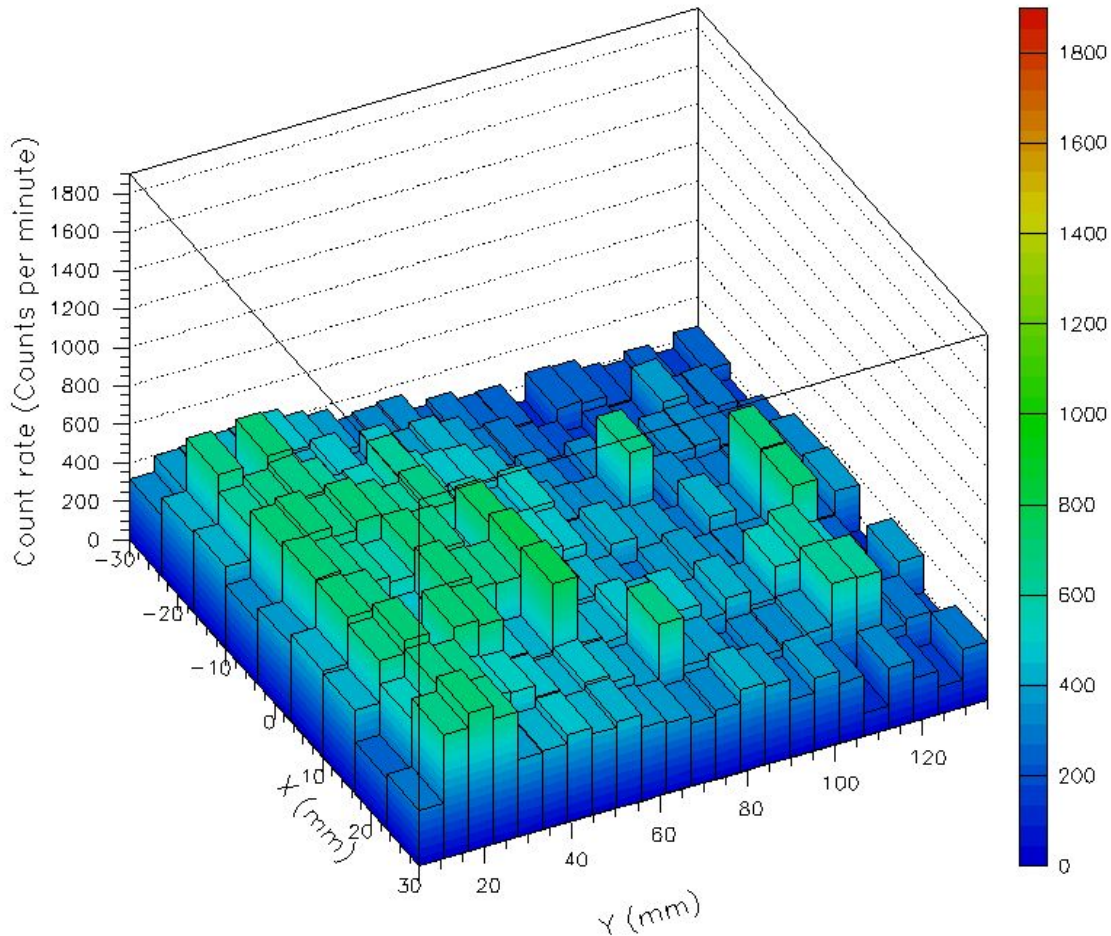


Figure 49. Count rate distribution along the locations of the PET sheet.

The cool colors (blue) indicate lower count rates and the warm colors (red) indicate higher count rates. This indicates the position dependence. For a more detailed examination, the count rates for the x and y-axes are monitored in the following figures.

Figure 50 shows the Am-241 count rate distribution along the y-axis of the PET sheet at $X = 0$ mm. The x-axis (mm) indicates the location on the y coordinate of the sheet. The y-axis represents the count rate (counts per min). The solid squares indicate the count rates at a given point. The blue lines indicate the maximum and minimum values observed. The peak is above the PMT window (around 40 mm). Thus, the count rates at $Y = 40$ mm are monitored.

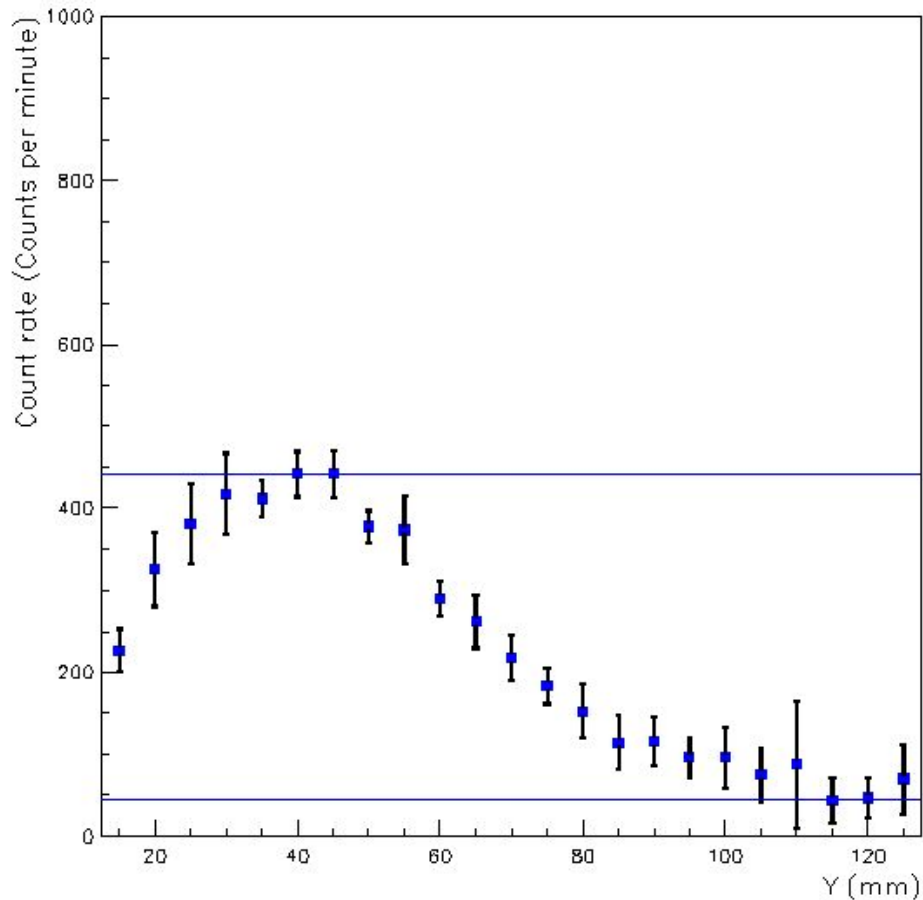


Figure 50. PET position dependence on the y-axis at $X = 0$.

Figure 51 shows the Am-241 count rate distribution along the x-axis of the PET sheet at $Y = 40$ mm. The x-axis (mm) indicates the location of the x coordinate of the sheet. The y-axis represents the count rate (counts per min). The solid squares indicate the count rates at a given point. The blue lines indicate the maximum and minimum values observed. The peak is around 0 mm. In addition, the count rate variability along the x-axis is lower than the count rate variability along the y-axis, as seen in the previous figure.

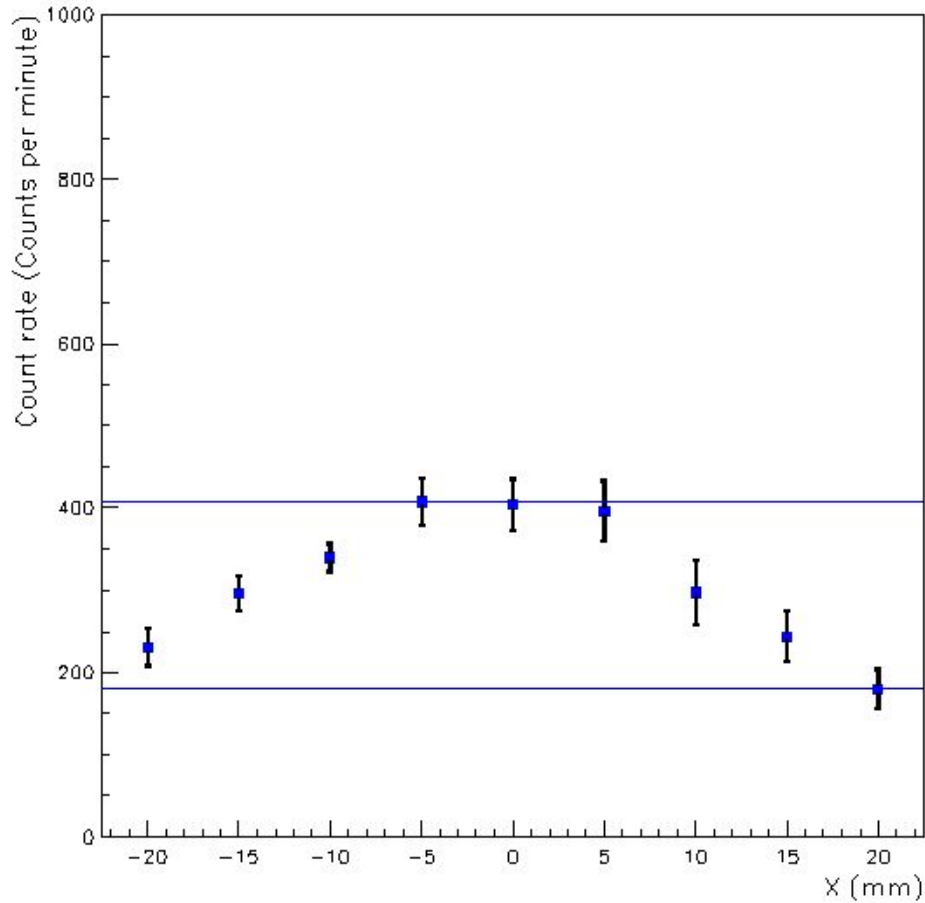


Figure 51. PET position dependence on the x-axis at $Y = 40$.

Figure 52 shows the Am-241 count rate distribution along the PEN sheet. It shows the position dependence, which is less than that of the PET sheet. To examine the in more detail, the count rates at the x and y-axes are monitored in the following figures.

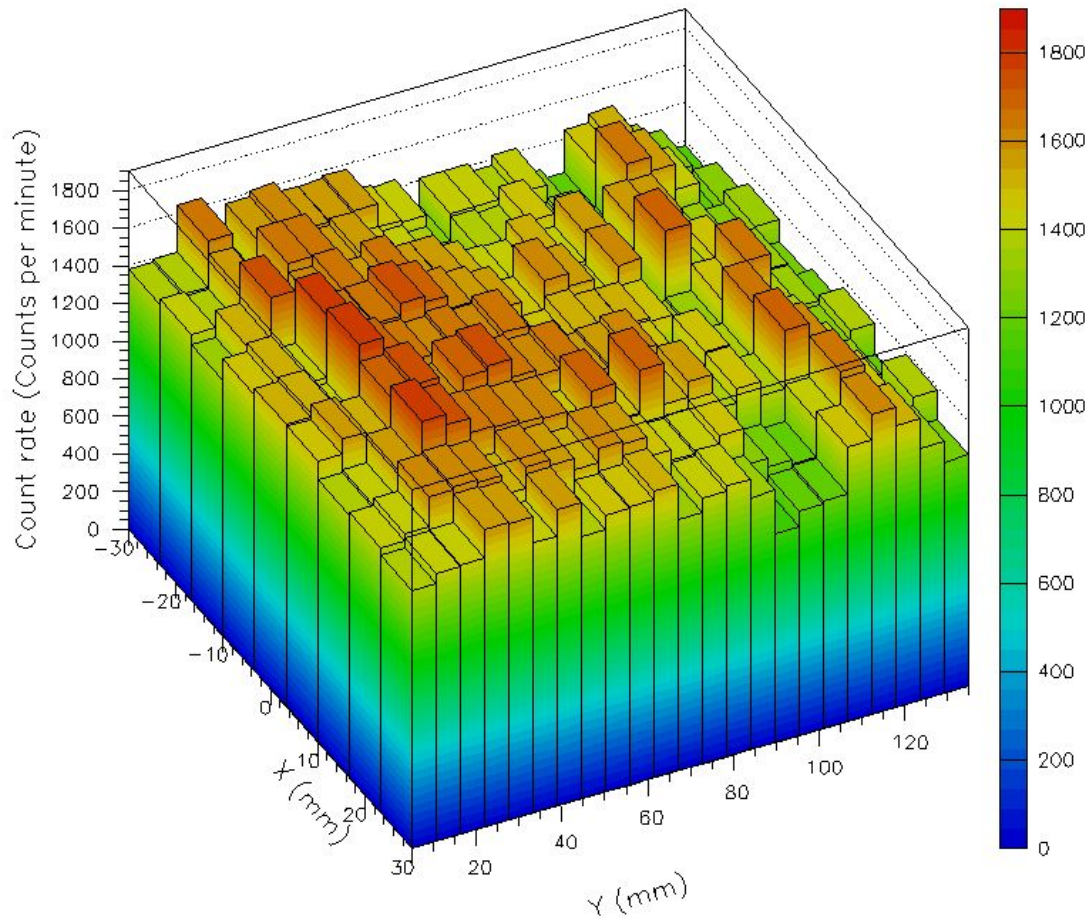


Figure 52. Count rate distribution along the locations of the PEN sheet.

Figure 53 shows the Am-241 count rate distribution along the y-axis of the PEN sheet at $X = 0$ mm. Here, the peak is around 30 mm.

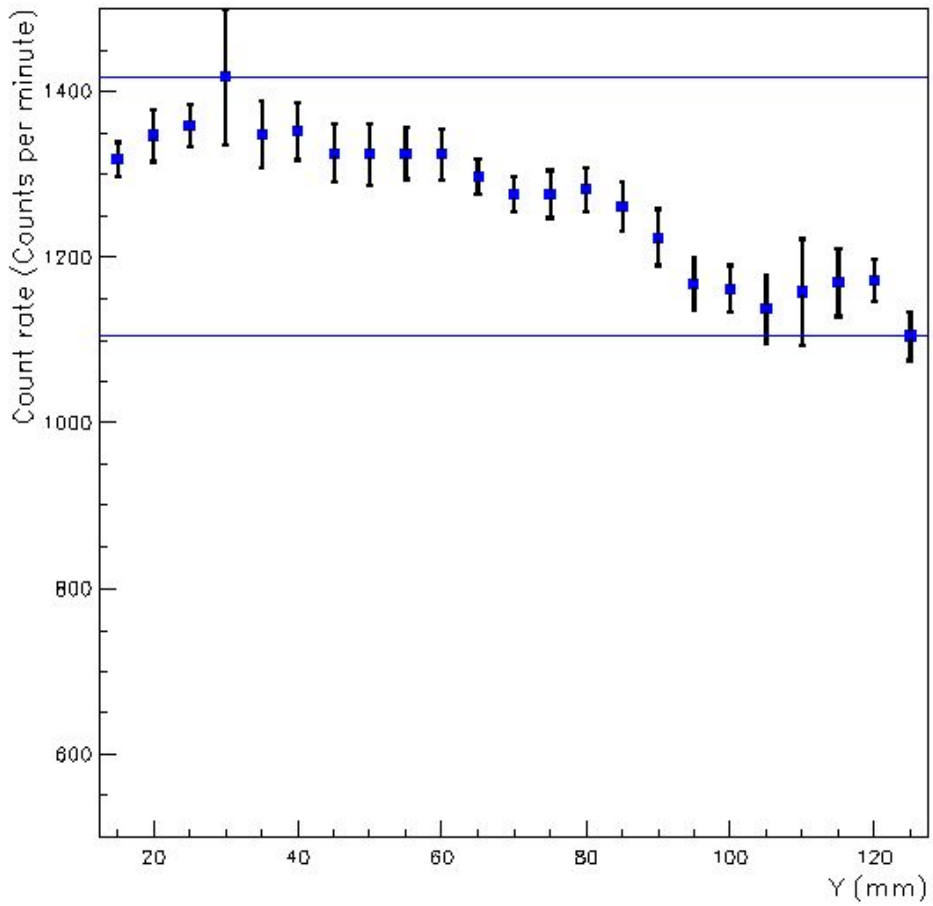


Figure 53. PEN position dependence on the y-axis at $X = 0$.

Figure 54 shows the Am-241 count rate distribution along the x-axis of the PEN sheet at $Y = 40$ mm. Here, the peak is around 0 mm. In addition, the count rate variability along the x-axis is lower than the count rate variability along y-axis, as seen in the previous figure.

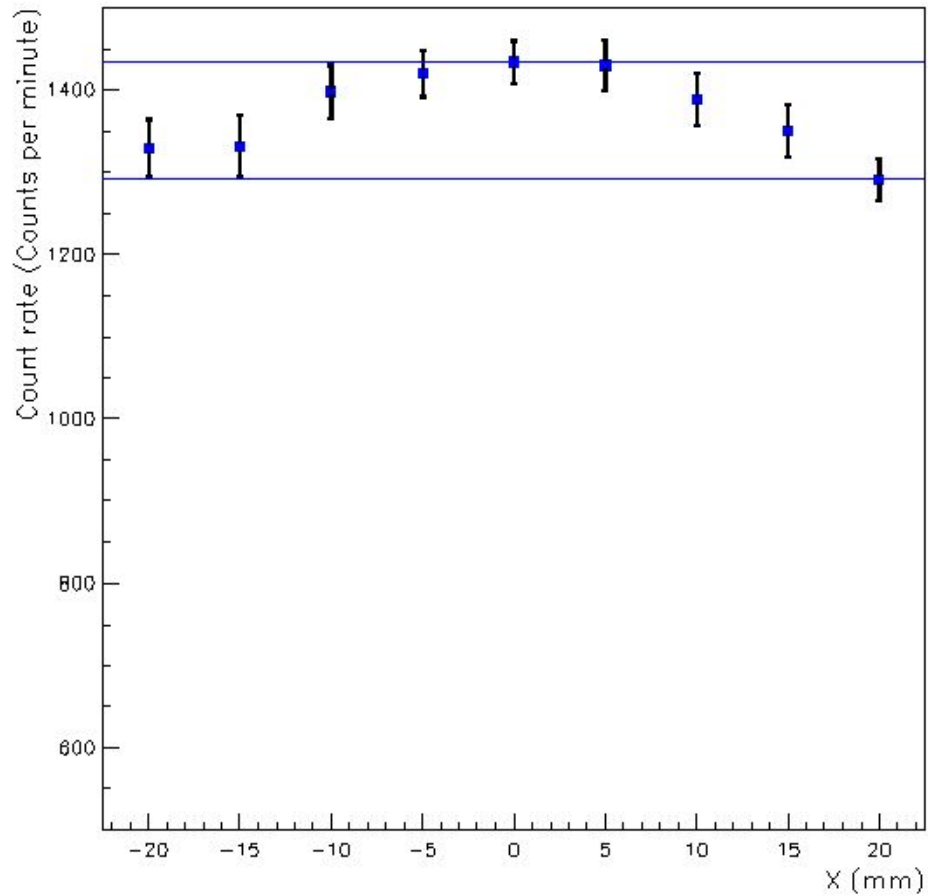


Figure 54. PEN position dependence on the x-axis at $Y = 40$.

Figure 55 shows the Am-241 count rate distribution along the PES sheet. It shows the position dependence, which is less than that of the PET sheet, but higher than that of the PEN sheet. To examine this in more detail, the count rates at the x and y-axes are monitored in the following figures.

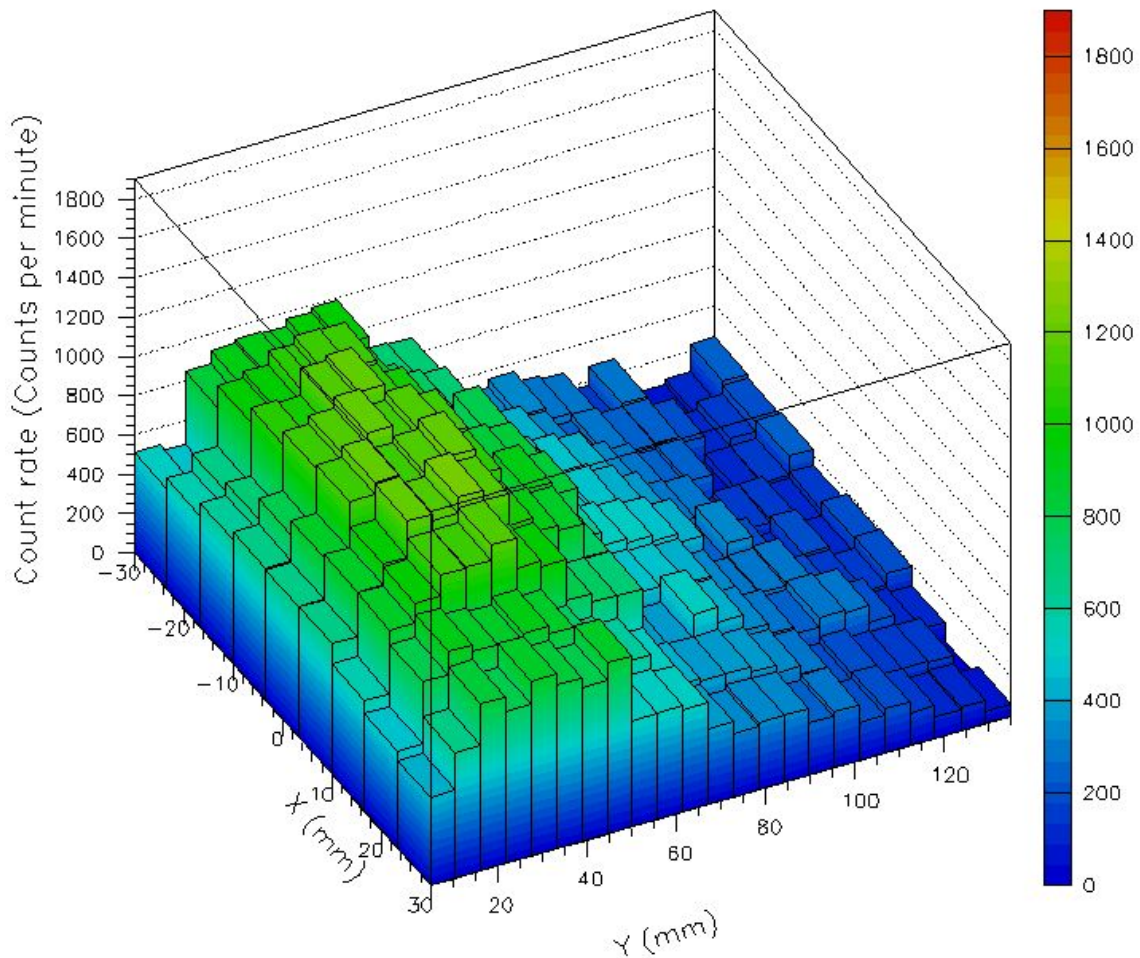


Figure 55. Count rate distribution along the locations of the PES sheet.

Figure 56 shows the Am-241 count rate distribution along the y-axis of the PES sheet at $X = 0$ mm. Here, the peak is around 40 mm.

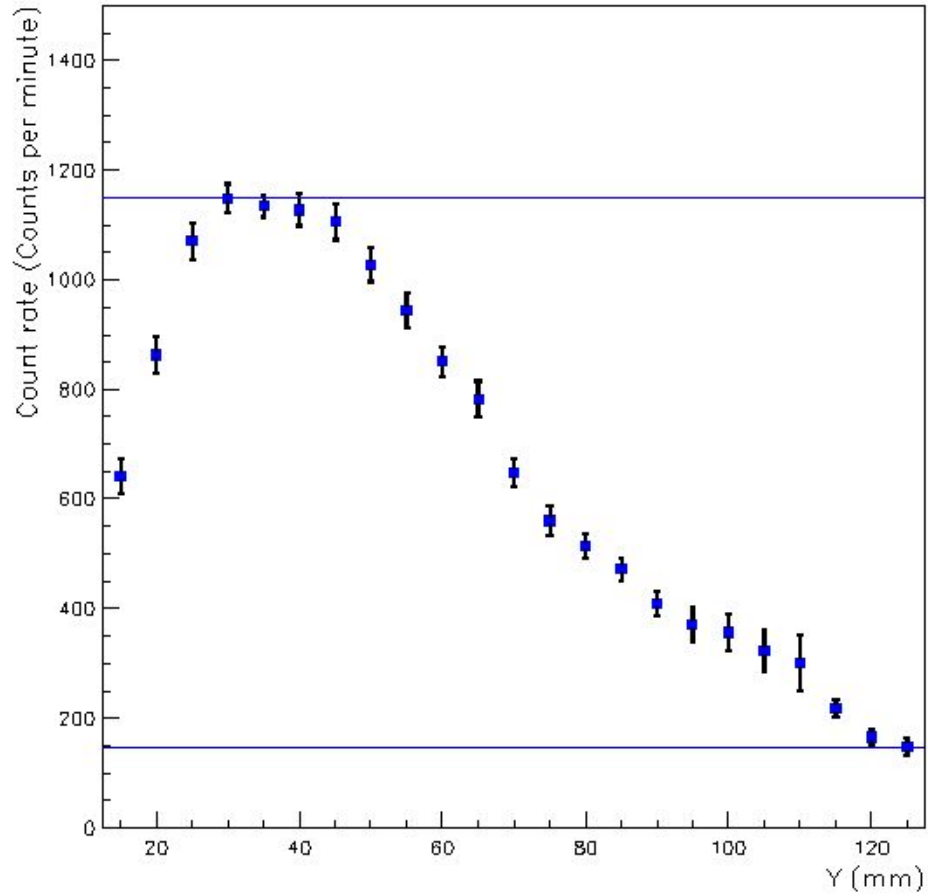


Figure 56. PES position dependence on the y-axis at $X = 0$.

Figure 57 shows the Am-241 count rate distribution along the x-axis of the PES sheet at Y = 40 mm. Here, the peak is around 0 mm. Additionally, the count rate variability is lower than the count rate variability along the y-axis, as seen in the previous figure.

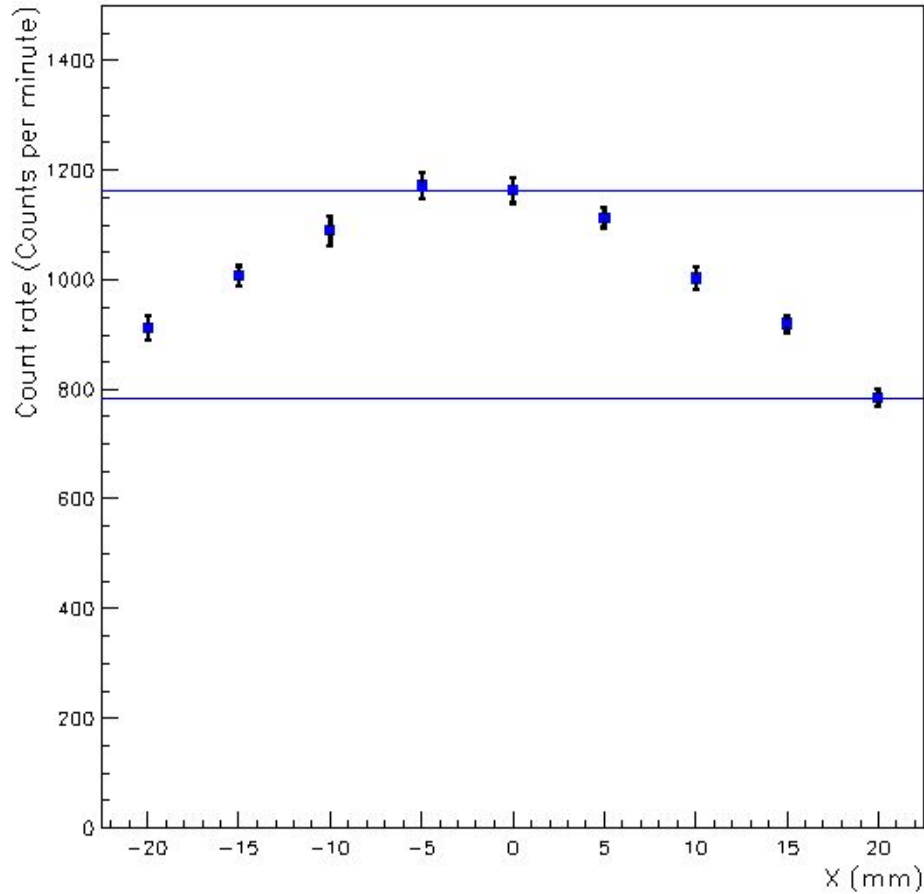


Figure 57. PES position dependence on the x-axis at Y = 40.

4.4 Discussion

We have demonstrated that the developed detection section can detect alpha particles. The pure alpha count rates for each sheet were extracted. For each sheet, it shows a plateau over the supply voltage in the PMT dynamic range. The comparison of the pure alpha particle count rates obtained by the PET, PEN, and PES sheet are shown in Figure 48. The extracted alpha particle count rates for PET (511 ± 63 CPM), PEN (5326 ± 77 CPM), and PES (1931 ± 103 CPM) were obtained.

The light yield from the PEN sheet outperforms PET and PES by 10.4x, and 2.8x, respectively. The light yields (normalized) are comparable to those in our previous studies [32][43]. The data for the count rates as a function of the supply voltage, however, are taken from the source positioned at the center of the sheets. Considering count rate variability, PEN has a more stable light yield, while the light yields vary more dramatically at the center for PET and PES.

Table 6. Light yield for alpha particles normalized to PEN.

Undoped Aromatic Ring Polymers	PET	PEN	PES
Light Yield (Normalized)	.10	1.0	.36

Position dependence was observed along the x-axis and the y-axis. The position dependence values were obtained by subtracting the minimum count rate from the maximum count rate on a given axis. For the PET sheet, the position dependence along the y-axis was 396 ± 56 CPM measured along $X = 0$, and the position dependence along the x-axis was 227 ± 52 CPM measured along $y = 40$. For the PEN sheet, the position dependence along the y-axis was 313 ± 117 CPM measured along $X = 0$, and the position dependence along the x-axis was 143 ± 51 CPM along $Y = 40$. For the PES sheet, the position dependence along the y-axis was 1001 ± 43 CPM along $X = 0$, the position dependence along the x-axis was 378 ± 39 CPM along $Y = 40$ as shown in Table 7.

Table 7. Position dependence along the x-axis at $Y = 40$ mm and y-axis at $X = 0$ mm in CPM.

Undoped Aromatic Ring Polymer	PET (CPM)	PEN (CPM)	PES (CPM)
x-axis ($Y = 40$ mm)	227 ± 52	143 ± 51	378 ± 39
y-axis ($X = 0$ mm)	396 ± 56	313 ± 117	1001 ± 43

The count rate variances along the x and y axes on each sheet were mainly generated by the geometry of the detection section, such as the location of the photocathode to the sheet as shown in Figure 58. The variances among the sheets were caused by the refractive indexes and the emission wavelengths. These data are useful for designing radiation detectors using these polymers.

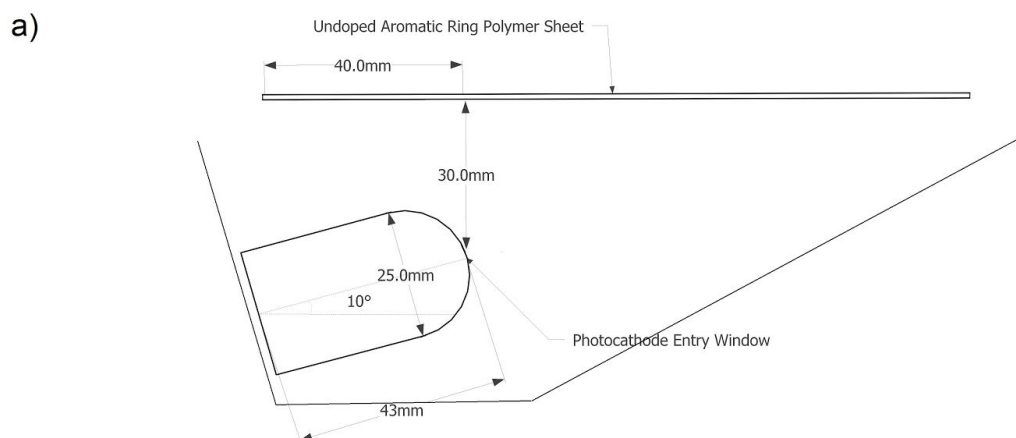


Figure 58. a) Schematic of the photocathode entry window to the sample sheet. b) Side view photo showing the angle of the PMT containing the photocathode.

To examine the contributions of the gamma rays from the Am-241 source to these data, the count rates for gamma rays were extracted from the count rates obtained with the aluminum foils and that obtained from the background. The result is shown in Figure 59. A plateau for each sheet can be seen. It demonstrates that the developed detection section with PET, PEN, and PES sheets also have the potential for low energy gamma rays. The performances for gamma rays can be increased by optimizing the thickness of the sheets.

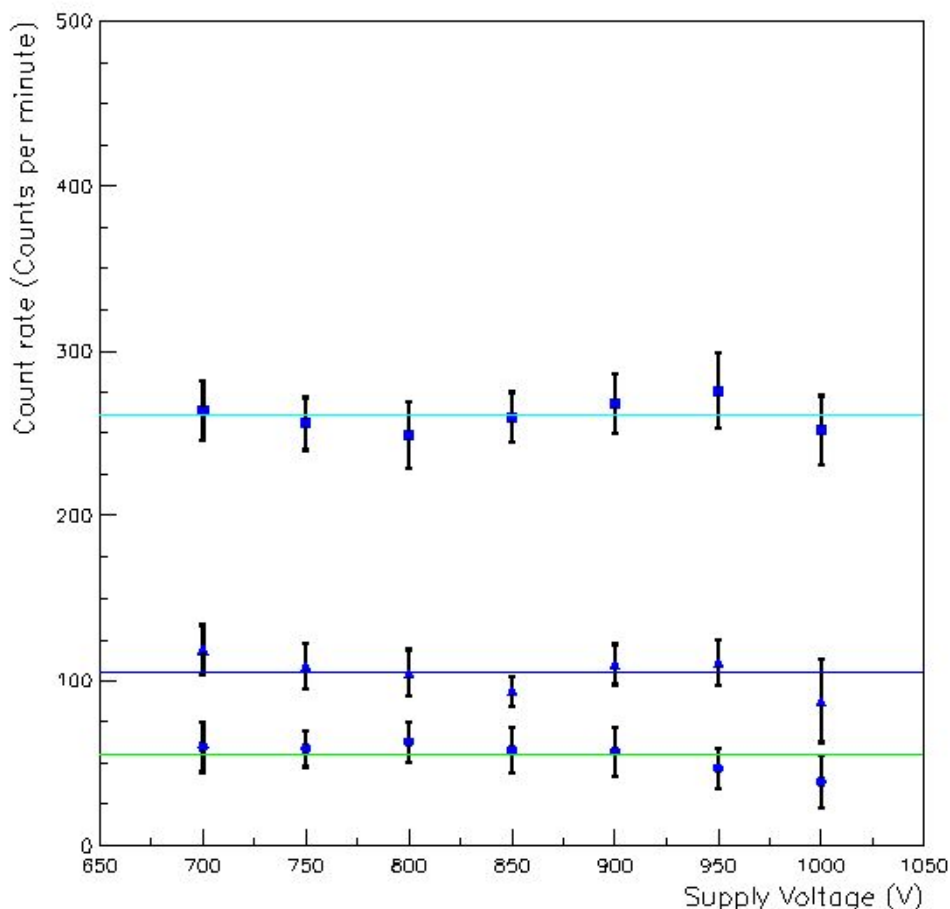


Figure 59. Extracted low energy gamma ray count rates for PET (circles), PEN (squares), and PES (triangles). The straight lines indicate linear fits for PET (green line), PEN (light blue line), and PES (blue line).

From chapters 3 and 4, we conclude that the undoped PET, PEN, and PES sheets can detect alpha particles, beta, and low energy gamma rays. By optimizing the detection geometry between the sheets and the PMT, including the sheet thickness and the type of PMT, the survey meter will be able to detect different radiation sources, have higher light yield and minimal count-rate variability. Thus, the undoped aromatic ring polymer survey meter has the potential to detect multiple types of radiation.

5. Conclusion

A prototype survey meter using the newly fabricated undoped aromatic ring polymer sheets has been developed. In this chapter, we demonstrate and compare its performance to that of a typical plastic scintillation survey meter.

5.1 Application of Aromatic Ring Polymers in a Survey Meter

The performances of the developed detection section were compared with that of the typical detection section in a plastic scintillation survey meter as shown in Figure 60. The typical detection section consists of a common plastic scintillation sheet, acrylic supporter, PMT, and light shield curtain [3]. Its dimensions are 290 mm x 92 mm x 62 mm, including the handle.

Here, the radiation window was exposed by the Sr-90 and Am-241 sources. Each source was placed at the center of the window. The 48 μm -thick aluminum foils and the 5 mm-thick PVC plate also were used, to extract the beta particles and alpha particles from the sources. The output signals were read by the meter and recorded by the data logger. The time constant of the meter was set to 30 s. The average of the 90–120 s signals in the meter was defined as its count rate. The count rates were taken 10x and averaged. The results are summarized in Table 8.



Figure 60. Photo of the detection section of a survey meter (OKEN - SPS210Z) using typical plastic scintillation material.

Table 8. Comparison of the count rates with the Sr-90 and Am-241 sources at the center of the developed detection section and the typical detection section.

Detection Section	Substrate	Beta particle count rate (Sr-90) (CPM)	Alpha particle count rate (Am-241) (CPM)
Developed	PET	194±25	278±16
	PEN	5367±27	5132±22
	PES	1336±57	1708±40
Typical	Plastic Scintillation Material	4657±25	0±12

From Table 8, the count rates for pure beta particles were extracted for each detection section and shown in Figure 61. The count rates with PET and PES are less than those of the typical detection section. However, the count rate with PEN is comparable to that of the typical detection section.

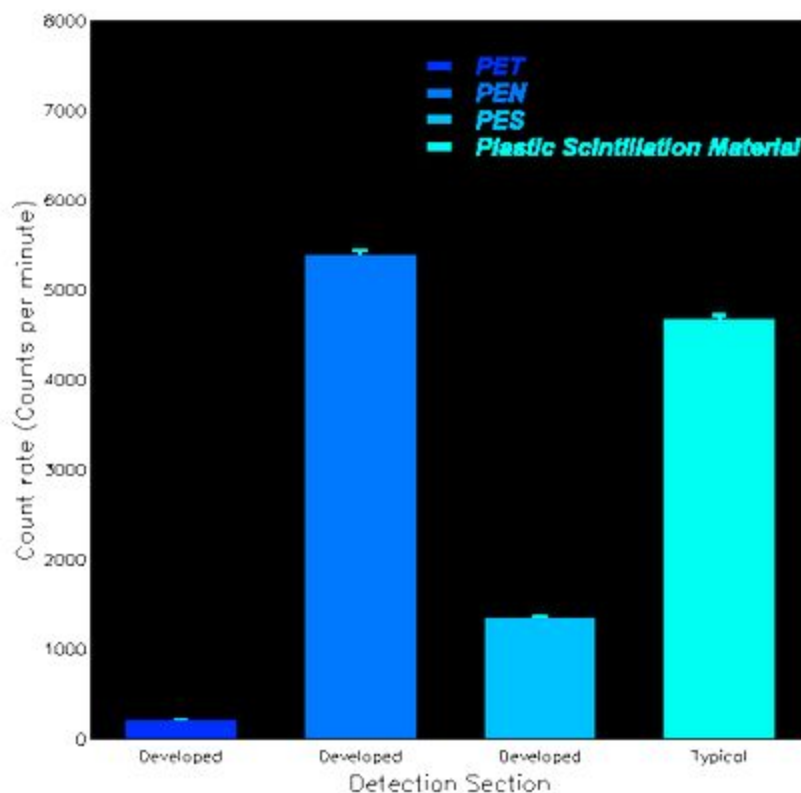


Figure 61. Beta count rates with the developed detection section, and the typical detection section. They exclude the background counts. These error bars are small.

From Table 8, the count rates for pure alpha particles were extracted for each detection section and shown in Figure 62. The count rates of the developed detection section are seen for each aromatic ring polymer sheet, although that of the typical detection section is not confirmed. Thus, it demonstrates that the alpha particle detection is an advantage in the developed detection.

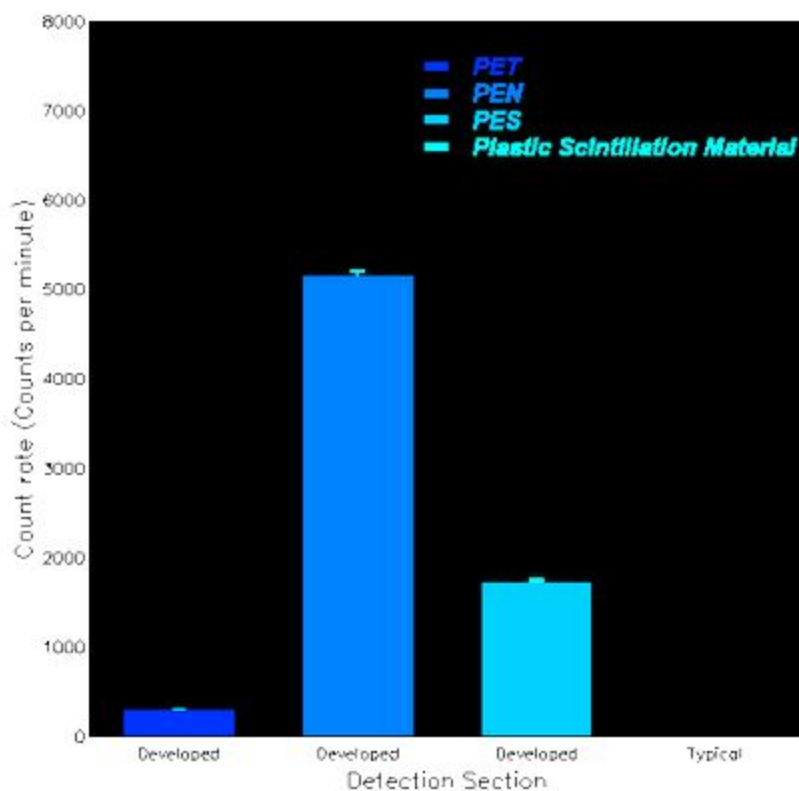


Figure 62. Alpha count rates with the developed detection section, and the typical detection section. They exclude the background counts. These error bars are small.

In this study, a multi-radiation type survey meter has been built and has two unique features, allowing the radioactive sources to be placed on top of the sheets and excluding the acrylic supporter. The performances demonstrate that the features work well. With optimization of the detection section, the count rate position dependence can be improved. Using other enhancements, such as surface treatment of the undoped aromatic ring polymer sheet, can improve the light yield [3][4][21][39][43][44]. Injection pressure and heat conduction during the injection molding will affect the optical characteristics of the sheets [45]. The use of blending the polymers of two undoped scintillation materials also will improve the performance of the detection section [38][43]. In addition, chemical modifications may also enhance the scintillation properties and obtain the desired emission wavelengths [46][47].

It is also important to demonstrate neutron response. Recently several research reported that PEN for example, has been shown to have good properties and potential for thermal neutron detectors, which can be used in medical imaging, nuclear safety, and national security, as well as its potential for gamma and neutron discrimination [48][49]. Moreover, it is advantageous to create discrimination methods for alpha particles, beta particles, gamma rays, and neutrons, which will be studied and reported on later.

5.2 Further Applications

This detection section design creates a significant contribution in radiation detection applications using undoped aromatic ring polymers. A multi-type radiation detector will help to provide personnel radiological protection as well as environmental radiological protection.

Undoped aromatic ring polymers can be used for radiation management at nuclear facilities in new radiation detectors. Such facilities use various high cost detectors that can be replaced by lower cost multi-radiation detectors with high light yield, such as ones using PEN. Large area detectors can also be developed at a much lower cost using undoped aromatic ring polymers. Furthermore, blended PET and PEN can offer advantages over PET for broad applications as new materials in industry [38]. Further studies of PET and PEN have been performed including property enhancements of PET, PEN, and their blends [42][50][51][52].

i. Medicine

These undoped aromatic ring polymers have potential for applications in biomedical imaging. Medical diagnostic imaging equipment uses plastic scintillation materials to detect high-energy particles generated at a particular region from instruments like positron emission tomography, computed tomography, and magnetic resonance imaging [53]. For diagnosis equipment, undoped aromatic ring polymers have potential as an alternative plastic scintillation material. A recent research has demonstrated that PEN be suitable for clinical dosimetric measurements for photon and electron beams with different energies and dose rates from <0.1 mGy/min to several Gy/min. With its superior properties, it may replace the current polyvinyltoluene-based scintillators for such applications especially for ophthalmic plaque dosimetry [54].

ii. Education

Undoped aromatic ring polymers can be used in radiation education owing to their wide availability as general-purpose plastics, ease of process, and durability [55].

Demonstration of radiation detection from potassium-40 in salt or from thorium in mantle lamps with readily available plastic bottles as an aromatic ring polymer can impress young students [56].

iii. Agriculture

In agriculture, plants have been suggested to use radiation in the ranges of 400–500 nm up to 4x more efficiently than the UV to violet ranges from 300–400 nm for photosynthesis [57]. Different techniques have been used to convert sunlight to these optimal ranges, such as using fluorescent materials as wavelength shifters.

With further studies and optimization, undoped aromatic ring polymers offer a lower cost and easily available option to achieve optimal ranges for photosynthesis in plants, leading to a more profitable production of crops.

iv. Elementary Particle

PET has been shown to be suitable for rare particles in cosmic rays because it has higher detection thresholds compared to other commercially available nuclear track detectors [58]. In addition, PET shows a faster time response than PEN for MIP (muon) response [59]. PEN has been shown to have a higher radiation tolerance (lower sensitivity and shorter recovery periods) than PET [60]. Both are valid candidates for high-energy physics.

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List of Abbreviations

Abbreviation		Page No.
PET	polyethylene terephthalate	1
PEN	polyethylene naphthalate	1
PES	polyethersulfone	1
IAEA	International Atomic Energy Agency	2
KURRI	Kyoto University Research Reactor Institute	2
ZnS	Zinc Sulfide	6
NaI(Tl)	Sodium Iodide doped with Thallium	6
PMT	Photomultiplier Tube	8
PS	polystyrene	12
PVT	polyvinyl toluene	12
DAQ	Data acquisition system	30
PAW	Physics Analysis Workstation	30
CPM	Counts Per Minute	38
MIP	Minimum Ionizing Particles	65

Appendix

A) Analysis Using PAW Software

PAW (Physics Analysis Workstation) is an interactive graphical data analysis program used in high energy physics developed by CERN (European Organization for Nuclear Research) in 1986. In this study, it is used for displaying radiation counting.

The manuals on PAW can be found at the following websites:

PAW Physics Analysis Station <http://wwwasd.web.cern.ch/wwwasd/paw/>

PAW Reference manual http://paw.web.cern.ch/paw/reference_manual/

PAW –An Introductory Tutorial 1995: <http://www.lpthe.jussieu.fr/~roehner/pawmanu.pdf>

PAW User's guide <http://www2.pv.infn.it/sc/cern/paw.pdf>

B) Data Logging Using Hioki MR8870 Data Acquisition Recorder

The Hioki MR8870 Data Acquisition Recorder is a monitoring and recording device to observe waveforms like an oscilloscope. It is used in this study to monitor and record the count rates received by the detection section

The manuals on the Hioki MR8870 can be found here:

https://www.hioki.com/en/products/detail/?product_key=5742

C) Previous Research

i. Position dependence for count rates in a polyethylene naphthalate survey meter

We previously developed a scintillation substrate from common polyethylene naphthalate (PEN), and evaluated its overall performances for beta count rates. In this setup, we used a 72×140×0.5 mm thin PEN sheet (Teijin, Ltd.) with one face enhanced with prism treatment mounted to a survey meter (SPS-210Z, Ohyo Koken Kogyo Co., Ltd.) with a large detection window and demonstrate its radiation counting response at different locations on the detection window. The schematic is shown in Figure A1.

The PEN sheet was irradiated by beta particles emitted from a ^{90}Sr radioactive source (149 Bq, 9 October 2008; Nuclitec GmbH) *via* an acrylic collimator with a 20 mm x 20 mm square hole. The center of the source was placed over a 9×23 array of different locations on the detection window. The time constant of the survey meter was set to 30 s, and the count rates were read after 90 s from the start of irradiation. At each location on the detection window, the data taking was performed 10 times and the results were averaged. A data logger was not used in this setup, as used in Chapter 3. The results are published [22]. The survey meter demonstrated beta response from an Sr-90 source and provides preliminary data for Chapter 3.

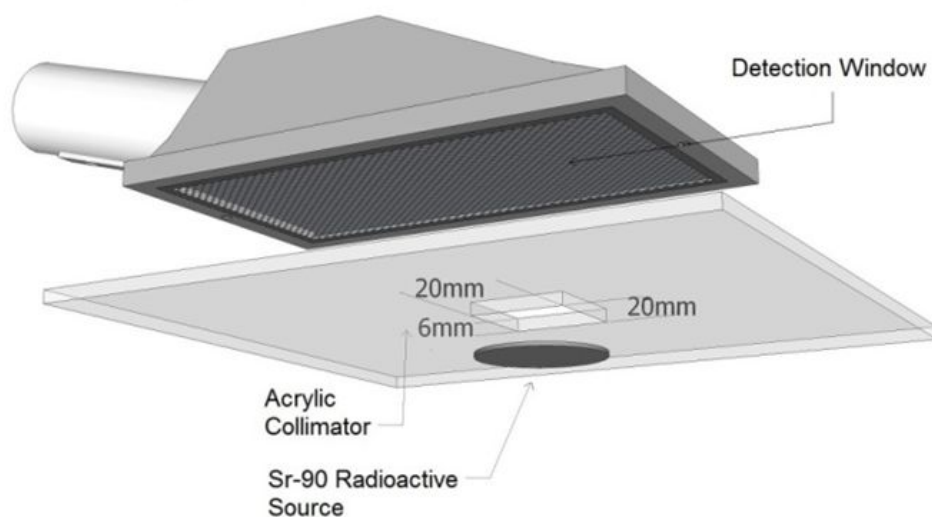


Figure A1. Schematic of the setup for measuring radiation counts. Beta particles emitted from a ^{90}Sr radioactive source *via* an acrylic collimator irradiate a 9×23 array of points on the detection window.

ii. Alpha particle response for a prototype radiation survey meter based on un-doped poly (ethylene terephthalate)

We have previously developed a prototype survey meter based on poly (ethylene terephthalate) (PET) that has been shown to be sensitive to beta particles and gamma-rays. A 140×72×1 mm PET plate with mirrored surfaces was fabricated. A unique detection section of the meter that directly detects alpha particles can be incorporated with the PET plate. The prototype survey meter acquired the response induced by alpha particles from a ^{241}Am radioactive source. The results are published [42]. It demonstrates that the undoped PET can detect alpha particles, as well as beta particles and gamma rays. It provides preliminary data for the research carried out in Chapter 4.