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Radiographic Imaging with Cosmic Ray Muons

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The discovery of x-rays by Roentgen[1] made it possible to view the internal structure of objects using the absorption of penetrating radiation. In the subsequent century, radiography has found enormous success. However, limitations of x-ray radiography include: an inability to penetrate very dense objects, an additional radiation dose to the object, and an inability to resolve 3-dimensional structure in a single projection. In this Letter we present a new technique, muon scattering radiography, which is free of the aforementioned limitations, and may supplement x-ray radiography in a number of applications. We demonstrate, using the angular deflection of cosmic ray muons, that high-Z material objects can be radiographed and located in 3 dimensions. Both experiment and simulations provide high contrast images of small high-Z objects in low-Z surroundings. The natural rate of cosmic ray muons[2], approximately 10000 m^{-2} min^{-1}, is sufficient to radiograph large objects with reasonably short exposures (~1 minute), using the large-area muon detectors widely used in high-energy experiments.

Conventional radiography uses the absorption of penetrating radiation to provide the contrast in an image. For X-rays, the areal density of an image pixel is determined by the attenuation of the incident beam caused by absorption and scattering: $N = N_0 \exp^{\left(-L/L_0\right)}$, where L is the path length through an object, and L_0 is the mean free path (or radiation length) for scattering and/or absorption[3]. The precision of radiographic measurements is limited by the Poisson counting statistics of the transmitted flux, $\frac{\Delta L}{L_0} = \frac{1}{\sqrt{N}}$. The maximum mean free path for photons occurs at a few MeV and is approximately 25 gm/cm^2 for all materials. This corresponds to less than 2 cm of lead. Penetrating objects of tens of radiation lengths requires a very large incident dose, harmful for any living organisms which may be present.

An alternative is provided by a new kind of radiography. Charged particles, such as protons or muons, interact with matter by multiple Coulomb scattering. The many small interactions add up to yield an angular deviation that roughly follows a Gaussian distribution: $\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$. The width of the distribution is related to the scattering material through its radiation length L_0: $\theta_0 = \frac{13.6MeV}{\beta cp}\sqrt{\frac{L}{L_0}}\left[1 + 0.038\ln(L/L_0)\right]$, where p is the particle momentum in MeV and βc is it's velocity[4]. In a layer 10 cm thick, a 3 GeV muon will scatter with a mean θ_0 of 2.3 milliradians in water (L_0 = 36 cm), 11 milliradians in iron (L_0 = 1.76 cm), and 20 milliradians in lead (L_0 = 0.56 cm). So by tracking the scattering angles of individual muons the scattering material may be identified. Each particle delivers, via its deflection, information about the path it traversed. This is unlike attenuation radiography, wherein each particle contributes only to a pixel count. If the scattering angle in an object is measured, and the particle momentum is known, then the path length can be determined to a precision of $\frac{\Delta L}{L} = \sqrt{\frac{1}{2N}}$, where N is the number of transmitted particles. The factor of 2 arises due to the two independent measurements of scattering angle that can be made (in X and Y planes). Thus each transmitted particle provides information about the thickness of the object. This approach has been used in proton radiography to probe the structure and dynamics of high-density objects with accelerator-derived protons[5,6]. While this technique requires large, expensive accelerators, the natural background of atmospheric muons is free and available everywhere on the Earth.

Atmospheric muons are produced via interactions of the primary cosmic rays in the air. At sea level, muons are the most numerous charged particles with a rate[2] of about 70 m^{-2}s^{-1}st^{-1}or ~1 cm^{-2} min^{-1} in horizontal detectors. Muons are highly penetrating;

a typical cosmic-ray muon of 3 GeV energy will traverse more than 1000 g cm^{-2} (e.g. 10 meters of water) before ranging out.

Alvarez and colleagues[7] successfully used cosmic-ray muons to radiograph the Pyramid of Chephren in search of hidden chambers. However, they relied on the absorption of muons, rather than their scattering. Because of the large absorption length of high momentum muons, this technique is only suitable for very thick objects. In contrast, our newly developed technique relies on the *scattering* of muons and hence allows the study of small and medium-sized objects such as passenger cars, sea containers, or commercial trucks.

In order to exploit cosmic-ray muons for radiography, we must determine whether we can produce a useful image in a reasonable time. Complicating factors include the clustering of muons in showers, and their distribution in momentum. The natural flux includes low momentum muons which scatter easily, and high momentum muons which scatter less. To prove that these complications could be overcome we developed an experimental prototype.

Our experimental apparatus is shown in Figure 1. We used four delay line readout drift chamber detectors[8] spaced apart at 27 cm. The active area of each detector was 60 x 60 cm^2, and particle position was recorded in two orthogonal coordinates (X and Y). Positions from the upper pair of detectors (D1 and D2) were used to construct the tracks of particles incident on the test object area. The scattered tracks were measured with the bottom pair of detectors (D3 and D4). The incident and scattered tracks were each measured in 8 planes, with 4 measurements in the X direction and 4 in the Y direction. The multiple measurements were useful in resolving an ambiguity in drift time correction in the detectors. Through calibration of the instrument with no scattering material in the object area, a position precision of about 400 μm (FWHM) was determined. A tungsten cylinder (W) of 5.5 cm radius and 5.7 cm height was used as a test object, supported by a lexan plate (L) and steel support beams (B). A pair of 30 cm square plastic scintillators placed below the bottom detector were used for triggering. Given the limited acceptance angle of this configuration the expected trigger rate was about 850 counts min^{-1} andthe observed trigger rate was 750 counts min^{-1}.

The path of a charged particle through the test material is stochastic, and can only be approximately reconstructed. In our experiment and simulation we use a simple technique for this reconstruction. We approximated the track through the object as having only a single scattering event, located by extrapolating the incident and scattered rays to their point of closest approach (Figure 2). The scattering signal from each muon was assigned to voxels along its track using a maximum likelihood technique that distributed the signal along the track according to the error in determing the point of scattering. Each scattering point was weighted by its scattering angle θ; we found that $\theta^{1.5}$ weighting provided the highest contrast in our images.

Figure 3 shows the reconstructed image of the tungsten cylinder. The tungsten is unambiguously detected, and the steel support beams are visible as well, and clearly distinguishable from the tungsten object. To confim these results against theory, and to establish a platform for investigating larger, more complex radiographic scenarios, we developed a simulation code that i) generated cosmic-ray muons with the appropriate distribution of energies and incident angles; ii) propagated them through a test volume, calculating their scattering in each 0.2 cm cubic resolution element; and iii) generated the positions at which they would be detected in four detector planes (two above and two below the test volume). The muon spectrum, angular distribution, and rate were appropriate for sea level[4]. Their scattering and propagation within the targets were calculated according to the multiple scattering law[4] described above. The geometry and densities of experimental test objects were reproduced in simulation, and the same reconstruction technique used for the experimental data was applied to simulated data. The right panel in Figure 3 illustrates simulated results. The reconstructed images look much the same, and scattering of the simulated muons through the different materials (tungsten, lexan and steel) was demonstrated to agree well with the scattering measured in the experiment.

Assured by the consistency of these results, we simulated some more complex objects in a large camera. The overall geometry is the same as for our experimental setup (see Figure 2). The detector pairs, assumed to have our experimental resolution of 400 μm (FWHM), are spaced 1 meter apart (h), and spanned a 4.5 meter high (l) test volume. The resolution of the image would be better if the pairs were more widely spaced (larger h), allowing better localization of the scattering point; however, this might demand too large an instrument in a practical application. Our first target was a big lead sheep-like sculpture (Figure 4a). Reconstruction of the data simulated for one-minute exposure (using 3 cm cubic resolution elements) shows reasonably good recognition of the rather complex shape of the object (Figure 4b). For a more realistic scene, we simulated a steel container that contained high-Z targets ("pigs"), surrounded by dozens of low-Z objects ("sheep'). The input geometry is shown in Figure 4c. The "pig" was detected at high confidence in a 1-minute simulated exposure: the signal in the 3 x 3 x 3 voxel core was, in arbitrary units, 54 ± 24, while the background in an adjacent volume was 1.9 ± 1.1. This means that with 90% confidence, we obtain a signal that is inconsistent with background at 20σ significance or greater. A typical reconstruction of a 1-minute simulation is plotted in figure 4d. In our reconstruction, we ignore muons with momenta greater than 20 GeV/c, because the small "scatter" angles introduced by measurement errors appeared significant in our momentum-weighted algorithm. We also reject all rays with a scatter angle less than 5 mrad to achieve higher contrast between high-scattering and low-scattering material in the image.

The signal-to-noise is a function of our knowledge of the muon momentum. In our analysis, we assumed rough knowledge of the momentum ($\Delta P/P$ of 50% in a log-normal distribution). This knowledge significantly improves the reconstruction. If the momentum is unknown, the same 90% worst case signal is inconsistent with background at a 3.5σ significance. However, if the momentum was known perfectly, the significance would be 29σ; if $\Delta P/P$ is 25%, the significance would be 26σ; and even a rough $\Delta P/P$ of 100% yields a significance of 10σ. Momentum information can be obtained inexpensively by measuring the multiple scattering in several layers of known material. This could be done by a scatter-detector sandwich that continues below the lowest detector plane. The precision in momentum determination would be $\Delta P/P=1/(2S)$, where S is the number of scattering layers (the factor of two arises because X and Y are measured independently). Even with just one layer of scatterer, one obtains $\Delta P/P = 0.5$, which is adequate for a momentum correction such as performed in the reconstructions above (Figure 4b,d).

The results are encouraging and there is a room for further improvement in both detection and reconstruction techniques. For instance, the displacement of the muon track (i.e. the minimum distance between the incident and scattering path) also provides a measure of multiple scattering, because multiply-scattered muons are more likely to undergo a significant displacement, while a single-point scattering necessarily has zero displacement. To achieve maximal contrast in images of different objects one may vary weighting algorithms and apply different angular cuts.

We conclude that muon radiography has a great promise as an inexpensive harmless technique for structural studying of medium-to-large size objects, especially of high-Z materials. Both our experimental results and our simulations demonstrate, for the first time, the feasibility of reconstruction of the three-dimensional shape of complex objects and detection of relatively small amounts of dense material hidden in much larger volume of organic material using the natural source of atmospheric muons generated by cosmic rays. We have confirmed that muon radiography of relatively large objects, on the order of the size of a commercial truck, can be performed in reasonably short time (~1 minute) making the method potentially attractive for a wide range of practical applications. The sensitivity of the method can be further improved by the application of a more elaborate reconstruction technique and utilization of additional information provided by the apparatus.

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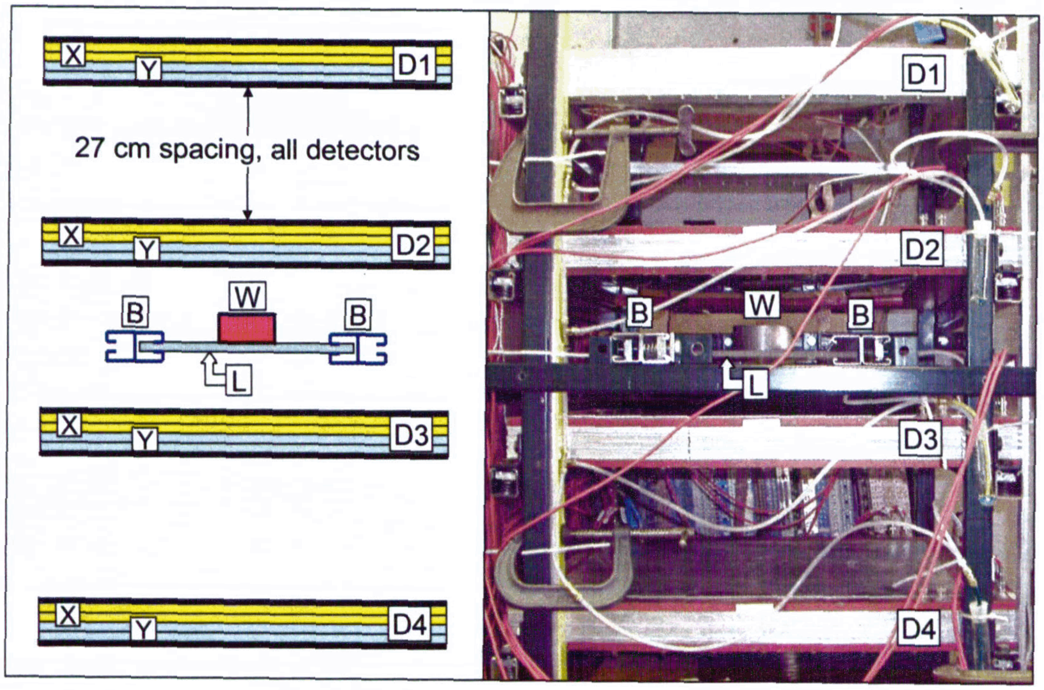

Figure 1. The experimental apparatus. Four muon detectors (D1-D4) with a 27 cm vertical spacing were used to obtain particle positions and angles in two orthogonal coordinates (X and Y). A tungsten cylinder (W, R5.5 x 5.7 cm height) was used for a test object, supported on a 1 cm thick lexan plate (L) and steel support beams (B).

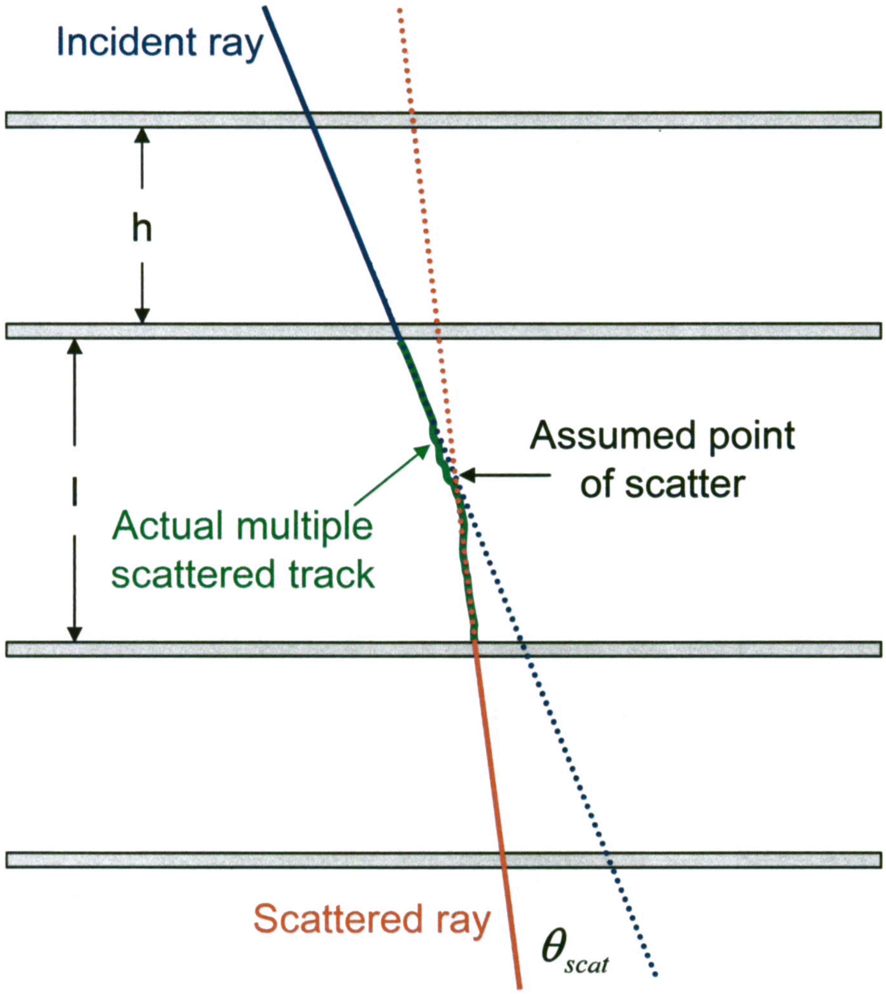

Figure 2. Muon scattering geometry used for reconstruction. The muon trajectory is measured in four planes, two above and two below the test object. The incident and scattered tracks do not need to intersect (in 3 dimensions), the tracks are extrapolated to a point of closest approach, which is designated the scattering point. Because the scattering angles are small, most of the error in locating the point of scattering is along the track. The mean distance of closest approach increases with the depth of the scattering material.

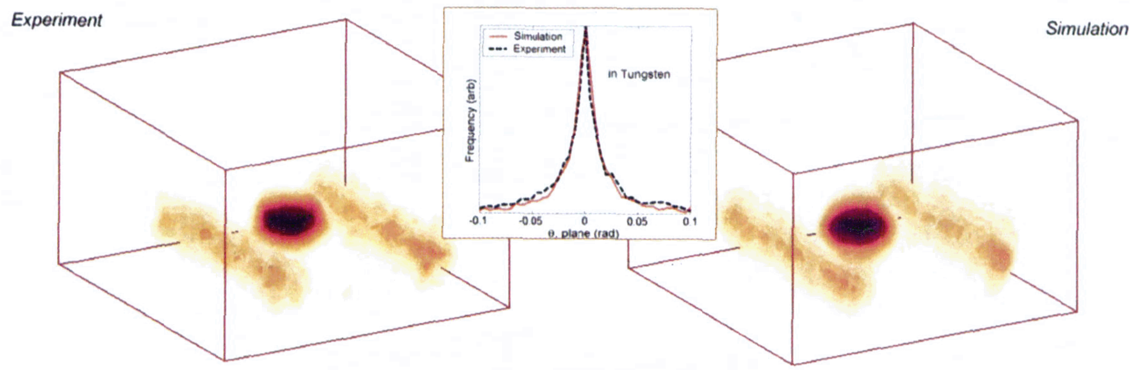

Figure 3. Reconstruction of test object from the data of experimantal run (*left panel*) and simulation run (*right panel*). Test object is the tungsten R5.5 x 5.7 cm^2 cylinder on lexan (35 x 60 x 1 cm^3) plate with two steel rails. Tungsten cylinder and iron rails are clearly visible in both experimental and simulation reconstructions. The width of the scattering distribution for rays passing through the tungsten target (shown in inset) is very similar for experimental and simulated data.

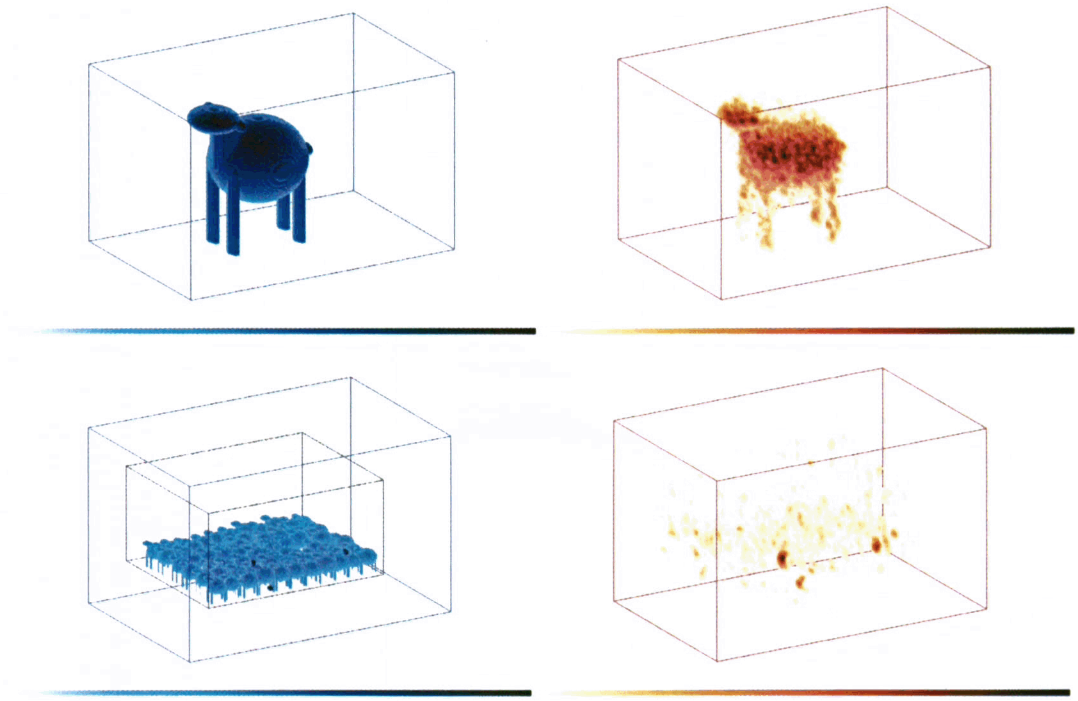

Figure 4. Muon radiograph of a complex targets, based on simulation. The test volume is 9 x 3 x 4.5 meters. The Object 1 (*upper left panel*) is a large lead sculpture of complex shape. Reconstructed image (*upper right panel*) based on one minute of exposure for cosmic-ray muon flux shows a lot of details presented in simulated object. The Object 2 contains a container 6 x 2.4 x 2.4 meters; the container walls were modeled to have a thickness equivalent to 3 mm of steel. Inside the container there are 69 “sheep” (made of water, shown in blue) each of complex form as the Object 1 above with body about 60 x 30 x 40 cm^3, and three uranium bricks 9 x 9 x 12 cm^3(shown in light blue). The simulation represents 1 minute of cosmic ray irradiation. The three “pigs” are clearly stand apart in the reconstructed image (lower right panel; the intensity of color in the two right panels corresponds to the significance of the signal, see the text for more details).