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Author(s): Larry J Schultz,
Konstantin N. Borozdin
John J. Gomez,
Gary E Hogan,
Chris L Morris,
William C Priedhorsky,
Alexander Saunders,

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Los Alamos
NATIONAL LABORATORY

Cosmic Ray Muon Radiography for Contraband Detection

Larry Joe Schultz*, K. N. Borozdin, J. J. Gomez, G. E. Hogan, J. A. McGill, C. L. Morris, W. C. Priedhorsky, A. Saunders, and M. E. Teasdale†

Los Alamos National Laboratory
Los Alamos, NM 87545 USA,
** and Portland State University, Portland, OR,*
† and the University of Hawaii, Hilo, HI.

Abstract – *The threat of the detonation of a nuclear device in a major US city has prompted research aimed at providing more robust border surveillance for contraband nuclear material. Existing radiographic techniques are inefficient for the detection of shielded material. These techniques also involve radiation hazards, real and perceived. We have invented a new technique which is capable of passively detecting small quantities of shielded SNM in a short time by using the multiple scattering of cosmic ray muons as a radiographic probe[1,2]. A chief advantage of this technique is that no artificial dose is applied to the object being radiographed. We describe the technique and discuss experimental and simulated results.*

I. INTRODUCTION

Of the threats posed by terrorist actions in the US, the most frightening is the detonation of a nuclear device in a major city. The toll of the deaths, destruction, and economic loss caused by such an action would be enormous. Recent events, along with scholarly evaluations of the probability of a terrorist group producing a nuclear weapon suggest the likelihood of such an event is significant. The size of the risk and the enormous consequence of such an event have moved the US in the direction of trying to develop strategies to prevent it.

One of the strategies is to reduce the ease with which nuclear material may be available to terrorists by controlling the material at its source. An additional reduction in risk can be obtained by increasing the likelihood of detection of illegal transport of these materials at transportation checkpoints, such as border crossings. US customs has begun using a set of radiation detectors and x-ray scanners at border crossings for this purpose.

SNM produces gamma, neutron and alpha radioactivity above natural background levels. However, passive counting does not provide robust detection of hidden SNM because all of the signals can be obscured using a relatively small amount of high Z (lead), hydrogenous (polyethylene), and neutron absorbing (lithium or boron) shielding. More sophisticated counting techniques, such as directional gamma and neutron counting, and better energy resolution improve the sensitivity and limit some options for hiding SNM. However, because of practical counting time limits and natural background rates, small well shielded quantities will challenge these systems.

X-ray radiography provides a method of examining cargo and transport vehicles for the presence of hidden material. New scanning x-ray machines in combination with neutron scatter and radiographic and x-ray back scatter might provide an approach for detecting shielded, hidden SNM. However, the potential doses to vehicle occupants and to operators limit this technology to examining only a small fraction cross border traffic.

We have invented a new technique which is capable of passively detecting small quantities of shielded SNM in a short time by using the multiple scattering of cosmic ray muons as a radiographic probe (Refs. 1,2). This technique is selective to high-Z materials, both SNM and gamma-ray shielding materials. This radiography is performed with no artificial dose applied, so inspection of vehicles with operators present is feasible.

II. COSMIC RAY MUONS, MULTIPLE SCATTERING, AND MUON RADIOGRAPHY

The earth is continuously bombarded by energetic stable particles, mostly protons. These protons interact in the upper atmosphere because of the nuclear force, producing showers of particles that include many short lived pions. The pions decay, producing muons. Muons interact with matter primarily through the Coulomb force, and have no nuclear interaction. The Coulomb force removes energy from the muons more slowly than nuclear interactions. Consequently many of the muons arrive at the earth's surface, as penetrating, weakly interacting charged radiation. The muon flux at the earth's surface in an energy and angular range useful for radiography is about 1 muon/cm^2/min.[3] Attenuation of the cosmic ray flux by large geographic features or structures has been used to perform radiography of those structures.[4,5,6] For our technique we rely on a different information source, multiple Coulomb scattering, which allows for radiography of much smaller objects.

When an energetic charged particle such as a muon moves through material, its trajectory results from the convolution of many small deflections due to Coulomb scattering from the charge of the atomic nuclei in the medium. The many small interactions add up to yield an angular deviation that approximately follows a Gaussian distribution[7]:

$$f(\theta_x) = \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp\left(\frac{\theta_x^2}{2\sigma_\theta^2}\right) \qquad (1)$$

The width of the distribution is related to the scattering material:

$$\sigma_\theta = \frac{13.5}{p\beta}\sqrt{\frac{L}{X}} \qquad (2)$$

where p is the particle momentum, β is the velocity divided by the velocity of light, L is the depth of the material, and X is the radiation length of the material. Radiation length decreases with Z, hence mean scattering increases, as illustrated in Fig. 1. The net angular and position deflection of the trajectory are very sensitive to the Z of the atomic nuclei. Charged particles are more strongly affected by SNM and the materials that make good gamma ray shielding (lead and tungsten) than by the materials that make up normal cargo such as water, plastic, aluminum and steel.

The use of multiple scattering of charged particles as an information source for radiography has been demonstrated via proton radiography[8,9], wherein objects are imaged using a proton beam from a linear accelerator. In our new technique we rely on this same information source, but obtain that information from the natural background of cosmic ray muons. Since only a small fraction of muons will be attenuated in radiography of relatively small objects, we get information from nearly every particle. If the particle momentum is known, then the fractional path length, $R = L/X$, can be determined to a precision of

$$\frac{\Delta R}{R} = \sqrt{\frac{1}{N}} \qquad (3)$$

where N is the number of particles transmitted. In other words, for a 10 cm cube of unknown material, we expect

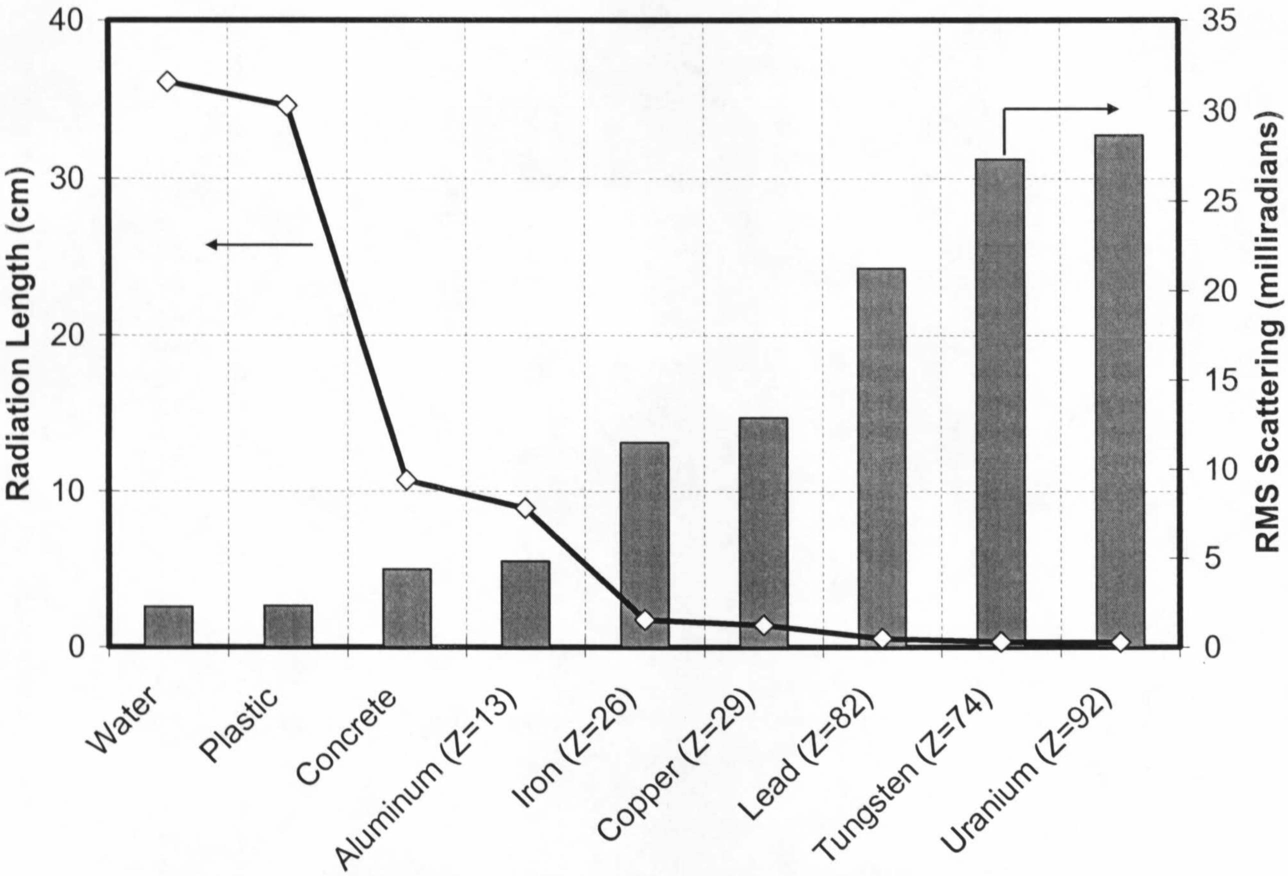

Fig. 1. Radiation length and RMS scattering for various materials, showing dependence on material Z number. Scattering is for 3 Gev muons passing through 10 cm of material.

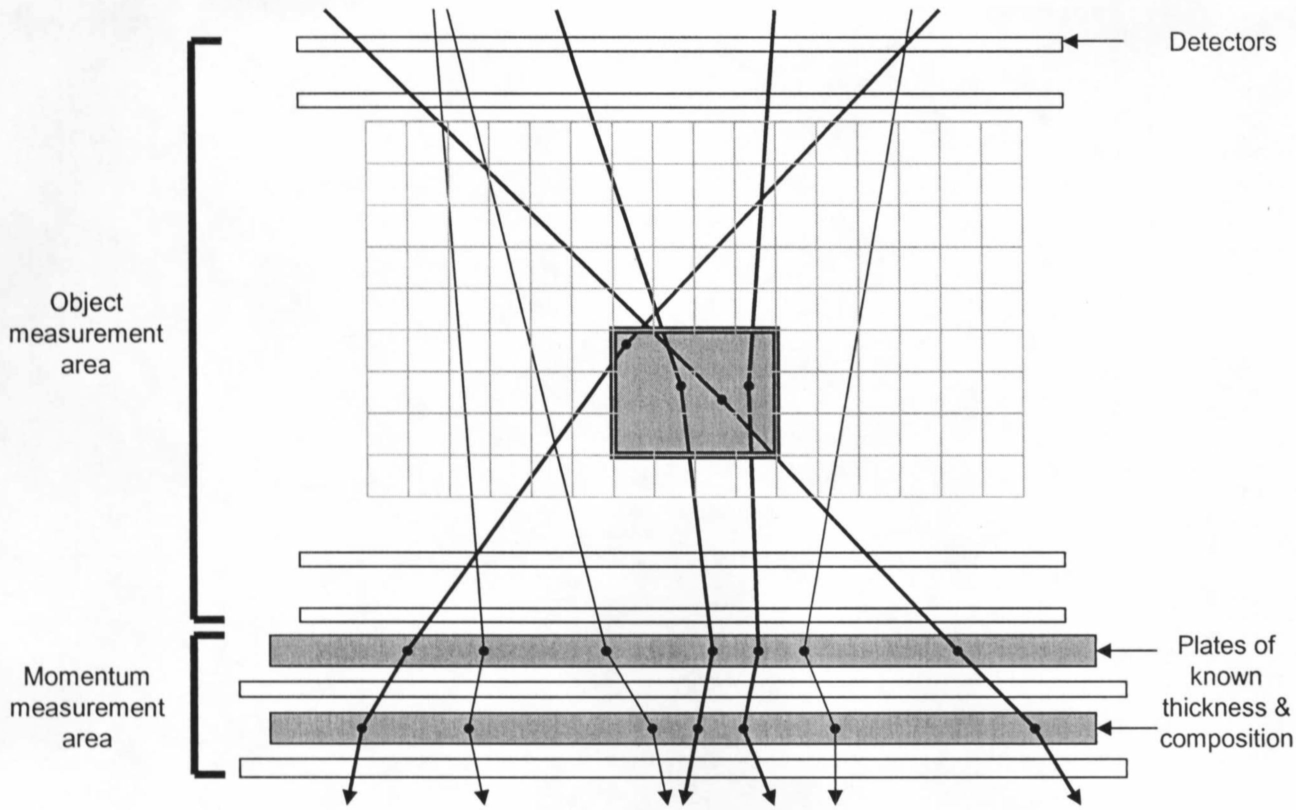

Fig. 2. Cosmic Ray Muon Radiography Concept

about 100 muons per minute, sufficient to measure its thickness in radiation lengths to a precision of 10%, which clearly allows us to distinguish between lead and iron, for instance. We will discuss an inexpensive method for momentum measurement below.

Our concept is shown in Fig. 2. Muons pass through two position sensitive detectors above an object volume, providing incoming angle and position. Particles pass through the object volume and are scattered to an extent dependant upon the material through which they pass. Scattered particle position and angle are measured in a lower set of detectors. Each detector measures particle position in two orthogonal coordinates, so we obtain two scattering measurements from each particle.

Below the object measurement area, we can place a sandwich of detectors and plates of known material and thickness. By measuring particle scattering through these plates we may infer particle momentum. It can be shown that, if we employ two such plates and detectors, we measure momentum with an uncertainty of $\Delta p / p \cong 50\%$.

III. EXPERIMENTAL DEMONSTRATION

A set of position sensitive delay line readout drift chambers[10] was assembled to demonstrate this idea. Two groups of detectors, each measuring particle position in two orthogonal coordinates, were placed above an object region and two groups were placed were below, as shown in Fig. 2. Two plastic scintillators in coincidence with the outermost drift chambers provided a timing trigger required by the delay line detectors. Signals from the detectors were amplified and discriminated in standard NIM electronics, were digitized in FERA ADCs, and read into a computer using a PC based data acquisition system, PCDAQ.[11] The detectors measured position to a precision of about 400 μm full width at half maximum (FWHM), and angles to about 2 mrad FWHM. For this initial prototype no momentum measuring planes were implemented.

The data were processed using a reconstruction technique wherein we approximated the multiple scattered path of a muon as a single scattering event, and located the estimated point of scatter by extrapolating the incident and scattered rays to their point of closest approach. This is similar to a nuclear scattering reconstruction technique previously described[12], but we use multiple scattering rather than single scattering. We first model the object volume in terms of a grid of voxels (3-D pixels). For each muon we identify the voxels through which the ray passed. The information signal for the muon is defined to be the square of the scattering angle in space for that muon. This signal is assigned to voxels along the ray track using a maximum likelihood technique that places most of the signal within the voxel containing the point of closest approach, but dis-

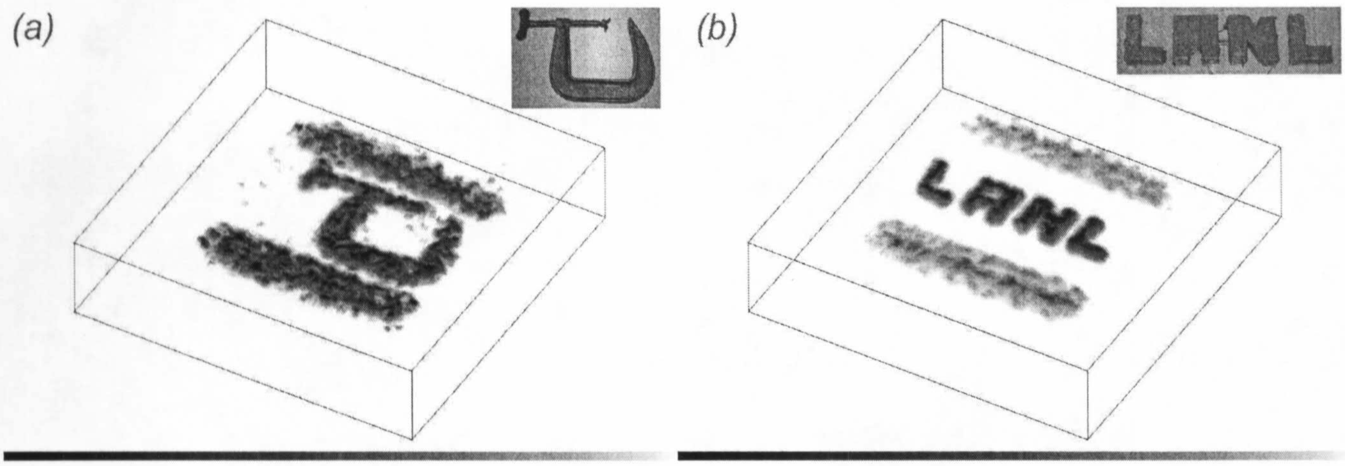

Fig. 3. Experimentally produced cosmic ray muon radiographs of (a) a steel c-clamp, and (b) "LANL" constructed from 1" lead stock. The bar-like features result from steel beams used to support a plastic object platform.

tributes the signal along the ray track according to the uncertainty in determining that point of scattering. We then sum the contributions from all muons to each voxel, and normalize by dividing the by the number of rays passing through each voxel. We will call this approach the point of closest approach (PoCA) reconstruction method

Two test objects and corresponding cosmic ray muon radiographs of those objects are shown in Fig. 3. These radiographs were produced via the experimental prototype and PoCA reconstruction method described above. The bar-like features appearing above and below the test objects in the radiographs are due to thin walled steel beams which were part of the support structure for the objects. The steel c-clamp, shown in Fig. 3a, is of similar thickness to the steel beams, so these two features appear with similar intensity in the image. The lead "LANL" letters, shown in Fig. 3b., produce much more scattering than do the beams, so the beams appear fainter in this normalized image. Each of these reconstructions was made using data from about 100,000 muons. The data were collected over several hours; an optimized detector system with near 100% efficiency and large solid angle could acquire as many muons in ~30 minutes. These long runs were made to clearly illustrate the structure of the objects for demonstration purposes. For simple yes/no detection decision considerably fewer muons, hence shorter exposure times, would clearly be adequate.

IV. MONTE CARLO SIMULATION AND CONTRABAND DETECTION

In order to examine how well this technique works for larger sized, more complex scenarios, we have developed a simulation code that generates cosmic-ray muons with the appropriate distribution of energies and angles, propagates them through a test volume, and generates the positions at which they would be detected in four detector planes. The muon spectrum, angular distribution, and rate were appropriate for sea level. We used experimental results for a tungsten block test object to validate our Monte Carlo simulation, as described in Ref. 1.

Using our Monte Carlo simulation, we examined, in Ref. 2, a 9 x 3 x 4.5 meter cargo container with 3 mm steel walls containing dozens of sheep. Hidden beneath the sheep were 3 $(10\ \text{cm})^3$ high-Z tungsten casks. We showed that, in one minute of simulated cosmic ray radiography, we could detect the casks at 90% confidence with 20σ rejection of false positives.

Here we examine the same cargo container containing two dozen car batteries. Each battery was modeled as a box of 27 x 15 x 21 cm consisting of several vertical lead plates separated by water. The bulk density of each battery was about 2.6 g/cm^3. One of the batteries, however, was constructed entirely of lead (a proxy for a lead cask shielding high-Z contraband). An overhead schematic of the placement of the objects is shown in Fig. 4a. We simulated one minute of radiography. A slice from the radiograph of this scene is shown in Fig. 4b. The lead block is clearly distinguishable from the batteries.

The PoCA reconstruction method relies on the simplifying assumption that scattering occurs at a point. Thus the method works well for relatively localized objects unobstructed by other objects, such as the examples of Fig. 3. However, the point scattering assumption is less well suited to more complex geometries wherein rays pass through multiple objects. It has been shown, for example, that when rays pass through both of two distinct objects, the PoCA method will tend to blend those objects together[13] (of course in such a case transmission radiography works no better without multiple projections at different angles). In spite of this phenomenon, we have been able to detect high-Z material in low-Z surroundings in realistic cargo containers, as described above.

Because cosmic ray muons arrive from angles spanning the upper hemisphere (though preferentially from the vertical), we can make use of the tomographic information so

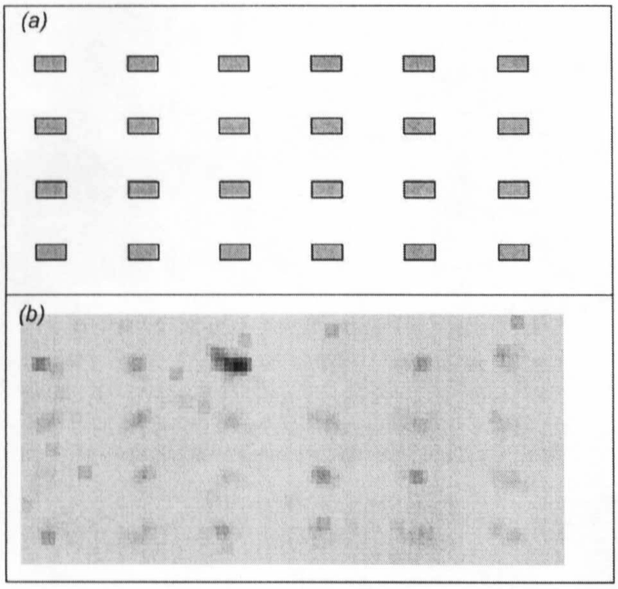

Fig. 4. Detecting a lead brick amongst car batteries. The lead brick (or cask of high-Z material) is in the top row, third column in the sketch (a), and is clearly distinguishable in the one minute radiograph (b).

provided to resolve such ambiguities. We have developed formalism for a full tomographic reconstruction algorithm using multiple scattering, based on maximum likelihood principles. We have done preliminary testing of this algorithm on small scale 2D problems and are currently adapting it for 3D scenarios.

We are also investigating an algorithm specifically designed to detect the presence of high-Z material in an object volume, as opposed to making a reconstructed imaged. For this algorithm we trace highly scattered rays to common crossing points within the object volume, highlighting local areas that produce high scattering. This algorithm shows promise in quickly detecting high-Z material even in extremely complex backgrounds.

V. SUMMARY

A technique for radiography using the multiple scattering of cosmic ray muons has been described and demonstrated. This technique is particularly sensitive to high-Z dense materials. We have confirmed that muon radiography of relatively large objects, on the order of the size of a commercial truck, can be performed in a reasonably short time (~1 minute or less). Our new technique can provide a method for detecting smuggled cargoes of SNM in incoming vehicles and commercial traffic at US borders with no additional radiation dose to vehicle occupants or border guards.

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