Identifying Nuclear Materials Using Tagged Muons

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Abstract

Experimental results from a new technique that uses neutrons generated by stopped cosmic-ray muons to identify nuclear materials are described. The neutrons are used to tag muon-induced fission events in actinides and laminography is used to form images of the stopping material. This technique allows the imaging of uranium objects tagged using muon tracking detectors located above or to the side of the objects. The specificity of the technique to significant quantities of nuclear material along with its insensitivity to spatial details may provide a new method for the task of warhead verification for future arms reduction treaties.

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1. Introduction

Cosmic-ray muons have been the topic of a considerable recent body of work\textsuperscript{[1]} because of the potential application to a wide range of difficult radiographic problems\textsuperscript{[2–11]}. Cosmic-ray radiography makes use of the scattering angles to measure the area density along a muon path. An ensemble of trajectories is used to generate a tomography of an object between the tracking detectors. Because every transmitted muon provides information, multiple scattering radiography has enabled nuclear threat detection in complex cargo scenes in \(\sim\)minute time scales using the natural
flux of cosmic-ray muons \cite{12}. Since this technique adds no artificial radiation dose, it is ideal for border protection where humans are potentially subject to large exposures from x-ray techniques.

Here we explore a new technique that uses cosmic-rays for a different application, namely warhead verification. The Strategic Arms Reduction Treaty and its follow-on agreements between the United States and the Union of Soviet Socialist Republics has led to the removal of about 80% of the existing strategic nuclear warheads. Implementation of the START Treaty has relied on verification methods that can verify the presence or absence of nuclear warheads without revealing information either country considers sensitive.

It is well established that cosmic-ray muons which stop in fissile material can induce a detectable amount of neutron emission \cite{13,14,16}. We show that cosmic-ray induced neutrons from a uranium target can be used to tag muons and, combined with the muons themselves, to produce images of the target. The result is an inexpensive method for verifying quantities of fissile material, which can potentially be applied as a warhead verification technology.

2. Methodology

Here we describe research into this new method that uses neutrons to tag cosmic-ray muons that interact in fissile material. Neutrons generated by stopped $\mu^-$ are used to tag cosmic-ray tracks that were captured in low-enriched uranium. The tracking information from these events is used to image the source volume.

Radiography can take advantage of both the intensity and the direction of the cosmic-rays \cite{17}. Tracking detectors above and below the object allows muons which stop in the material to be identified and used for image reconstruction. We have used the apparatus shown in Fig. 1 to measure stopped cosmic-rays in an object placed between the two detector planes. The trajectory information can be used to generate a focused transmission image at any distance from the detector.

A trajectory is defined by its coordinates of intersection with a plane and its direction cosines. Trajectories will put an object into focus if they are projected to the plane where the object is located.

The stopping length $\lambda$ of cosmic-rays in material is inversely proportional to the stopping rate and can be related to the energy spectrum, $dN(E)/dE$, as
Figure 1: (color online) Photograph of the Mini Muon Tracker (MMT). The MMT consists of an upper and a lower tracker. Each tracker has 12 planes of drift tube detectors, the detector orientations were crossed between planes to provide tracking in both horizontal directions. Objects for study were placed in the approximate two-foot (60 cm) gap between the two detector supermodules.

\[
\frac{1}{\lambda} = \frac{1}{N} \frac{dN}{dE} \frac{dE}{dx}
\]  

A plot of the energy spectrum for overhead muons at sea level is shown in Fig. 2. The energy loss can be calculated using the Bethe-Bloch formula \[18–20\]. Over a wide range of momentum, the energy loss for cosmic-ray muons in material varies only logarithmically with momentum and is approximately proportional to the electron density, \(Z/A\), where \(Z\) is the material’s atomic number and \(A\) is the mass number. For dense materials, \(\lambda\) is short compared to the muon decay length \(l = \beta c \gamma \tau\), where \(\beta\) and \(\gamma\) are the usual relativistic kinematic quantities, \(c\) is the velocity of light, and \(\tau=2.2\ \mu s\) is the muon lifetime. The muon energy loss can be understood as the shifting of the spectrum shown in Fig. 2 to the left, with the loss of muons with energies below zero (stopped).

A positive muon (\(\mu^+\)) at rest decays into a positron and two neutrinos, \(\mu^+ \rightarrow e^+ + \nu + \bar{\nu} e\). However, when a negative muon encounters the nuclear Coulomb field, it may be captured into an atomic orbital and rapidly de-excite into the ground state, emitting a set of high-energy muonic x-rays. In light nuclei, negative muons can also decay as a free particle, but when they
are stopped in a material with high atomic number \( Z \), they can be captured by a bound proton and produce a neutron and a neutrino, \( \mu^- \otimes A \rightarrow n + (A - 1)^+ + \nu^\mu \). The excited nucleus \((A - 1)^+\) decays, possibly by emitting a neutron. In fissile nuclei the final nucleus can fission, emitting several neutrons.

The stopping rate is given by the density divided by the stopping length, and scattering is proportional to the square root of the density divided by the radiation length. Both the transmitted flux and the stopped flux can provide radiographic signatures.

3. Experiment

Data were taken with the Los Alamos Mini Muon Tracker (MMT) [22] imaging a 19 kg (1000 cm\(^3\)) low enriched uranium (LEU) cube (19.7% U-235). The LEU cube was mounted on a wooden platform on top of the MMT lower “supermodule,” which consists of six planes of aluminum drift tubes. The cube was imaged using muon scattering, muon transmission, and muon absorption techniques, as well as using neutron tagging in coincidence.
with muon scattering or absorption (see Fig. 3 for an illustration of these techniques).

![Figure 3: (color online) (Top) Illustration of four types of radiography possible with muons. The tagged data are a sum of tagged stopped and transmitted events. (Bottom) Examples of images obtained using the techniques shown above.](image)

Muon-induced fission events in the LEU cube produced neutrons that were detected in two 12.5 cm diameter by 5 cm deep EJ-301 liquid scintillator detectors. The neutron detectors were mounted side by side 17.5 cm from the center of the LEU cube as shown in Fig. 4. The liquid scintillator signal has two light decay time constants that can be used to discriminate signals due to gammas (fast) and neutrons (slow). The times of neutron signals from the detectors were recorded in the data stream along with the drift tube data.

Measurements were performed for 48 hours with a measured fluence of $3.33 \times 10^5$ cosmic-rays interacting with the LEU. From this measured fluence, $1.04 \times 10^4$ particles stopped in the LEU, and the rest of the flux was scattered to the lower detector. Los Alamos sits at 2100 m elevation where the integrated muon flux is a factor of $\sim 1.5$ higher than at sea level. The larger muon flux at altitude is consistent with our measurements.

4. Results

The spectrum of times between measured cosmic-ray tracks and neutron detection for both stopped and through tracks is shown in Fig. 5. The
Figure 4: (color online) Experimental configuration of EJ-301 liquid scintillator detectors and the LEU cube target. The active region of the detectors is located 17.5 cm from the center of the LEU cube target. Both the detectors and uranium cube sit on a wooden platform located between the MMT supermodules.
signal-to-noise ratio is more than 100:1 averaged over the entire field of view of the tracker (\(\sim 1.2 \text{ m} \times 1.2 \text{ m}\)). Approximately half of the detected neutrons, which are in coincidence with stopped tracks, appear to be emitted with a time constant of 85\(\pm 3.3\) ns, which is within 12\% of the muonic lifetime measured in low-enriched uranium \cite{23}, as determined using a linear combination of lifetime values for 19.7\% \(^{235}\text{U}\) and 80.3\% \(^{238}\text{U}\). Systematic effects that impact this observation may be due to time uncertainties in the track fitting process and the presence of other species, e.g. electrons, in the cosmic-ray particle spectrum.

![Figure 5: (color online) Spectrum of coincidence time between neutrons and muons. The time signal for the muons is provided by the track fitting routine. The plot shows the difference in the detected neutron time and the muon time for stopped and through trajectories. A log likelihood fit was used to fit the data. The exponential time constant of this fit was 85\(\pm 3.3\) ns.](image)

There is also a neutron signal produced by through tracks (detected in both the top and bottom detector supermodules). The number of through track neutrons is about half of the amount from stopped tracks. Bremsstrahlung induced photo-fission may also induce neutron emission, however; more work is needed to fully understand this effect. This process may produce a fraction of the signal in the prompt neutron component of the coincidence
measurement for both stopped and through tracks.

The image reconstructed from neutron-tagged events can be assessed on different planes between the detector supermodules. The source of the neutrons is assumed to be within the plane with the sharpest reconstructed image. This plane is chosen to be the same between all four methods of imaging. A set of images from all four methods of muon radiography is shown in Fig. 6. The neutron tagged image (Fig. 6, right column) is seen to have a signal-to-noise ratio that matches the quality of the scattering image, although the statistics and position resolution are not as good.

Scattering provides good images within minutes. By one hour the size and shape of the object is clear. With neutron tagged tracks, the object is detected with high reliability in an hour; an accurate determination of the shape requires tens of hours.

5. Conclusion

In this paper we have presented cosmic-ray image data taken of a 1000 cm$^3$ cube of uranium enriched to 19.7% $^{235}$U using the Los Alamos National Laboratory MMT. We have measured coincident neutrons using $n - \gamma$ discrimination in two liquid scintillator detectors. We have presented images made using the scattering, transmission, stopping, and tagged track data. Analysis confirms that images with a high signal-to-noise ratio can be made using muon tomography techniques and shows similar high quality images using neutron tagged cosmic-ray tracks.

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Figure 6: (color online) Slices from muon radiographs showing four kinds of radiography possible with cosmic-rays. The object is a 19 kg cube of low enriched uranium. The scale for each of the grey scale images is linear where black is zero. Exposure times were varied (vertical direction) from 1 to 44 hours.
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