# COSMIC-RAY MUON TOMOGRAPHY AND ITS APPLICATION TO THE DETECTION OF HIGH-Z MATERIALS

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## ABSTRACT

Each minute, about 10000 muons rain down on every square meter of Earth. These charged elementary particles are produced by cosmic rays striking the upper atmosphere. Millions of highly penetrative muons pass through our bodies, cars and houses daily. Penetrating the objects, muons interact with atoms of different materials, mainly electromagnetically. They are more strongly deflected, or scattered, by high-Z materials, including nuclear materials, like uranium and plutonium, and gamma-ray shielding materials, like lead, tungsten or gold. This allowed us to develop a technique which uses multiple scattering of cosmic-ray muons to detect shielded packages of nuclear materials in a background of normal cargo. The advantages of this technique are that it is passive, does not deliver any radiation dose above background, selective to high-z dense materials, and is suitable for large amount of shielding. Physical basis of the technique, current status of our research and its possible perspectives will be discussed.

## INTRODUCTION

The detonation of a nuclear device in a major city is widely recognized as the most frightening threat posed by the modern international terrorism. Reduction of this threat requires enhanced detection capability of nuclear materials at transportation checkpoints, in particular, border crossings. US customs has begun using a set of radiation detectors and x-ray scanners for this purpose. Unfortunately, it has been demonstrated that existing methods are not always effective in detecting compact, well-shielded packages of strategic nuclear materials (SNM). Both SNM and most effective gamma-ray shielding materials have high densities and atomic numbers (Z). A new technique capable of passively detecting such high-Z materials have been recently developed at Los Alamos [1, 2]. The technique is based on the detection of the increased scattering of cosmic-ray muons by the high-Z objects.

## COSMIC RAYS

Primary cosmic rays are energetic particles and nuclei, mostly protons, incident at the top of the terrestrial atmosphere. Cosmic rays interact with atmosphere producing showers of secondary particles. By the time the shower of “atmospheric” cosmic rays reaches the Earth’s surface, it is comprised mostly of neutrinos and muons. Muons are the most numerous charged particles at sea level. The mean energy of the muons at the ground is about 4 GeV. The integral intensity of vertical muons above 1 GeV/c at sea level is ≈70 muons/m$^2$/sr/s or ≈1 muon/cm$^2$/min for horizontal detectors [3]. Fig.1 shows an approximation of cosmic-ray muon spectrum which we used in our simulations.

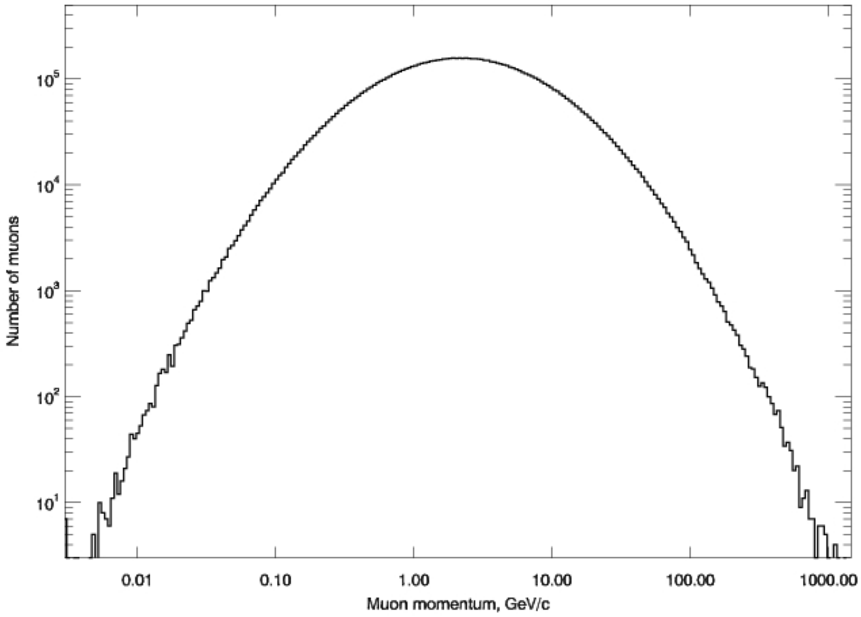


Figure 1. Approximation of cosmic-ray muon spectrum we used in our GEANT4 simulations (integral for all directions). 10 million muons were simulated.

**INTERACTION OF MUONS IN MATTER**

Penetrating the matter, cosmic-ray muons change their directions due to the multiple scattering, lose their energy and finally get stopped. A muon traversing a medium is deflected by the electromagnetic field of many nearby nuclei, this effect is called multiple Coulomb scattering. The Coulomb scattering distribution is roughly Gaussian for small angles, but it has larger tails. The width of the distribution is approximated as

$\theta_0 = \frac{13.6MeV}{\beta cp}\sqrt{\frac{L}{L_0}}\left[1 + 0.038\ln(L/L_0)\right]$, where $L$ is a path length, $L_0$ is the radiation length, $p$ is the particle momentum in MeV/c and $\beta c$ is its velocity [4]. Radiation length is a characteristic amount of matter for scattering and other nuclear interactions and decreases with increasing material Z number, hence mean scattering increases. The net angular deflection of the trajectory is very sensitive to the atomic number Z. This sensitivity, coupled with the long range of muons, makes muon scattering of particular interest as an information source for the detection of high-Z material in low-Z surroundings.

Moderately relativistic muons lose energy in matter primarily by ionization and atomic excitation. Energy loss function has a broad minimum at the momenta ≈300-400 MeV/c. Below 100 MeV/c energy loses increase sharply, while they rise slowly between minimum ionization and 100 GeV/c. Above 100 GeV/c radiative losses become significant and total energy losses increase dramatically. If the thickness of material is large enough, muon is stopped in the material, where it is either decays or forms a muonic atom. Experimentally the easiest technique to study objects with cosmic-ray muons is by the stopping power of the object. Knowing incident flux of muons and measuring flux of muons passed through the object one can measure density length, i.e. density times geometrical length, of material. Range of high-energy muons in rock is measured in hundreds of meters or even kilometers, so this method is used to study large structures as pyramids and volcanoes [5, 6]. Information obtained from absorption is relatively poor, so the method requires long exposure times to study anomalies of 1-10% of the object size.

By tracking scattering angles of individual incoming and outgoing muons we develop a new type of tomography suitable for meter-scale objects placed in between two sets of position-sensitive detectors. Measuring the scattering is more challenging, but provides us with more information about the object in shorter time. One can get even more information by measuring energy losses for individual muons, however, an apparatus for such measurement would be rather complex and expensive. Muonic x-rays can be used for nondestructive elemental analysis, however, it seems there are too few muonic atoms formed with stopped cosmic-ray muons for practical applications without use of artificial muon source.

## PROTOTYPE COSMIC-RAY MUON SCATTERING EXPERIMENT

To prove the concept of scattering muon tomography, we developed a small-scale experimental detector system. The detector stack consists of four ionizing radiation tracking chambers that measure a total of eight X and eight Y locations for each muon. The active area of each delay line drift chamber detector [7] was 60 x 60 cm$^2$. The top two detectors measured the incident muon track, while the bottom two measured the track after scattering. The multiple measurements were used to resolve a directional ambiguity in drift time correction in the detectors. By calibrating of the instrument with no scattering material in the object area, we determined that our position precision was about 400 μm (FWHM). Data was taken using a Windows® based data acquisition program developed at Los Alamos [8]. A pair of 30 cm square plastic scintillators placed below the lowest detector were used for triggering. Fig.2 shows a reconstruction of test object (lead letters) using data from the apparatus.

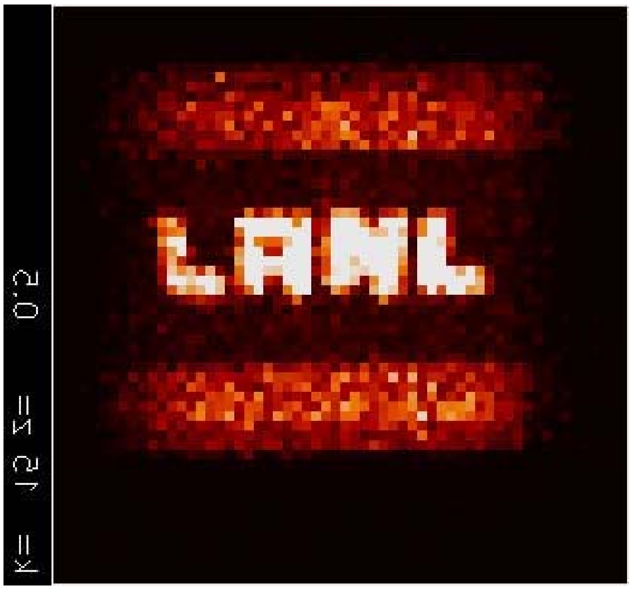

Figure 2. Reconstruction of 1-inch thick lead letters after their exposure in prototype apparatus. Two strips above and below letters are iron bars used as a support for plastic object plate.

## SCATTERRING SIGNAL STRENGTH

For practical application of scattering muon tomography to nuclear surveillance it is important to understand what is the sensitivity of the method in detecting of high-Z objects hidden in regular cargo or vehicles. To answer this question we are developing a large experimental prototype in parallel with extensive simulations of different scenes and development of image reconstruction and object detection methods. Some results of these studies have been presented elsewhere [9-11]. Here we would like to discuss a simple illustrative case.

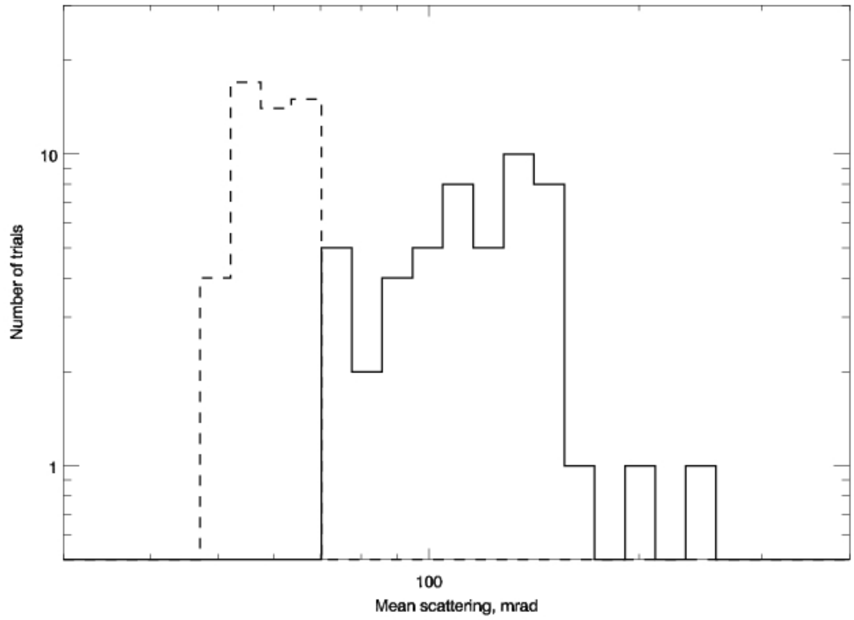


Figure 3. Distributions of mean scattering angle from shielded HEU (solid line) and car engine (dashed line) in 15 sec simulated exposure. Even in a short exposure these distributions can be separated. Test objects are described in more detail in the text. GEANT4 simulations.

Let us consider the shipment of highly enriched uranium in a passenger car. The object is 20 kg uranium sphere (0.8 of IAEA "significant quantity") surrounded by an inch-thick lead shield. Most evident sources of false positives are the engine block and car battery. We approximate engine block as a 300-kg aluminum sphere with a diameter of two feet. Real engine block will likely to weight less and to be less dense. Fig.3 shows distribution of the signals from these objects in a hundred of GEANT4[1] simulations of 15 seconds of exposure. The distributions can be separated with adequate choice of the threshold. With additional effort we can do better than that. Scattering depends on both parameters of the material and momentum of the muon. If we can estimate momenta of individual muons, even roughly, we can achieve more reliable separation of the signal from noise. 3-D reconstruction of the scene allows us to determine each object's size and consequently normalize the signal on the muon path lengths proportional to the object size. Location of the signal provides us with useful information as well. One can expect to get higher scattering levels from engine block, but the same scattering from passenger salon is a subject for concern (and if one will try to hide high-Z object inside the engine block, the signal will increase in comparison to the "naked" object). Of course, exposure time is the most valuable resource for our technique, and radiation lengths of the objects can be measured with increasingly higher precision for an increased exposure.

Our simulations show that there is enough signal to detect the shipment of SNM or other high-Z material in a short time. The challenges are to build the apparatus able to collect this signal efficiently and to develop reconstruction methods able to distinguish this signal from the surrounding clutter.

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[1] GEANT4 is a toolkit for the simulation of the passage of particles through matter, widely used in high energy physics, nuclear experiments and other areas (http://wwwasd.web.cern.ch/wwwasd/geant4/geant4.html)

## EXPERIMENTAL ISSUES

We are currently developing a large muon tracker composed of multiple drift tube modules. This apparatus can be used to address several technical issues for practical application of muon tomography.

Track by track momentum estimation has been shown in simulations to be instrumental to achieve object detection in short counting times [12]. If we don't measure muon momenta at all we may assume them all being of the same average energy. Muons with energy above the average will scatter less than expected and hence will reduce the signal from high-Z objects. Muons with energy below the average will scatter more and consequently will increase the false positives rate. We are primarily concerned with measuring momenta for softer muons, with hard muons being of second priority. Momentum measurement for charged particles like muons is a routine procedure in high energy physics experiments, and multiple methods for this have been developed [13]. For practical applications of muon tomography we need to consider the most economical methods, even if they do not provide the same precision as more sophisticated expensive detectors. One method of momentum measurement is ranging out muons with additional slabs of material below the main apparatus. Large range of high-energy muons creates practical problems for this method though it can be used more easily for softer muons. Alternatively, one can use multiple scattering from known object to measure the momentum. Additional slabs of material and detector planes can be introduces either below main apparatus or between basic detector planes. We consider relative advantages and disadvantages of these solutions. Another idea is to use scattering in the material of drift tubes as the source of information about the momentum. Softer muons deflect more significantly from the straight line, and approximation of their tracks with the straight line has higher chi-square values. Fig.4 illustrates this effect.

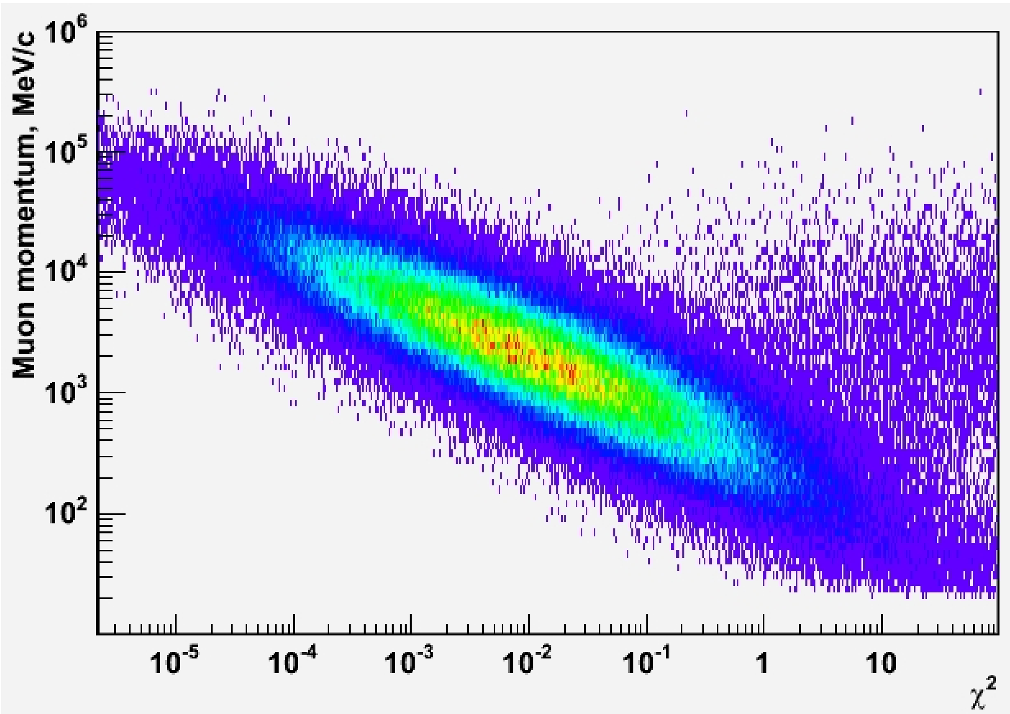


Figure 4. Chi-square of the track linear fit versus energy of the incident muon. GEANT4 simulations of a drift tube detector with perfect positional resolution. In real detector small values of chi-square are expected to increase because of the errors of the track position knowledge.

In our first wire chamber prototype we use scintillators to generate the trigger and measure initial time of muon passage. In our next experiments we would like to get rid of this scintillator and use drift tube signals instead. Measuring the total pulse duration for each tube we should be able to calculate the time of muon passage. We are currently working on experimental confirmation of this method.

With large muon tracker we will study backgrounds more extensively. Modular technology of our large tracker makes it scalable for even larger sizes required for practical applications.

## IMAGE RECONSTRUCTION, OBJECT DETECTION TECHNIQUES

Scattering muon tomography creates an interesting image reconstruction problem. Conventional tomography uses the absorption of man-made, penetrating radiation to provide image contrast. The direction and spectrum of the radiation can be controlled, and the signal measured is the number of photons or other particles stopped by the object. In contrast, cosmic-ray muon tomography relies on the production of muons by cosmic rays, without any human intervention. The directions of incoming muons have a wide distribution around vertical. The average spectrum of muons is known, but the momentum of any particular particle is difficult to measure. Cosmic ray muons are deflected in matter in the process of multiple Coulomb scattering, with quasi-Gaussian distribution. The center of the distribution is the same (corresponding to zero deflection) for all materials, and its width depends on both parameters of the object and muon energy.

Tomography usually refers to the reconstruction of an object from projections taken from multiple directions. In our case we do not have set directions and projections, but we can use tomographic techniques using our measurements of incoming and outgoing tracks for individual muons. The object is modeled as a set of voxels filled each uniformly by the material of chosen radiation length. The size of the voxel is restricted by the required accuracy of reconstruction, the amount of available data and computational considerations. For meters-sized objects 10x10x10 $cm^3$ voxels seem to be a reasonable compromise. For each muon we find the voxels which it penetrates, calculate total radiation length from the model of an object, and define the probability of the scattering at the measured angle. The likelihood of the whole data ensemble can be calculated and used for the model evaluation. Then we change the model of the object and repeat the procedure until the most likely configuration of the object given the data is found. A tomographic reconstruction algorithm for cosmic ray muon scattering radiography was developed by marrying the algebraic framework with a statistical model of the information source and applying maximum likelihood methods [14]. We were able to perform full three-dimensional reconstruction of simulated passenger car using maximum likelihood method (see Fig.5). Optimization of the method let us to reduce computational time significantly, which is important for real-time applications.

In applications like nuclear contraband detection we often do not need full three-dimensional reconstruction of the image, but rather a simple yes/no detection of a threat object. We have experimented with support vector machines (SVM, [15]) based classifiers for this task [11]. Raw muon radiography data are not suitable for SVM, their pre-processing being of crucial importance. We have success with cubes of 3x3x3 voxels represented by mean scattering angle in a voxel. With appropriate training, a SVM was able to classify properly cubes containing high-Z objects in the central voxel from other cubes. To make classification of larger objects we need to be able to identify the cubes with objects of potential interest in the center. Pre-processing of voxels based on the amount of scattering may provide us with a list of potential candidates for SVM classification.

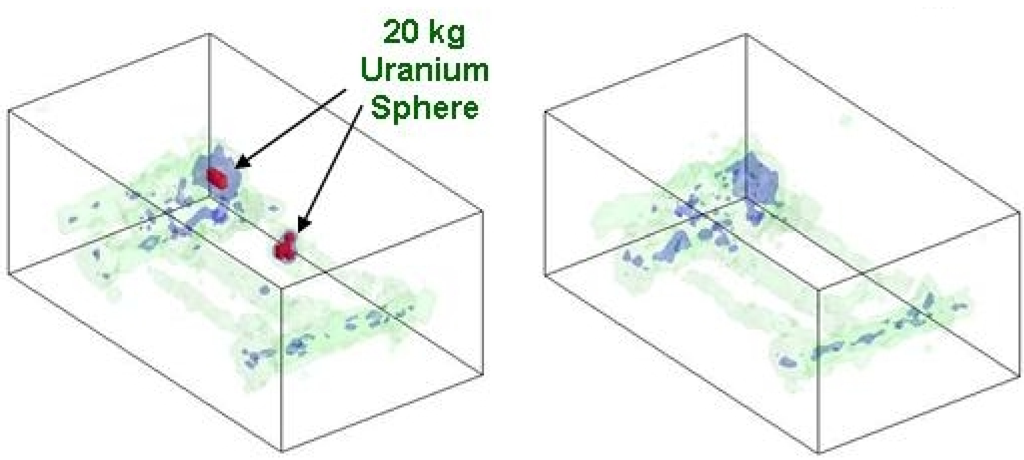


Figure 5. Maximum likelihood reconstrcution of the simulated 1-minute exposure of the passenger car. Left car has two high-Z objects, inside the battery and in the middle of passenger salon. Right car is identical, but has no high-Z objects.

Efficiency of the methods discussed above is affected by voxelization of the object. Voxel-independent localization of the scattering object is important for efficient object detection. We have developed clustering and likelihood algorithms for the selection of likely locations of dense high-Z material [16]. The algorithms use physically motivated distance function to utilize our directional knowledge in the uncertainty of the scattering location (large uncertainty along the track, much smaller uncertainty in perpendicular direction). The likely locations may be used as a pre-processing for SVM-based classification or as a separate method of high-Z object detection based on the compactness of the corresponding cluster.

## SEQUENTIAL INSPECTION

Inspection time is an important parameter for border crossing inspection. The theory of sequential testing gives us a practical method of reducing average inspection time for chosen false negative and false alarm rates [17]. Generally, the idea is that we can deal fast with simple cases and spend more time for more difficult cases. Knowing the distribution of the signal we can set the thresholds for different times. Lower threshold will reject the presence of the high-Z object in the scene, while upper threshold will provide positive detection of the object. If the strength of the signal is between the thresholds the inspection should be continued to assure specified percentage of both false positive and false negative cases.

## COMPARISON AND SYNERGY WITH OTHER TECHNIQUES

Muon tomography as a technique for high-Z materials detection is very different from other known methods of such detection. Cosmic-ray tomography doesn't use any artificial irradiation of the object, so it doesn't cause any safety concerns complicating the application of other methods, like x-ray scanning and active interrogation. The absence of artificial irradiation means also that the object under inspection doesn't need to know, that it is being inspected, and consequently can not react on salvage trigger, another concern for active methods. Muon tomography detects not only SNM, but also its gamma-ray shielding and can be used most effectively together with high-resolution radiation detectors. Detection of small amount of high-Z material with muon tomography will require longer exposure times, because natural muon flux can not be increased. However, other existing methods are also not very effective in such detection for various reasons. Having multiple methods of inspection to provide different information about the object is probably the best strategy in stopping illicit traffic of nuclear materials. The data provided by muon tomography gives unique view of the object and can not be superseded by other existing methods.

## CONCLUSIONS

Penetrating the matter, cosmic-ray muons collect the information about objects they passed through. We recently developed the technique to extract this information from the measurement of scattering angles for individual muons. In particular, this technique is sensitive to small high-Z, high density objects hidden inside low-Z material. Consequently it may be used for cargo and vehicle inspection in search for illicit traffic of strategic nuclear materials. We have demonstrated the principle with small-scale prototype and build now large muon tracker to address several experimental issues. In parallel, we are developing image reconstruction and object detection algorithms, which should allow real-time detection of high-Z objects for practical applications.

## AKNOWLEDGEMENT

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