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Detector design for Muon Tomography: An instrumentation technique for Nuclear Waste Materials

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Introduction

Under Nuclear instrumentation techniques and applications, Muon Tomography is a method useful for nuclear waste identification which is studied using GEANT4 software. Imaging of nuclear materials by cosmic ray muons based on the absorption and multiple Coulomb scattering is investigated. The nuclear waste barrels containing a certain amount of bulky radioactive waste have been analyzed[1] regarding the scattering angle and the absorption rate by using GEANT4 simulations for application in muon scattering tomography. The PoCA algorithm is applied to identify the 3-dimensional structure of the inner materials in dry cask storage using multiple Coulomb scattering interactions of muons within the material[2]. The parameters such as energy loss, radiation length, and scattering angle are investigated for five materials Concrete, Iron, Lead, and Uranium match with C Jewett data and are further extrapolated to higher energies [3].

Methodology

The geometry of the current hodoscope setup consists of the three top and three bottom plastic scintillators made of polystyrene with a thickness of 0.5 cm filling material is ordinary concrete that contains the nuclear material of 20 cm cubic box. The scattering angle of a muon means the three-dimensional positive angular difference between the direction of the entering muon through the nuclear material and the direction of the same exciting muon from the same material and this angular angular deviation is caused by the interactions that stochastic-ally occur between the propagating muons and the nuclear material [1]. An image inversion algorithm, PoCA, uses data from the multiple Coulomb scattering of muons through nuclear material. It approximates the closest point obtained by the least-square fitting of the interaction in the detector and calculates the scattering angle between the two fitted tracks. The shortest line between the tracks is calculated by finding the closest pair of points between the two lines. The mid-point of the line is considered the muon's scattering point [2].

Fig 1. shows the simulated geometry of the tomographic setup as well as the nuclear waste drum in GEANT4. The dimension of the simulation box is a rectangular box with lengths along X, Y, and Z axes are 170 cm, 100 cm, and 100 cm where Cartesian coordinates situated symmetrically in the interval of (-85 cm, 85 cm), (-50 cm, 50 cm), and (-50 cm, 50 cm), respectively. Using a narrow planar multi-energetic mono-directional beam the is generated at (85 cm, [0.5, 0.5] cm, [0.5, 0.5] cm) via G4ParticleGun and the generated muons are propagated in the vertically downward direction as shown in red color in Fig 1, i.e. from the top edge of the simulation box through the bottom edge. The momentum direction of the muon is (0, -1, 0) and number of particles is 10^5. A uniform energy distribution lying on the interval between 0 and 8 GeV with the energy cut-off of 0.1 GeV, which is selected to minimize the probability of the muon absorption in the top detector layers as well as to

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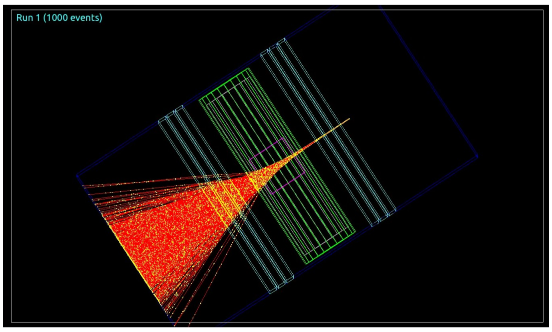

FIG. 1: Scattering of muons when they passes through the hodoscope setup.

maximize the encounter between the incoming muons and the nuclear material box.
All the materials in the simulation geometry are defined in agreement with the GEANT4 NIST material database. FTFP BERT is the reference physics list used for the current study. FTFP BERT physics list contains FRITIOF string model (> 4 GeV), and P for the G4Precompound model, BERT Bertini Cascade model (< 5 GeV) used for deexcitation. Four Geant4 physics processes are created for the simulation of muon interactions:

- G4Mu-Ionization
- G4MuBremsstrahlung
- G4MuPairProduction
- G4MuNuclearInterraction

The muon tracking is maintained by G4Step and the registered hit locations will be post-processed by the aid of a Python script where the scattering angle is first calculated for every single non-absorbed or non-decayed muon, then the uniform energy spectrum bounded by 0.1 and 8 GeV will be partitioned into 16 bins by marching with a step of 0.5 GeV, and each obtained energy bin is labeled with the central point in the energy sub-interval. The computation of the scattering angle requires the construction of two independent vectors by utilizing exactly four muon hit locations in the detector layers where the first vector is the difference between the scintillators' locations in the second top detector layer and the third top detector layer, while the subtraction of the hit position in the first bottom plastic scintillator from the second bottom plastic scintillator yields the latter vector. $\theta_{WB} \pm \delta\theta$ is the average scattering angle with standard deviation of muons with air inside the waste barrel. $\theta_{WB+U} \pm \delta\theta$ is the average scattering angle with standard deviation of muons with Uranium inside the waste barrel.

Results

TABLE I: .Comparison of average scattering angles of the nuclear waste barrels and their corresponding standard deviations over the energy interval between 0.75 and 2.25 GeV with reference [1]

E[GeV]	$\theta_{WB} \pm \delta\theta$	$\theta_{WB} \pm \delta\theta$[1]	$\theta_{WB+U} \pm \delta\theta$	$\theta_{WB+U} \pm \delta\theta$[1]
0.75	43.36±31.87	78.99±47.12	159.17±128.73	289.98±161.25
1.25	23.89±18.96	43.52±24.56	92.35±75.46	168.245±92.78
1.75	16.86±13.35	30.72±17.37	59.39±49.86	108.19±58.34
2.25	22.96±10.65	23.60±12.96	44.47±37.87	81.01±43.14
2.75	10.67±8.87	19.446±10.58	35.01±29.79	63.78±34.00

Analysis of data for muons' average scattering angle and standard deviations is tentative. Calculation of average scattering angles is in processing by using Python script in which hit locations of muons will be post-processed.

Acknowledgments

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