Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Detecting special nuclear material using muon-induced neutron emission

Elena Guardincerri [a], Jeffrey Bacon [a], Konstantin Borozdin [a], J. Matthew Durham [a], Joseph Fabritius II [a], Adam Hecht [c], Edward C. Milner [b], Haruo Miyadera [a], C.L. Morris [a], John Perry [a,c], Daniel Poulson [a]

[a] *Los Alamos National Laboratory, Los Alamos, NM 87545 USA*
[b] *Southern Methodist University, Dallas, TX 75205, USA*
[c] *University of New Mexico, Albuquerque, NM 87131, USA*

A R T I C L E I N F O

Article history:
Received 10 September 2014
Received in revised form
23 March 2015
Accepted 25 March 2015

Keywords:
Muon tomography
Neutron tagged muons
Cosmic ray tracking
Muon tracking
Muon radiography
Muon imaging

A B S T R A C T

The penetrating ability of cosmic ray muons makes them an attractive probe for imaging dense materials. Here, we describe experimental results from a new technique that uses neutrons generated by cosmic-ray muons to identify the presence of special nuclear material (SNM). Neutrons emitted from SNM 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 SNM-bearing objects tagged using muon tracking detectors located above or to the side of the objects, and may have potential applications in warhead verification scenarios. During the experiment described here we did not attempt to distinguish the type or grade of the SNM.

1. Introduction

Imaging with cosmic-ray muons has been the topic of a considerable recent body of work [1] because of the potential application to a wide range of difficult radiographic problems [2–11]. Cosmic-ray radiography makes use of muon scattering angles to measure the areal density along the muon's path. With muon tracking detectors on opposite sides of an object, an ensemble of trajectories can be used to generate tomographic images of the object's internal structure. Multiple scattering radiography enables threat detection in complex cargo scenes in $\sim$minute time scales, using only the natural flux of cosmic-ray muons [12]. As this technique adds no artificial radiation dose, it is ideal for border protection and cargo scanning, where humans would potentially be subject to large exposures from more conventional x-ray radiography techniques.

In this report, we explore a new technique that neutrons generated via interactions with cosmic-rays to detect the presence of fissile material. It is well established that cosmic ray muons which stop in fissile material can induce a detectable amount of neutron emission [13–16]. We show that cosmic-ray-induced neutrons from a uranium target can be used to tag the cosmic-ray tracks which impinge on the target and produce images of the volume of fissile material. The result is an effective method for verifying the presence of fissile material, without revealing precise details on the exact amount or isotopic composition. The insensitivity of the technique to details make it potentially useful as a warhead verification technology, in a scenario where parties to a treaty agree to demonstrate the presence or absence of weapons components without revealing potentially sensitive aspects of weapons designs.

2. Methodology

We describe the new method that we developed to tag cosmic-rays and use them as a probe of nuclear materials. Neutrons generated by secondary cosmic rays are used to tag cosmic-ray tracks. 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 [17]. Tracking detectors above and below an object allow cosmic-rays which interact in the object material to be detected and used for image reconstruction. We have used the apparatus shown in Fig. 1 [18] to measure stopped and transmitted cosmic-rays in an object placed between the two detector modules. The detector consists of a 576 drift tubes arranged in planes. Each of the two modules in Fig. 1 consists of 6 planes of drift tubes, three of which are oriented along the

http://dx.doi.org/10.1016/j.nima.2015.03.070
0168-9002/

horizontal X direction, and three of which are oriented along the horizontal Y direction, perpendicular to X. Each module can independently track cosmic rays and 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.

Conceptually, the stopping length, λ, of cosmic-rays in material is inversely proportional to the stopping rate and can be related to the energy spectrum, $dN(E)/dE$, as

$$\frac{1}{\lambda}=\frac{dN}{Ndx}=\frac{1}{N}\frac{dN}{dE}\frac{dE}{dx}\quad .$$

The majority of cosmic rays in the atmosphere are muons and electrons [19,20]. The flux of muons at sea level is approximately 1 $\text{cm}^{-2}\,\text{min}^{-1}$, and the electron flux is about 35–40% of the muons. A small hadronic component, consisting of mainly protons and neutrons, is also present and it amounts to $\sim$10% of the total flux at the 2200 m elevation of Los Alamos, where the measurement was conducted.

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 [21–23]. Over a wide range of momentum, the energy loss for cosmic-ray muons varies only logarithmically with momentum and is approximately proportional to the electron density, Z/A, where Z is the atomic number and A is the atomic mass. For dense material λ is short compared to the muon decay length, $l=\beta c\gamma\tau$, where β and γ are the usual relativistic kinematic quantities, c is the velocity of light, and $\tau=2.2\ \mu s$ is the muon lifetime.

Fig. 1. 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".

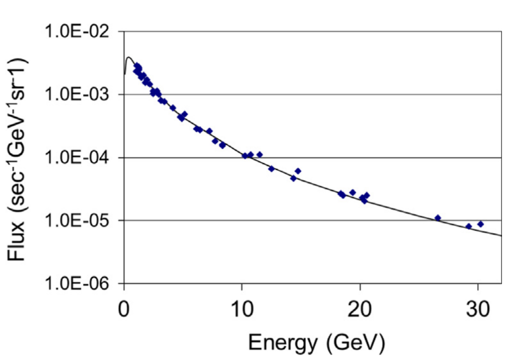

Fig. 2. Spectrum of vertical cosmic-ray flux at sea level. Solid symbols are the data [24]. The line is a parameterization.

The stopping rate for muons 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 provide radiographic signatures. For objects that are thin compared to λ, measuring the stopped flux typically provides smaller statistical uncertainty than the scattering signal.

Cosmic ray muons which encounter fissile material may induce neutron emission through three different mechanisms: photo-emission, muon-induced fission, and neutronic gain. As the highly relativistic muons pass through high-Z material, they will lose energy by emitting bremstrahhlung photons. Prompt photoneutrons may be liberated when the heavy nuclei interact with these photons.

Muons which lose sufficient energy will come to rest inside the object. A positive muon (μ^+) at rest will decay into a positron and two neutrinos, $\mu^+\rightarrow e^+ + \nu_\mu + \overline{\nu_e}$. 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, $\mu^-\rightarrow e^- + \nu_e + \overline{\nu_\mu}$, 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, $\mu^- \otimes A \rightarrow n + (A-1)^* + \overline{\nu_\mu}$. The lifetime of a muonic atom depends on its atomic number and was measured to be 71.6 ± 0.6 ns for ^{235}U and 77.2 ± 0.4 ns for ^{238}U[25].

In fissile material, neutrons liberated via photo- or muon-induced fission processes can trigger fission chains, leading to the emission of several neutrons, depending upon the effective multiplication of the neutronic system. Each fission reaction produces several gamma rays, 2–3 neutrons, and fission fragments. The time scale for neutron emission between subsequent fission events is typically on the order of $\sim$10 ns, so these secondary fission neutrons will be delayed relative to the primary neutron.

We note here that an additional source of neutrons may be present due to the protons that make up $\sim$10% of the cosmic ray flux. These high-energy protons can also liberate neutrons from atomic nuclei through spallation reactions. The produced spallation neutrons are "prompt" with respect to the incoming protons and their multiplicity is proportional to the energy of the incident protons [26]. As our tracker cannot discriminate between proton and muon tracks, these will also be present in our data.

For any of these sources, the products of this muon-induced neutron emission create a distinctive signature that can be coupled to muon trajectories. Cosmic ray tracks which point to fissile material will be correlated with neutron emission, and can be used to create a tagged image within a coincidence window.

The amount of fast and thermal fission events depends upon the geometry of the object, the quantity of fissile material, as well as other materials that may reflect, absorb, or moderate neutrons, and it is described by the Boltzmann transport equation [27] through a series of losses and gains in the neutronic system.

There is a practical challenge in measuring signals from fast or thermal fission. A fast signal resulting from muon-induced fission consists of neutrons and gammas emitted in a narrow time window on the order of hundreds of nanoseconds. The challenge with this energy region is that the mean free path of a neutron in uranium is large (order of centimeters). On the other side, if neutrons from thermal fission are to be measured, the timing coincidence window must be extended by hundreds of microseconds to account for the moderation time. The wider coincidence gate results in higher rate of accidental coincidences due to random background.

Please cite this article as: E. Guardincerri, et al., Nuclear Instruments & Methods in Physics Research A (2015), http://dx.doi.org/10.1016/j.nima.2015.03.070