Design and Performance of the Muon Tomography System using Wavelength-shifting Fiber Array

Woo Jin Jo

The Graduate School
Yonsei University
Department of Radiological Science
Design and Performance of the Muon Tomography System using Wavelength-shifting Fiber Array

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Woo Jin Jo

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This certifies that the master’s
Thesis of Woo Jin Jo is approved.

___________________________
Thesis Supervisor: Prof. Yong Hyun Chung

___________________________
Thesis Committee Member #1: Prof. Bong Soo Han

___________________________
Thesis Committee Member #2: Prof. Chul Hee Min

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ABSTRACT

Design and performance of the Muon Tomography system using Wavelength-shifting Fiber Array

Woo Jin Jo
Dept. of Radiological Sciences
The Graduate School
Yonsei University

Muon tomography is a useful method for monitoring special nuclear materials (SNMs) using multiple Coulomb scattering of muons. Tracking the incoming and outgoing trajectories of muons enables the detection of SNMs and shielding materials. We designed a muon tomography system consisting of four detector modules. The incident and scattered muon tracks were calculated by two top and two bottom detectors, respectively. The degree of the scattering angle represented the atomic number of the material. The proposed detector module for the muon tomography system was composed of a plastic scintillator, wavelength-shifting (WLS) fiber arrays placed on the top and bottom of the scintillator orthogonally, and a position-sensitive Photomultiplier (PSPMT).
Light photons in the scintillator were absorbed by the WLS fibers, and the re-emitted green lights were guided to the PSPMT. The light distribution among WLS fibers determined the position of the muon interaction. 3-D tomographic images were obtained by extracting the crossing points of each muon track with a point-of-closest-approach algorithm. The aim of this study was to optimize the design parameters of a muon tomography system using DETECT2000 and GEANT4 and to experimentally evaluate the performance of the proposed detector. The detector module consisted of a 10 x 10 cm$^2$ plastic scintillator (BC-408 equivalent, Epic-crystal), 0.2 x 0.2 x 50 cm$^3$ WLS fibers (BCF-91A, Saint-Gobain), and a PSPMT (H7546A-300 MOD, Hamamatsu). The images were obtained using a 420 nm laser light source. The experimental results agreed well with simulation. These results indicate that the detector module is feasible for a muon tomography system, and they verify the Z-discrimination capability of the muon tomography system.

Key Words: Muon tomography, Plastic scintillator, Wavelength-shifting fiber, Z-discrimination
1. Introduction

1.1 Background of the research

Brain Global demands for nuclear energy from various applications increase as time passes, and the need to monitor nuclear material is increasing rapidly with this demand. In 2012, the second Nuclear Security Summit was held in Seoul. Part of the adopted “Seoul Communiqué” is described below: “Nuclear terrorism continues to be one of the most challenging threats to international security. Defeating this threat requires strong national measures and international cooperation given its potential global political, economic, social, and psychological consequences” [1]. Thus, monitoring nuclear materials is required for the use of nuclear energy and for avoiding nuclear terrorism.

There are two general methods for monitoring nuclear materials. The first involves detecting radiation from the nuclear materials, while the second involves irradiating the nuclear materials. The former is called neutron activation analysis, while the latter includes the methods of dual-energy radiography and backscatter x-ray [2]. Radiation from the nuclear materials can be eliminated by shielding materials. Radiography using x-rays and gamma rays requires an additional radiation source, and the use of radiation involves risks due to the radiation exposure of the radiation workers and the public.

To solve these problems, muon tomography was suggested as an alternative technique. Muon tomography does not require an artificial radiation source or beams. Muon Coulomb scattering, a major principle of muon tomography, is proportional to the atomic
number of the material through which the muons pass. Because muons have very high energy, they are good candidates for detecting shielded nuclear materials.

1.2 Research objective

In this work, the effects of the design parameters—including the spatial resolution, the field-of-view (FOV) (which is the distance between the top and bottom detectors), and the distance between the top two detectors—were analyzed and evaluated by simulation. We designed a small muon tomography system based on the simulation results and suggested a detector design consisting of a plastic scintillator, two arrays of wavelength-shifting (WLS) fibers, and a position-sensitive photomultiplier (PSPMT). The performance of the prototype muon detector we developed was evaluated by experiment. The aim of the study was to analyze the characteristics of the muon tomography system using the proposed detector and to evaluate the feasibility of the detector and the system.
2. Background information

2.1 Tomography

The word tomography is derived from the Greek *tomos*, which means “cut” or “section,” and *graphein*, which means “image” or “write.” Tomography involves imaging an object by sections. The first use of tomography using an X-ray source was the computed tomographic (CT) scanner invented by Sir Godfrey Hounsfield [3]. In addition to medical applications, there are other applications for tomography, such as non-invasive surveying for ruins [4], imaging for looking inside the earth, and ocean acoustic tomography for measuring regions of the ocean [5]. Modern tomography requires projections from many directions and uses a reconstruction algorithm for producing the desired results (i.e., 2-D or 3-D images). Muon tomography is a promising technique and can produce 3-D images.

2.2 Muon tomography

2.2.1 Cosmic ray muons

Muons were discovered in 1936 during the study of cosmic radiation. The Earth is constantly being bombarded by high-energy particles from our solar system. These particles, called primary cosmic rays, are generally stable. The interaction of the primary
cosmic rays in the upper atmosphere produce other secondary particles, which in turn interact with the atmosphere and produce showers of secondary particles. Figure 2.1 shows these processes. The primary particles (mainly high-energy protons and heavy atomic nuclei) interact with other atmospheric nuclei and produce pions. Charged pions decay into charged muons. Muons have a mass of 105.7 MeV/c$^2$ (about 200 times heavier than an electron) and are similar to the electron with a unitary negative electric charge. Muons are highly penetrating with a mean energy of 3–4 GeV, and they are affected by the Coulomb force due to their electric charge. The flux of muons is 1/cm$^2$/min at sea level and depends on latitude and azimuth angle.

Figure 2.1 Primary cosmic rays collide with molecule of atmosphere and produce many other secondary particles, including pions and muons.
2.2.2 Multiple Coulomb scattering

![Diagram of muon interaction]

Figure 2.2 Muons interact with atomic nuclei as they pass through material. This phenomenon, multiple Coulomb scattering, results in different angular scattering distributions depending on material type.

Charged particles, including muons, are affected by the Coulomb force as they pass through material. As muons pass through atoms of material, they may strike electrons and remove electrons from their molecular orbital, which is called ionization. Because muons interact with atomic nuclei in the material, they undergo many small angle deviations and lose their energy through electromagnetic interactions. This phenomenon results in multiple Coulomb scattering. The angular scattering distribution is approximately Gaussian, and the width of the distribution $\theta_0$ is characterized by:
where $p$ is the momentum of the muon, $x$ is the thickness of the material, and $X_0$ is the radiation length of the material. Generally, high-energy charged particles lose energy in matter by bremsstrahlung and high-energy photons by pair production. Thus, the probability of the occurrence of bremsstrahlung and pair production represents the radiation length. Radiation length, which is a characteristic of a material, is defined by:

$$X_0 = \frac{716.4 \text{ (g/cm}^2\text{)}}{\rho} \frac{A}{Z(Z+1)\log(287/\sqrt{Z})}$$

where $A$ is the atomic mass of the material, $\rho$ is the density of the material, and $Z$ is the atomic number of the material. Table 2.1 shows the radiation lengths of various materials. Radiation length decreases as the atomic number and density of the material increases. Therefore, the scattering distribution of muons increases as the atomic number and density of the material increase.
Table 2.1 Radiation lengths of various materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Z #</th>
<th>Radiation length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
<td>36.08</td>
</tr>
<tr>
<td>Polyethylene</td>
<td></td>
<td>47.9</td>
</tr>
<tr>
<td>Shielding Concrete</td>
<td>13</td>
<td>10.7</td>
</tr>
<tr>
<td>Aluminum</td>
<td>26</td>
<td>8.9</td>
</tr>
<tr>
<td>Iron</td>
<td>29</td>
<td>1.76</td>
</tr>
<tr>
<td>Copper</td>
<td>74</td>
<td>1.43</td>
</tr>
<tr>
<td>Tungsten</td>
<td></td>
<td>0.35</td>
</tr>
<tr>
<td>Lead</td>
<td>82</td>
<td>0.56</td>
</tr>
<tr>
<td>Uranium</td>
<td>92</td>
<td>0.32</td>
</tr>
</tbody>
</table>

2.2.3 Muon tomography

Multiple Coulomb scattering is proportional to Z and allows for the identification of materials. Denser materials with higher Z cause more deflection in the trajectories, making muons a possible tool for the detection of high-Z materials such as uranium (Z-discrimination). The muon tomography system consists of four horizontal position-
sensitive detectors, as shown in Figure 2.3. The top two detectors measure the incoming angle and trajectories of the incident muons, and the bottom two detectors measure the angle and trajectories of the scattered muons emerging from the object volume. Then, the scattering angle indicates the kind of material (approximately), and scattered points can be calculated by their trajectories.

Figure 2.3 Schematic diagram of a muon tomography system consisting of four position-sensitive detectors
2.3 GEANT4 simulation toolkit

Development of the detectors used for particle detection in particle physics is difficult due to their very large research scale. Thus, extensive simulation and theoretical study were needed before the development and experiment. Simulation is important in particle physics as well as high-energy physics, space science, nuclear medicine, and fields that study the interaction between particles and matter. The GEANT4 simulation toolkit is a platform developed by CERN for particle tracking in matter using Monte Carlo methods [6]. It was designed using object-oriented programming (C++), and it has a large degree of functionality and flexibility. Thus, it is easy to trace the trajectories of muons by GEANT4 simulation.

2.4 DETECT2000 simulation toolkit

DETECT, a Monte Carlo computer model, was developed for the study of light distribution in a scintillation neutron detector by Knoll et al. in 1988 [7]. DETECT written with PASCAL can measure the light distribution while simulating the behavior of light photons. DETECT2000 re-written with objective-oriented programming (C++) was achieved better performance, modifiability, and user convenience after DETECT97 (i.e., the upgraded version of DETECT) [8].
2.5 Reconstruction algorithm for a muon tomography

Muon tomography determines the target location by the intersection of incoming and outgoing muon tracks and the atomic number of the material by the difference in the degree between the tracks. As described above, muons undergo many small angle deviations as they pass through the material. If the muon was scattered at one certain point, we could easily get the location at which the muon was scattered, because there is one solution of the simultaneous equations of two muon tracks. Due to the multiple Coulomb scattering of muons, we could not specify one certain location at which the muon was scattered, as illustrated in Figure 2.4. In order to solve this problem, the Point-of-Closest-Approach (PoCA) algorithm, which calculates the closest points of skew lines, was used for the reconstruction of muon tomography [9].

Figure 2.4 The intersection of incoming and outgoing muon tracks usually does not exist when muons pass through the material. In this case, muon tracks are skewed.
Figure 2.5 (L) Two lines are closest at unique point $P(s_c)$ and $Q(t_c)$ for which vector $w_c$ is the unique minimum and perpendicular to both lines. (R) Intermediate point of vector $w_c$ was assumed to be the reconstructed point at which the muon was scattered.

Vector $u$ was the track of the incident muon, and vector $v$ was the track of the outgoing muon. Then, two vectors that did not intersect and were not parallel were called skew lines. The PoCA algorithm finds the closest point $P(s_c)$ and $Q(t_c)$ for which vector $w_c$ is the unique minimum and perpendicular to both lines. The intermediate point of vector $w_c$ was assumed to be the reconstructed point at which the muon was scattered, and the difference in the degree between the tracks was calculated by vectors $u_n$ and $v_n$ that passed through the intermediate points.
3. GEANT4 simulation study

3.1 Scattering angle distribution

The scattering angle distribution was simulated in various materials to validate GEANT4. The pencil-beam muons (3 GeV) impinged on five $20 \times 20 \times 10 \text{ cm}^3$ target materials composed of high-enriched uranium (HEU), Pb, Cu, Fe, and Al. The scattering angle distributions were calculated by the incoming and outgoing muon track.

3.2 Evaluation of system performance as function of design parameters

The measure of how closely lines or points can be resolved in an image is called the spatial resolution. Therefore, detectors with good spatial resolution can accept a small scattering angle of muons. The reconstructed volume is the FOV, which is the distance between the top and bottom detectors. Muon tomography is composed of the top two position-sensitive detectors and the bottom two detectors, because the trajectories of the line described by muons moving through space can be calculated by at least two points. The distance between the top two detectors (same as the distance between the bottom two) is called the distance between detectors.
The GEANT4 toolkit was used to evaluate the performance of the muon tomography system and to optimize the design parameters, including the spatial resolution of the muon detector, FOV, and the distance between detectors. Then, three GeV mono-energetic muons were generated, with the direction of the incident beam being perpendicular to the top detector plane. A 20 × 20 × 10 cm$^3$ HEU was located in the center of the FOV. The acquisition time was 10 min (12,560 muons) based on the natural cosmic-ray muon flux, and the area of the detector was 100 × 100 cm$^2$. The Z-discrimination capability was measured, while the spatial resolution varied from 4 mm to 0.1 mm, FOV varied from 50 cm to 500 cm, and the distance between detectors varied from 1 cm to 100 cm.

We defined the two characteristic factors for the quantitative evaluation of the performance of the muon tomography system as a function of design parameters as follows.
\[ Sensitivity = \frac{\text{The number of detected muons}}{\text{The number of incident muons}} \]  

\[ Z - \text{discrimination} = \] 
\[ \frac{\text{The number of muons that are scattered more than 2° in the target volume}}{\text{The number of detected muons}} \]  

Figure 3.2 shows the reconstructed images of muon tomography. X and Y in the image indicate the area of the detector, and Z represents FOV size. The color bar represents the scattering angle of muons in degrees. Thus, Figure 3.2 includes the four-dimensional information. Sensitivity is the ratio of the number of detected muons to the number of incident muons; this is the ratio of the number of reconstructed points to the number of incident muons in Figure 3.2. Most of the muons that passed through the HEU target used in the simulation were scattered 2 – 3 degrees. Z-discrimination indicates the ratio of the number of muons that are scattered more than 2 degree in the target volume to the number of detected muons. Z-discrimination contains the information of the position of the target and the type of material (Z number). The performance of the system improves as the values of sensitivity and Z-discrimination increase.
3.3 Simulation results

3.3.1 Scattering angle distribution

The scattering angle of 3 GeV muons impinging on five 20 × 20 × 10 cm³ target materials (i.e., HEU, Pb, Cu, Fe, and Al) was simulated in GEANT4. The scattering angle distributions calculated by the incoming and outgoing muon tracks are illustrated in Figure 3.3. The results agree well with other published results [10].
3.3.2 Evaluation of system performance as a function of design parameters

To obtain a quantitative evaluation of the system performance, sensitivity and Z-discrimination as defined above were simulated using GEANT4. Figure 3.4 shows the sensitivity and Z-discrimination with different spatial resolutions of 0.1 mm, 1 mm, 2 mm, and 4 mm as a function of the distance between detectors. FOV was fixed at 50 cm. Sensitivity and Z-discrimination increased as the distance between detectors increased up to 20 cm and then reached a plateau. Sensitivity increased gradually and Z-discrimination increased more quickly as the spatial resolution of the detector increased. Therefore, the appropriate distance between detectors was found to be 20 cm.
Figure 3.5 shows the reconstructed images of the PoCA points with an FOV of 50 cm and distance between detectors of 20 cm at different spatial resolutions of 0.1 mm, 1 mm, 2 mm, and 4 mm. To clearly visualize the shapes of the target, the spatial resolution of the detector should be less than 2 mm.

To evaluate the function of FOV size, the reconstructed images with 20 cm of distance between the detectors and less than 2 mm of spatial resolution of the detector as derived above are illustrated in Figure 3.6. In the sensitivity and Z-discrimination as shown in Figure 3.7, there was no significant change in the sensitivity; however, Z-discrimination decreased as FOV size increased. Both sensitivity and Z-discrimination are important in muon tomography, but Z-discrimination is more important, because it contains two pieces of information on the target. Thus, the appropriate FOV size is 50 cm.
Figure 3.4 Characteristic factors of a muon tomography system as a function of the spatial resolution of the detector and distance between detectors with 50 cm FOV.

Figure 3.5 Reconstructed images of the PoCA points with different spatial resolutions as a function of the distance between detectors.
Figure 3.6 Reconstructed images of the PoCA points with different spatial resolutions and 20 cm of distance between detectors as a function of FOV size

Figure 3.7 Characteristic factors with different spatial resolutions as a function of FOV size
4. Muon detector

4.1 Muon detector requirements

The muon detector for muon tomography should meet the following requirements: (1) coincidence timing, (2) spatial resolution, and (3) energy determination [11]. To distinguish muons from the background, we need a coincidence triggering system. Due to the speed of muons, nanosecond coincident timing is required. Because muons are affected by multiple Coulomb scattering as they pass through the material, we need to detect the small change in angle between the incoming and exit muon trajectories. A muon detector requires good spatial resolution for distinguishing small angle deviations. Scattering distribution is also sensitive to muon energy (momentum).

4.2 Plastic scintillator

The first type of muon detector to consider would be a plastic scintillator. A plastic scintillator consists of organic scintillating molecules. Because of its low price and the ease with which it can be shaped and fabricated, plastic scintillators have become widely used for various applications using scintillators. Since they are especially sensitive to charged particles, including muons, plastic scintillators can also be used in high-energy particle physics. The relatively large light output of plastic scintillators (25–30% of NaI(Tl)) [12] and short decay time makes them well suited for muon tomography.
4.3 Wavelength-shifting fiber

It is difficult to couple a large-area scintillator with a PSPMT directly because of the limitation of the photocathode area of the PMT. We can resolve this problem by using a WLS fiber, which provides an efficient method for collecting light generated in very large-area scintillators. A WLS fiber can absorb the violet light (~425 nm) isotropically and re-emit the green light (~650 nm) to the end of the fiber. The short wavelength light (<520) is almost attenuated through the length of WLS fiber; however, the attenuation of longer wavelengths is very low. The features of plastic also make it easy to fabricate and shape the WLS fiber. Thus, the WLS fiber is essential for a muon tomography system using a large-area scintillator.

4.4 Design of a muon detector module

The detector proposed in this work is illustrated in Figure 4.1. The detector module consists of a plastic scintillator and WLS fibers that absorb light from all sides of the fiber and re-emit light to the end of the fiber, unlike other optical fibers. Figure 4.2 shows the optical spectra of a WLS fiber (BCF-91A, Saint-Gobain) [14]. The feature of the WLS fiber achieves the detector design as shown in Figure 4.1. Light photons produced by muons inside the plastic scintillator are absorbed by the WLS fibers, and the re-emitted green lights (500 nm for a wavelength of maximum emission) are guided by total internal
reflection to the PSPMT. WLS fiber arrays are aligned orthogonal to each other and represent the light distribution in the x and y directions, respectively. Light distributions from the WLS fibers determine the location of muon interaction by Anger logic [15]. Figure 4.3 illustrates how the muon interaction point was determined in the proposed detector.
Figure 4.1 Design of the proposed muon detector module composed of a plastic scintillator and WLS fiber arrays

Figure 4.2 Optical spectra of BCF-91A WLS fiber [13]

Figure 4.3 Light photons produced by muons inside the plastic scintillator are absorbed by the WLS fibers, and re-emitted green lights to the end of fibers. Thus, light distribution from scintillator can be delivered to photo-sensor.
5. DETECT2000 simulation study

5.1 Evaluation of detector performance with DETECT2000 simulation

The imaging performance of the proposed detector module was evaluated by DETECT2000 simulations. The detector module consisted of a $10 \times 10 \times 0.5 \, \text{cm}^3$ plastic scintillator and $0.2 \times 0.2 \times 20 \, \text{cm}^3$ WLS fibers, as shown in Figure 5.1. Twenty-two WLS fibers were aligned with a 4 mm pitch on the top and bottom sides in the x and y directions, respectively. Muon interaction was generated at the center of the detector, and a total of 10,260 light photons were produced, accounting for the light conversion efficiency of the plastic scintillator as the deposition energy and the quantum efficiency of the PMT’s photocathode. The re-emitted light output was detected at the end of the WLS fibers, and the light distribution of the WLS fiber array was measured. The position of the muon interaction was extracted by the Anger equation as follows [15], and then the spatial resolution of the detector was calculated.

\[
X = \frac{x^+ - x^-}{x^+ + x^-} \quad Y = \frac{y^+ + y^-}{y^+ + y^-}
\]

\[
X^+ = \sum_{w=1}^{22} w \cdot WLS_w \quad X^- = \sum_{w=1}^{22} (23 - w) \cdot WLS_w
\]

\[
Y^+ = \sum_{w=23}^{44} w \cdot WLS_w \quad Y^- = \sum_{w=23}^{44} (45 - w) \cdot WLS_w
\]

$X$: the position of muon interaction in the X direction
$Y$: the position of muon interaction in the Y direction
$WLS_w$: the number of light photons at the end of $w_{th}$ WLS fiber
$w$: weighting factor
Figure 5.1 The detector module, consisting of a $10 \times 10 \times 0.5$ cm$^3$ plastic scintillator and 22 WLS fiber on each side in the x and y directions, respectively.

5.2 Simulation results

Figure 5.2 Simulated image with DETECT2000 shows approximately 2 mm FWHM and profile of simulated image.

The imaging performance of the proposed detector was evaluated by DETECT2000. The spatial resolution, defined as the full width at half maximum (FWHM) of the point profile, was calculated as 1.9 mm FWHM.
6. Experimental study of a prototype muon detector

6.1 Development of a prototype muon detector module

Figure 6.1 shows the materials of a prototype detector module consisting of (a) a plastic scintillator, (b) PSPMT, and (c) WLS fibers. The $10 \times 10 \times 0.5$ cm$^3$ plastic scintillator made by Epic crystal (China) was equivalent to the BC-408 made by Saint-Gobain (USA). The $0.2 \times 0.2 \times 50$ cm$^3$ WLS fibers were BCF-91A made by Saint-Gobain (USA). The $8 \times 8$-channel PSPMT used in the experiment was a H7546A-300MOD made by Hamamatsu (Japan). The spectral response of the PSPMT commonly used has 420 nm for a wavelength of maximum absorption. H7546A-300MOD has more light efficiency accounting for the re-emitted light photon’s wavelength from the WLS fiber.

The proposed detector needs housings for fixing several materials due to the design of the detector. The housing for the plastic scintillator and WLS fibers and the other housing for the PSPMT and WLS fibers were developed as shown in Figure 6.2. The housing material used was black acetal for minimizing the interference with detector materials. Figure 6.3 illustrates the combination of WLS fiber arrays and the combination of WLS fiber arrays and the plastic scintillator.
Figure 6.1 Materials of a detector module: (a) plastic scintillator, (b) PSPMT, (c) WLS fibers
Figure 6.2 Housings for a prototype muon detector module
Figure 6.3 (a) WLS fiber arrays were combined with the housing, (b) WLS fiber arrays and plastic scintillator were combined (c) A prototype muon detector module combined with all detector materials.

6.2 Experiment using a prototype muon detector

The performance of the prototype muon detector was experimentally verified for the muon tomography system. Light distribution was acquired by irradiation of the 420 nm laser beam on the center of the plastic scintillator through seven channel WLS fibers. Then, the spatial resolution of the prototype muon detector was calculated. Figure 6.4 shows a schematic diagram of configures of the experiment.
Figure 6.4 Evaluation of developed detector was performed. FWHM was calculated by irradiation of the 420-nm laser on the scintillator.

To obtain the signal of PSPMT, we configured the data acquisition system as shown in Figure 6.5. The 64 anode outputs from the PSPMT were multiplexed into four positioning signals using an SIB164-1018 interface board (Vertilon, USA) that included a pre-amplifier and a resistive charge divider. The dynode output signal was sent to a constant-fraction discriminator for triggering. The four output signals were converted by ADC using trigger signals from CFD and sent to a computer using a DAQ board.

Figure 6.5 Block diagram of data acquisition system from PSPMT
6.3 Experiment results

The signals directly from the scintillator have shorter decay times than those from the WLS fibers and the scintillator. These signal features could assist in determining the appropriate experimental acquisition conditions.

Figure 6.6 Experimental image using developed detector and profile of acquired image

Figure 6.6 illustrates the image acquired with a prototype muon detector using a 420-nm laser light and a profile of the image. The FWHM of the experiment was 2.49 mm.
7. Discussion

The simulation and experimental results indicate that it is possible to monitor nuclear materials using cosmic-ray muons and the proposed detector.

As described in GEANT4 simulation results, sensitivity and Z-discrimination increased as the distance between detectors increased up to 20 cm, after which point sensitivity and Z-discrimination did not change. In the simulation study, the muons were generated with the direction of the incident beam being perpendicular to the top detector plane in order to evaluate only for the geometric parameters of system. Therefore, if sufficient distance between detectors is guaranteed to identify the maximum scattering angle, distance between detectors cannot affect system performance. As FOV size increases, all reconstructed PoCA points also increase regardless of whether they are in the target or not. Z-discrimination decreases as FOV size increases, but sensitivity increases as FOV size increases. The key benefit of muon tomography is its ability to measure the muon scattering angle corresponding to the atomic number of the object. Z-discrimination is more important than sensitivity, because Z-discrimination contains the key points of the muon tomography system. Therefore, the performance of the muon tomography system is better with smaller FOVs. With a high-resolution detector, the effect of the geometric configuration on the image quality is not significant, but as the detector resolution degrades, a large gap between detectors is required.

The results of the DETECT2000 simulation show that a spatial resolution of approximately 2 mm can be achieved by our detector design. The FWHM of a prototype muon detector is approximately 2.5 mm. This difference is due to the following causes: (1)
the light sharing of PSPMT, (2) the difference in the surface treatment of the WLS fibers, and (3) the thickness and location of the generation of laser light. The PSPMT commonly used has a glass window for transmitting the lights on the photocathode, which converts light photons into electrons as shown in Figure 7.1. Because of the glass window, lights from the WLS fibers spread and interfere with other fibers. If seven channel fibers are simultaneously acquired, the spatial resolution degrades to 12 mm. The source difference between the simulation and the experiment also degrades the spatial resolution. The experimental results agree well with the simulation, considering the reasons described above. The performance of the developed detector can be improved by applying the appropriate surface treatment to WLS fibers and applying individual photo-sensors (e.g., SiPM, PIN-diode).

Figure 7.1 The PMT commonly used has a glass window on the photocathode that converts light photons to electrons. This results in a spreading of lights and degrades the spatial resolution.
8. Conclusion

In this study, we designed a muon tomography system composed of four detector modules consisting of a large-area plastic scintillator, WLS fiber arrays coupled to the top and bottom sides of the scintillator, and a PSPMT.

The evaluation of the effects as a function of the design parameters—which included FOV size, distance between detectors, and the spatial resolution of the detector—was simulated using GEANT4.

Based on the results of two simulations and experiment, the appropriate geometric parameters of the muon tomography system were derived. There is still room for improvement in spatial resolution of the detector by applying individual photo-sensor.

In this thesis, these results indicate that the proposed detector module is feasible for a muon tomography system and verify the Z-discrimination capability of the muon tomography system.
References

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국문 요약

파장변이섬유를 이용한 뮤온 토모그래피
시스템의 설계 및 특성 연구

연세대학교 대학원
방사선학과
조 우 진

뮤온 토모그래피는 뮤온의 다중쿨롱산란 현상을 이용하여 물질의 위치 및 종류를 식별하는 방법이다. 뮤온의 다중쿨롱산란 정도는 뮤온이 통과하는 물질의 길이, 밀도, 원자번호에 비례하게 된다. 따라서 원자번호가 높은 핵물질 감시에 아주 효과적이다. 본 연구에서는 뮤온 토모그래피 시스템을 위해 이차원 검출기를 사용하며 상부에 두 개, 하부에 두 개를 배치하여 설계하였다. 상부의 검출기를 통해 뮤온의 입사 궤적을 계산하며 하부의 검출기를 통해 산란된 뮤온의 출사 궤적을 계산하게 된다. 이때 산란된 각도의 크기는 다중쿨롱산란에 따라 물질의 원자번호와 비례하여 증가한다. 뮤온 토모그래피 시스템을 구성하기 위한 검출기로 본 연구에서는 플라스틱 섬광체와 파장변이섬유, 광전자 증배관으로 구성하였다. 플라스틱 섬광체

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윗면과 아랫면에 파장변이섬유 배열다발을 수직으로 배치하고 빛 분포의 획득을 위해 광전자 증배관을 사용한다. 플라스틱 섬광체에서 뮤온에 의해 발생된 빛의 분포는 파장변이섬유에 흡수되어 변이된 파장으로 제 방출하며 이는 광전자 증배관을 통해 수집된다.

본 연구의 목적으로는 뮤온 토모그래피 시스템의 기하학적 설계변수에 따른 영향을 분석하며, 소형 뮤온 토모그래피를 설계, 뮤온 토모그래피에 적합할 수 있는 검출기 제작 및 평가이다. GEANT4 시뮬레이션을 통해서 뮤온 토모그래피 시스템의 기하학적 설계변수 (FOV 크기, 검출기간 거리, 검출기 공간분해능)에 물질 구분능력 및 민감도에 따라 영향을 평가하고, 적절한 설계변수를 도출하였다. 이를 바탕으로 소형 뮤온 토모그래피를 설계하였으며 플라스틱 섬광체, 파장변이섬유, 광전자 증배관으로 이루어진 프로토타입 검출기를 제작하였다. 프로토타입 검출기는 10 x 10 cm2 면적을 가지는 플라스틱 섬광체 (BC-408 equivalent, Epic-crystal), 0.2 0.2 50 cm3 크기의 광전자 증배관 (BCF-91A, Saint Gobain), 광전자 증배관(H7546A-300 MOD, Hamamatsu)을 이용하여 제작되었다. 공간분해능 획득 실험을 통해 제작된 검출기의 성능이 DETECT2000 시뮬레이션과 잘 일치하는 것을 확인하였다.

본 연구결과를 통해 소형 뮤온 토모그래피 시스템의 적절한 설계변수를 도출하였으며, 제작된 검출기의 뮤온 토모그래피 시스템에서의 설현가능성을 확인하였으며 뮤온 토모그래피의 물질 구분능력을 검증할 수 있었다.

핵심 되는 말: 뮤온 토모그래피, 플라스틱 섬광체, 파장변이섬유, 물질구분능력(Z-discrimination)
감사의 글

짧으면 짧다고 생각되며 길다면 길었던 석사 논문을 마무리하면서 그 동안 도움을 주셨던 모든 분들께 감사의 뜻을 전합니다. 무엇보다도 철 모를 시절 연세대학교 방사선학과를 거쳐 적지 않은 시간을 같이 보내주시고 설 Paragraph 형 교수님께 감사의 인사를 드리고 싶습니다. 교수님과 함께 지냈던 약 3 년의 시간은 계으론 저에게 매번 움직일 수 밖에 없는 활력이 되어 주셨고 (많이 반성하고 있습니다) 누구보다도 뛰어난 학문적 길을 보여주셨습니다. 학교를 나와 있는 지금에서도 교수님의 이름을 들을 때마다 자신감이 생기고 자랑스러움을 감출 수가 없습니다.

또한 학부 때부터 수업뿐만 아니라 저의 부족한 부분을 메워해주시고 채워주신 김희중 교수님, 한봉수 교수님, 조효성 교수님, 민철희 교수님께도 감사의 사별을 전합니다. 모든 교수님들 덕분에 제가 석사과정을 무사히 마치게 된 것 같습니다.

대학원 생활을 하면서 사실상 가족보다 더 많은 시간을 함께 보내고 동료동학한 분이라도 연구실 선배배님들께도 감사를 드립니다. 연구실 산업 멤버인 철형형, 승형형 철부지 동생이 들어와서 물을 많이 흘린 것 같지만 잘 받아주셔서 고맙습니다. 본인도 총업 때문에 귀찮고 자주 떨어져 왔다 왔다 차근차근 잘 가르쳐주신 김현우나, 박범년 총업 때문에 자주 귀찮게 해서 미안한 정형형, 3 년 동안 정말 연구실에서 같이 먹고 자고 연구했던 현일형, 수진누나, 최영형 형님 내 분명하던 또 들어주고 놓아주고 응원해준 세 사람은 평생 잊지 못할 것입니다. 그리고 멀리 떨어진 학교에서 또 멀리 떨어진 학교로 들어온 형들과, 친구, 들어온 지 얼마 되지 않았지만 진형이까지 나이 한 두 살 많다고 너무 부러워서도 아닌가 모르겠지만 정말 많은 도움 되었고 감사의 인사를 전합니다. 다른 연구실이지만 동기로서 든든한 유나, 수진누나 그리고 마침가지 다른 연구실이지만 같은 연구실같이 느껴질 만큼 잘 대해준 예슬누나, 영형형 그리고 같이 총업하는 동형형과 형수인 현주누나까지 정말 감사합니다. 그 밖에도 언급하지 못한 대학원 여러 선배배님들도 고맙습니다.

마지막으로 서울에서 열심히 일하며 귀엽고 사랑스러운 은채, 하우, 수진, 영형형 형수인, 부족한 아들이 하고 싶다는 대로 부친 고집을 잘 받아주시고 훌륭한 삶을 살아가도록 지금도 아깝고 끊임없는 도움을 주시는 아버지, 어머니께 이 논문을 바칩니다.

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