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Material discrimination using scattering and stopping of cosmic ray muons and electrons: Differentiating heavier from lighter metals as well as low-atomic weight materials

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ABSTRACT

Reported is a new method to apply cosmic-ray tomography in a manner that can detect and characterize not only dense assemblages of heavy nuclei (like Special Nuclear Materials, SNM) but also assemblages of medium- and light-atomic-mass materials (such as metal parts, conventional explosives, and organic materials). Characterization may enable discrimination between permitted contents in commerce and contraband (explosives, illegal drugs, and the like). Our Multi-Mode Passive Detection System (MMPDS) relies primarily on the muon component of cosmic rays to interrogate Volumes of Interest (VOI). Muons, highly energetic and massive, pass essentially un-scattered through materials of light atomic mass and are only weakly scattered by conventional metals used in industry. Substantial scattering and absorption only occur when muons encounter sufficient thicknesses of heavy elements characteristic of lead and SNM. Electrons are appreciably scattered by light elements and stopped by sufficient thicknesses of materials containing medium-atomic-mass elements (mostly metals). Data include simulations based upon GEANT and measurements in the HMT (Half Muon Tracker) detector in Poway, CA and a package scanner in both Poway and Socorro NM. A key aspect of the present work is development of a useful parameter, designated the "stopping power" of a sample. The low-density regime, comprising organic materials up to aluminum, is characterized using very little scattering but a strong variation in stopping power. The medium-to-high density regime shows a larger variation in scattering than in stopping power. The detection of emitted gamma rays is another useful signature of some materials.

1. Introduction

Decision Sciences International Corporation has commercialized technology utilizing cosmic-ray background radiation for the interrogation of maritime cargo containers and other cargo conveyances for nuclear and conventional weapons of mass destruction (WMD) [1]. The principal physics signal that has been exploited thus far has been the scattering of muons and to a lesser extent electron scattering. A technical and operational overview of the technology as previously deployed will be presented. The Multi-Mode Passive Detection System tracks muons and electrons generated in cosmic-ray interactions with the atmosphere before and after passing through a volume of interest. Measured multiple Coulomb scattering and attenuation interactions in the volume are used to reconstruct the three-dimensional distribution of materials in the volume. This distribution can reveal the presence of WMD, as well as components and precursors, without interfering with the flow of commerce.

The MMPDS utilizes large arrays of drift tubes, above and below the volume of interest. A thin wire is strung down the center of a simple aluminum tube. Each tube is filled with a gas to provide controlled ionization and propagation (drift) of these ionized electrons to the wire and permanently sealed. In operation, a voltage is applied to the wire. Charged particles traversing the gas volume ionize the gas. Electrons from this ionization drift at a predictable rate toward the wire and avalanche near the wire to provide a pulse measurable at the end of the wire. The drift tubes provide sub-millimeter position resolution perpendicular to the wire with widths of 5 cm and lengths up to 12 m, providing geometric acceptance for very large scan volumes at relatively low cost (less than $300 per channel with a 20 year lifetime). Tubes are placed in orthogonal layers to track charged particles in three-dimensions.

Incoming and outgoing particle trajectories are evaluated for multiple Coulomb scattering and attenuation caused by objects in the volume of interest. These data are processed using imaging

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techniques based in medical imaging, particularly PET and SPECT imaging, to reconstruct the 3D material distribution in the VOI [2]. This distribution is then automatically evaluated to determine the presence of defined threats.

The MMPDS does not apply radiation to the scene being scanned. This means scanning can be performed concurrently with existing operations without endangering workers, operators or drivers. Scan results are delivered in real-time with no human interpretation required, reducing impact on commerce flow and operational costs. Another advantage of this technology is the ability to acquire additional information with extended scanning. Typical scan times are in the order of 1–2 min for clearing of benign cargo. For suspicious configurations, more detail can be obtained by extending the scan time up to 10 min, providing for the clearance of benign cargo or enhanced information for responders in the event of threat detection.

Reported here is a new method to apply cosmic-ray tomography in a manner that can detect and characterize not only dense assemblages of heavy nuclei (like Special Nuclear Materials, SNM) but also assemblages of medium- and light-atomic-mass materials (such as metal parts, conventional explosives, and organic materials). Characterization may enable discrimination between permitted content in commerce and contraband (explosives, illegal drugs, and the like). The combination of scattering and stopping data may assist in anomaly detection as well.

As explained above, our commercialized Multi-Mode Passive Detection System (MMPDS) currently relies primarily on the muon component of cosmic rays to interrogate Volumes of Interest (VOI). Muons, highly energetic and massive, pass essentially un-scattered through materials of light atomic mass and are only weakly scattered by conventional metals used in industry. Substantial scattering and absorption only occur when muons encounter sufficient thicknesses of heavy elements characteristic of lead, tungsten and SNM. Since electrons are appreciably scattered by light elements and stopped by sufficient thicknesses of materials containing medium-atomic-mass elements (metals, etc.), combining the response of muons and electrons can extend the range of material detection and characterization beyond SNM to other types of contraband.

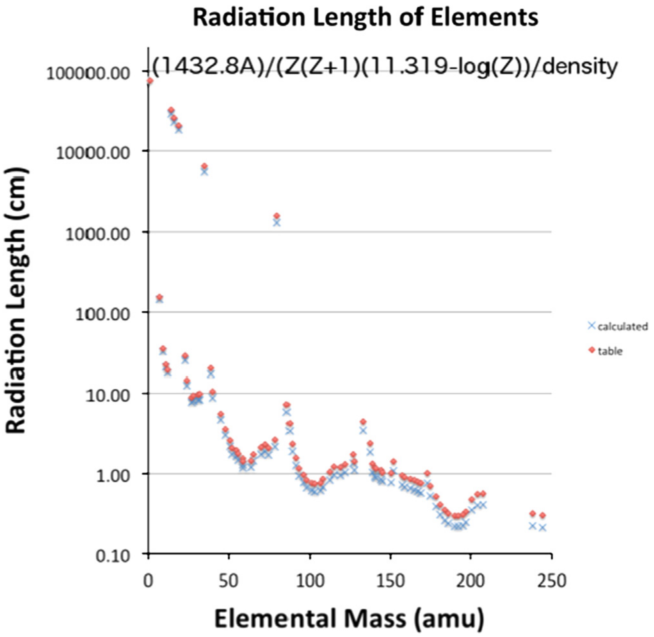

Fig. 1. The radiation length of most of the elements.

Data include simulations based upon GEANT and measurements in the HMT detector in Poway, CA and a package scanner in both Poway and Socorro NM. The HMT is comprised of 2 supermodules 7.5 m wide, 11 m long and 0.6 m thick above and below the scan volume, which can accommodate a 20 ft shipping container on a trailer. Each supermodule consists of 4320 sealed aluminum drift tubes. In the earlier configuration the package scanner had 2 supermodules, top and bottom, of size 1.8 by 2.4 by 0.6 m^3 and a total of 1008 drift tubes. The two supermodules which were later added on as sides are 1.8 by 1.8 by 0.6 m^3 bringing the total to 1872 drift tubes.

An earlier work focused on the radiation length and energy loss of metals [3]. The pioneering work of Alvarez used shadowing to measure the attenuation of the particles by a pyramid [4]. Instead of the long scan times utilized in those works, we are demonstrating that the identification of materials can be made in a few minutes or less. A key aspect of the present work is development of a useful parameter, designated the “stopping power” of a sample. It was developed to mitigate effects of sample geometry and placement within the detector. A raw measurement of stopping is affected by sample placement: more un-stopped tracks can exit without passing through the detectors when samples are located near the edges of the detector array. The raw stopping number, then, overestimates stopping since fewer scattered tracks are detected because of the geometry. Since not all scattered tracks are detected equally efficiently in all parts of the detector (particularly near the edges of the arrays), dividing by the number of scattered tracks normalizes for variations in detection efficiency.

2. Simple model

Stopping power is defined by a relation invented and disclosed by DSIC under the title, “Discrimination of Low-Atomic Weight Materials Using Scattering and Stopping of Cosmic-Ray Electrons” (Blanpied et al., 2013) [5]. It is given by the expression

$$\text{Stopping power} = \frac{[(\#\text{stoppedtracks}/\text{area}/\text{time}) \times <p>]}{[(\#\text{scatteredtracks}/\text{area}/\text{time}) \times \text{samplethickness}]}$$

where $<p>$ is the average momentum of the incident cosmic rays. The present work shows that the ratio of stopping power to scattering, where the latter is given by the expression

$$\lambda = (<\theta> <p>)^2/[\text{sample thickness}]$$

where $<\theta>$ is the average sample scattering angle, which enables one to eliminate sample thickness as an unknown (since stopping power is also normalized by sample thickness, so the ratio eliminates that variable). One first identifies the material from the ratio and then the mean scattering angle and known radiation length can be used to compute the sample thickness.

The expression used to connect the scattering to the number of radiation lengths of a material is from Rossi [6] which is when one assumes the average momentum is 3 GeV, then $\lambda = 21.47/R$ cm where R is the radiation length of the material. Here we use the first order expression and ignore the corrections which go as the logarithm of the ratio of thickness to radiation length.

The radiation lengths of most of the elements is given in Fig. 1 [7–9].

For matter such as water we can use the elemental data to compute the radiation length using the formula and bulk density

$$R(H_2O) = 3/\{[2/(R(H) \times \rho(H))] + [1/(R(O) \times \rho(O)]\}/\rho(H_2O).$$

The actual stopping (per thickness) depends on dE/dx, on the tracking of electrons through the detector, and the density of the material. Since the electrons have lower momenta (up to 1 GeV) than the muons, they scatter more in the aluminum walls of the