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A Preliminary Study on a Compact Muon Tomography Station for Educational Exhibition Purposes

Suhyun Lee [a*], Cheong-Soo Lee [a], Hwan Shin [a],
Yu-Sun Yeom [a], Ji Eun Park [a], Sung Ho Yoo [a], Seo Kon Kang [a]
[a] *Radiation Emergency Medical Team, Radiation Health Institute, Korea Hydro & Nuclear Power Co., Ltd.,*
172 Dolma-ro, Bundang-gu, Seongnam-si, Gyeonggi-do, 13605, Korea
[*] *Corresponding author: sam4328@gmail.com*

1. Introduction

The view that radiation is a unique physical entity, which is hard to experience in everyday life, is a common misconception that the general public has. It is one of the negative factors that influences the public acceptance and perception of radiation.

The fact that most of the radiation application techniques are based on artificial radiations has been dominantly informed, and this circumstance may strengthen the misconception which mentioned above. From this point of view, therefore, it is essential to improve the public awareness of the usualness and promote the receptivity of radiation.

In the meantime, there have been several strategies to emphasize the usualness of it. It is typical to explain or visualize the concept of the environmental and the natural radiation. However, a demonstration of the actual applications of the natural radiation seems to be a more aggressive approach.

Muon tomography is one of the most suitable techniques for this intent because it employs only a natural radiation, cosmic ray, which is always coming from the universe into the Earth, as well as can be practically used for a border security monitoring in terms of homeland security. [1−3]

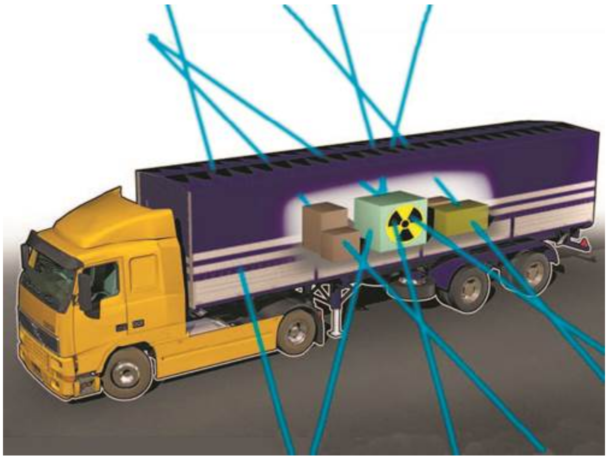


Fig. 1. A schematic view of a muon tomography system [3]

Muon tomography is a technique to acquire an image of the inside of an object by using interactions with muons and materials. As a charged particle, the muons make multiple Coulomb interactions with the materials.

In the cases that the object is made of high-*Z* or dense material, it is refracted at a large scattering angle. In this principle, muon tomography can be used as a cargo inspection technique for searching special nuclear materials because nuclear materials are composed of heavy elements.

Most of the currently proposed muon tomography stations are designed to be suitable for a cargo container scanner. However, since this study aims to design a station which can be used as an educational exhibit in a limited area, it should be miniaturized. In this paper, the feasibility of a compact muon tomography station to search a small object made of high-Z materials has been investigated. [4−6]

2. Goals and Methods

This section describes the goals and methods of the study. Accordingly, a brief description of the simulation toolkit and how to simulate the toy model of the muon tomography station including geometric settings will be described.

2.1 Goals

The compact muon tomography station is, in principle, not different from the cargo inspection muon stations, but it requires changes in hardware specifications due to its compact size. As the active volume decreases, the size of the target object is limited, and the scatter angle decreases.

Furthermore, since the trajectory of the muon is also shortened, the positional deviation due to scatterings becomes small. Therefore, it is necessary to optimize the spatial resolution and the channel number of the detectors in consideration of the above conditions.

In this study, we would like to evaluate scattering angles for some materials, assuming a target object of about 50 cm in radius.

2.2 Simulation Toolkit

In this study, Geant4, which is a toolkit for the simulation of the passage of particles through matter, was employed. In order to simulate the scattering angle according to some materials, calculations for multiple Coulomb scattering for high energy particle up to a few GeV should be performed as a random process step. Also, specific energy losses should be estimated.

Geant4 is a powerful tool for carrying out these processes. Initially, this tool was developed for high-energy physics research. But now, applications of Geant4 have been rapidly expanded, for example, accelerator science, medical science, astrophysics and radiation science.

This study uses the physical model QGSP_BERT 3.0 released by the Geant4 collaboration, and the physical models commonly employed in Geant4 are shown in Table 1. [7−8]

Table 1. The employed PhysicsList. The physical models are suitably selected by considering the energy of particles.

Name	Model	Range
QGS	Quark Gluon String Model	>~20 GeV
BERT	Bertini Cascade Model	<~10 GeV
HP	High Precision Neutron Model	< 20 MeV

2.3 Scattering Angle

It is known that when a muon interacts with an object, its average scattering angle is given by Eq. (1).

$$\sigma_\theta = \frac{13.6\ \mathrm{MeV}}{\beta c p}\sqrt{\frac{x}{X_0}}\left[1 + 0.038\ln\frac{x}{X_0}\right] \qquad (1)$$

p and βc are the momentum and velocity of muon respectively. x is the thickness of a target, and the radiation length of the matter is denoted as X_0. [9−10]

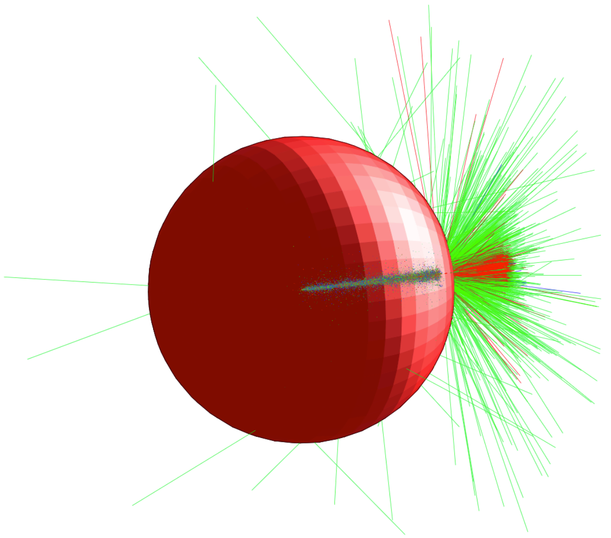


Fig. 2. A schematic view of the geometrical setup for the simulation

However, in actual measurement, it is hard to identify materials by using only the scattering angle if the distribution of angle is not considered.

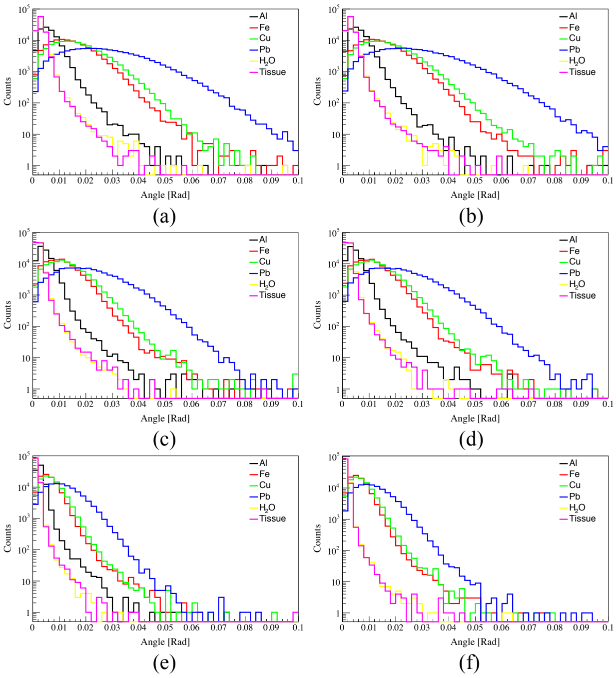
Therefore, in this study, the distribution and tendency of scattering angle have been investigated by calculation via the Geant4 simulation. A spherical object was assumed to eliminate the effect of the shape of the object, and all muon particles supposed that they always pass the center of the object.

In this simulation, four homonuclear compounds and two heteronuclear compounds were selected. Also, mono-energy single particle Monte Carlo simulation was performed with 10^5 times. Since the goal is to track the muon's trajectory, the geometry of the detector is not considered.

3. Results

Fig. 3 shows the scattering angle distribution of muons for each material as a consequence of the computational simulation. The energy of muon was set to 4 GeV, the mean energy of muons at sea level, and negatively charged muon, μ^- and positively charged muon, μ^+ were taken into account for the calculation.

As can be seen in Fig. 3, the higher-Z materials accompany the larger scatter angle, for instance, lead (Pb) shows the largest scattering angle. Especially, it is very encouraging that the average scattering angle of the organic structure (or H_2O) and lead are about five times different in that the distinction between organic matters and heavy elements is important in the cargo inspection.



(a) (b)

(c) (d)

(e) (f)

Fig. 3. The distribution of Coulomb scattering angle for each material. (a), (c) and (e) are the scattering angle distribution when μ^- pass through a 50, 30 and 10 cm thick object, respectively. (b), (d) and (f) are for μ^+ in the same manner.

If the difference in atomic number *Z* is not so large such as copper and iron, however, an identification of material is quite difficult to perform in practice. Besides, it can be concluded that the thickness of an object must be at least 30 cm in order to distinguish materials made of heavier elements than lead.

4. Conclusions

As the result shows, the higher atomic number accompanies, the larger average scattering angle and the wider distribution of angle.

In particular, it is important that the refraction angle of lead is clearly different from that of organic matter. Because of this, given the fact that there is no need to use educational exhibits in harsh conditions, it can be expected that the feasibility of the compact muon station is sufficient.

Also, because the deviation of the angle between each material is an essential criterion for regarding the spatial resolution, this result can provide an important clue for a conceptional design of the compact muon tomography station.

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