Simulation for Material discrimination and identification using multiple scattering muon tomography

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Introduction

Highly penetrating cosmic ray muons shower the Earth at the rate of 10,000 m^{-2} min^{-1} at sea level. The mean energy of muons at sea level is about 3–4 GeV, sufficient to penetrate several meters of rock(Avg $\rho \approx 2.6$).

Due to their highly penetrating characteristics, they can be used for radiographic imaging of dense material. Using this freely available particle to detect the high Z material is very useful for homeland security application related to Shielded Nuclear Materials (SNMs). In this paper we will show the result of Geant4 [1] simulations to discriminate and identify homogeneous material using multiple scattering of muons of 3 GeV.

Principle of Muon Tomography :

The muon passing through the material is deflected by many small angles, scatters off the nuclei of the material [2]. The traversal is totally stochastic and it emerges at an average scattered angle of Θ, and displaced from unscattered exit point by distance x. The angular scattering distribution is approximately Gaussian (with long tails), but the central 98% is well described by gaussian with zero mean and standard deviation is given by

$$\sigma_\Theta = \frac{13.6MeV}{\beta cp}\sqrt{\frac{L}{X_0}}\left[1 + 0.038 ln\left(\frac{L}{X_0}\right)\right] \quad (1)$$

Simulation Setup

Our simulation setup consist of 4 Resistive Plate Chambers (RPC)[3] placed in Z direction. Each RPC is of 1m x 1m surface area and having two readout planes, one in X direction and other in Y. Each of these are having 32 readout strips. In simulation we have considered these RPCs to be 100% efficient. The top two RPC gives us incoming muon direction and bottom two will give direction of outgoing muon. The object under test is kept in between.

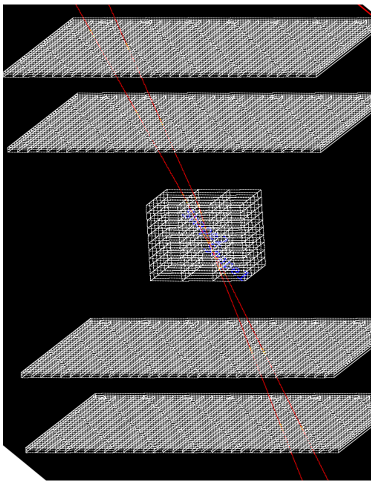

Fig 1: Simulation Setup

Earlier we have also shown how the width of distribution varies with atomic number (Z) of material under test [3]. The higher is the Z the more is the width of scattering angle distribution.

Material discrimination and identification

Materials can be discriminated by calculating the standard deviation of the measurement of scattering of N muons passing through the object. This can tell that one material is having more Z relative to other, but one cannot tell anything specific about the material, because it may happen that two material of different thicknesses may give same scattering angle distribution. In order to detect the correct material one has to estimate some material property. For our study we have chosen the Radiation Length which can be used to detect the material with more confidence level. Formula 1 show the relation between scattering and Radiation length. In our simulation we have worked with three materials Al, Fe and Pb. As per the literature the radiation lengths of these material are as follows : Al : 8.897 cms, Fe : 1.757 cms, Pb : 0.5612 cms.

To make our calculation easier we have used the following form of above formula

$$\sigma_{\Theta} = \frac{13.6 MeV}{\beta cp}\sqrt{\frac{L}{X_0}} \qquad \textbf{(2)}$$

Using above formula one can calculate the standard deviation of scattering for materials of different thicknesses as shown in table below.

Length (cms)	Al (X_0 **8.897** cms)	Fe (X_0 **1.797** cms)	Pb (X_0 **0.5612** cms)
10	5.30088	11.9285	**21.1063**
15	6.49223	14.6093	25.8498
20	7.49658	16.8694	29.8488
25	8.38143	18.8605	33.3719
30	9.1814	20.6607	36.5571
34	9.77435	**21.995**	38.918

From the above table one can clearly see that 34cm of Fe gives almost same scattering as 10cm of Pb. This clearly indicates that by just measuring scattering one cannot certainly determine the content of object under test.

In our simulation we have tried to calculate the radiation length of these three materials by measuring the standard deviation of scattering angle from simulated data.

Fig 2. shows the histogram of scattering angle for above mentioned different materials of 10 cms thickness and its clearly visible that how width of distribution changes with material. In order to identify material we tried to calculate its radiation length. The simulated test case chosen here, consist of 34 cms of Fe and 10 cms of Pb both of which gave almost same scattering, as mentioned in table above. The simulation is done for 200 K events, and data is store in ROOT [4] Tree format which is identical to the format in which data is stored by our data acquisition system.

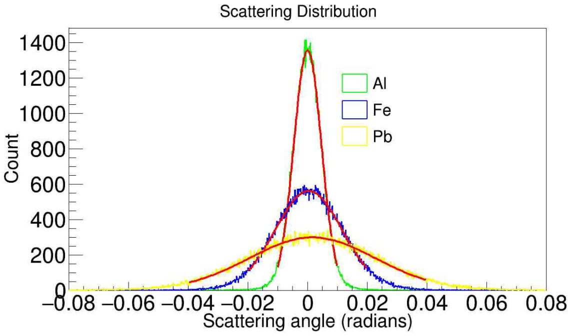

Fig 2: Scattering angle histogram

Here we have considered only one material of known thickness at a time. The scattering that we get from 34 cms of Fe is around 22.36 mrad, and that from 10 cms of Pb is around 21.217 mrad. Using formula 2 we have calculated the radiation length X_0 , and the corresponding values for Fe comes out to be 1.7001 cms and for Pb it is 0.5553 cms, which matches closely with the theoretical values specified in table above. Once we have the data from experimental setup, we will apply the same algorithm to it and will compare that how closely it matches from the simulation results.

Outlook:

Muon tomography is very promising tech. for the detection of high Z materials. Work is in progress to validate experimental data with simulation results. Four 1m x1m glass RPCs have been configured to collect cosmic data in the hodoscope [5]. Work is also going on to develop good visualization software using OpenGL with ROOT. We will also try to implement a more robust reconstruction algorithm called MLEM, which may be very much useful to identify the composition of composite scatterer.

References :

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