Remarks on Muon Radiography

M. Szeptycka and P. Szymański

Abstract Non-proliferation is one of the key aspects of the safe use of nuclear energy. The legal framework on transport of nuclear material and other dual use technologies requires ways of control of its proper application. Verification of the cargo contents is one of such ways. Different methods can be applied. In this paper we discuss feasibility of the use cosmic muons for identification of materials transported in the sealed containers. The state-of-the-art in muon radiography is discussed. We present Monte Carlo based results on cargo material dependence of some observables. Influence of the detector system performance and layout on the detection capabilities is discussed.

Keywords: Non-proliferation, cosmic rays, illicit trafficking, nuclear material, homeland security, nuclear security, nuclear safety, cargo, inspection, boarder control

1 Introduction

The non-proliferation is one of the key aspects of the safe use of nuclear energy. Verification of the contents of cargo containers is one of the ways to prevent illicit trafficking of nuclear materials. It must be fast, reliable and safe for people working in the proximity of the test facility. Cargo examination method must not harm people hidden inside the container. Due to the large quantity of cargo transported in the world non-invasive control methods are necessary. Most of them use ionizing radiation to penetrate sealed containers and identify chemical composition

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and shapes of transported material. Balancing of the effectiveness and safety hazard represents one of the challenges in the design of the cargo inspection system. System exploiting the cosmic muons is free from the radiation safety restrictions. It could be deployed practically everywhere, especially at truck parking lots. Lack of the radiation source should make them relatively cheap. This justify the interest in use of the cosmic ray muons for the cargo inspection in a search for nuclear material.

2 Muons and their properties

Muons are produced by particles of cosmic radiation interacting with the Earth atmosphere. Charge of muons equals ± 1, mass 105.65 MeV/c^2. They decay predominantly into electron, neutrino and anti-neutrino. The lifetime of approximately 2.2 µs allows relativistic muons to travel up to 660 m in vacuum. The flux of muons at the sea level equals on average 100 muons/m^2/sr/s. Muons do not interact strongly. Relatively large lifetime and small interaction cross-section allow muons to travel large distances.

For relativistic muons energy loss is approximately independent from muon momentum and amounts to ≈ 2 MeV/g/cm^2 which corresponds to 1.4 GeV per meter of steel.

$$E_{tot}^{loss} \sim L\,[\mathrm{cm}] \cdot \rho\,\,[\mathrm{g/cm^3}] \tag{1}$$

E_{tot}^{loss} is the muon total energy loss in the layer of thickness L of the material of density ρ.

Muons passing through matter undergo multiple Coulomb scattering. For muon with momentum p [MeV/c] traversing material of thickness L average scattering angle $\Theta_0[rad]$ is approximated by the equation 2 where L_0 denotes material radiation length and β is muon reduced velocity.

$$\Theta_0 = \frac{13.6}{\beta c p}\sqrt{\frac{L}{L_0}}\left[1 + 0.038 \cdot \ln\left(\frac{L}{L_0}\right)\right] \tag{2}$$

Values of Θ_0 for 4GeV/c muons passing through 5 cm of various materials are shown in Table 1. The scattering angle Θ_0 can be MEASURed only if it is larger than the detector resolution.

Table 1 Mean scattering angle Θ_0 for 4 GeV/c muons passing through 5 cm of various materials

Material	Θ_0 [mrad]
Air	0.04
Plastic	1.5
Aluminum	3.5
Steel	8.4
Lead	15.6
Uranium	21.0

3 Comparison of cargo screening technologies

Comparison of various cargo screening technologies has been presented in [1], the source of Table 2. The methods using neutrons, X and γ rays are compared to cosmic ray muons.

The flux attenuation for muons as a function of lead layer thickness is presented in Fig. 1 taken from [2]. The 4 cm thick layer of lead stops approximately 90% of 500 keV X-rays.

One may conclude that cosmic muons are the most versatile radiation for the cargo inspection. It is naturally occurring radiation, with no danger of exposing persons hidden in cargo to dangerous doses of radiation. There are no radiation safety regulations to implement. Muons show detectable interactions with heavy elements, allowing for nuclear material detection. They can also penetrate heavy shielding. However intensity of the cosmic rays is relatively low, which may lead to long inspection times. Small scattering angles may require elaborate complicated systems, leading to operational problems and high cost. The detector system must be sensitive enough to measure quite small changes of muon characteristics caused by passing through matter.

Table 2 Comparison of the cargo screening technologies [1]

<table>
<tr><th>Feature</th><th>μ detector</th><th>Fast neutrons</th><th>X rays</th><th>γ rays</th></tr>
<tr><td rowspan="2">Identify nuclear weapons, materials and dirty bomb</td><td rowspan="2">Yes</td><td rowspan="2">Yes</td><td>0.1–5MeV; no</td><td>No</td></tr>
<tr><td colspan="2">Passive detection only</td></tr>
<tr><td>Locate hidden voids</td><td>Yes</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td rowspan="2">See through all materials</td><td rowspan="2">Yes</td><td rowspan="2">No
not hydrocarbons, plastics</td><td>No</td><td>No</td></tr>
<tr><td colspan="2">not heavy metals</td></tr>
<tr><td>Immunity to false alarms</td><td>Potentially high</td><td>High</td><td colspan="2">Depends on operator skill</td></tr>
<tr><td rowspan="2">Artificial radiation free operation</td><td rowspan="2">Yes</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td colspan="3">special licensing required</td></tr>
</table>

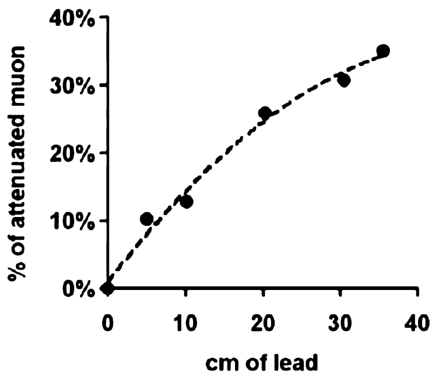


Fig. 1 Muon attenuation in lead [2]

4 The idea of the muon cargo screening technology

The idea of the cargo screening with muons relies on the measurement of the muon parameters before and after passing through the cargo container. The analysis of the muon trajectory and distribution of coordinates of scattering points allows to identify the change of the density of cargo material.

The Fig. 2 [2] shows the vehicle transporting nuclear explosive device and the muon detection system. Muon detectors installed above the inspected vehicle record the directions of muons before entering the inspected vehicle. Detectors under the road surface register directions of muons after passing through the cargo. The vehicle must remind stationary for the time necessary for the effective inspection. The detectors used for muon detection must be able to operate in variable conditions of temperature/humidity. For the detector design it is necessary to determine the precision necessary for material identification.

Some properties of muon detectors will be presented in the next section.

5 Muon detectors

Two types of muon detectors: scintillator counters and gas multiwire detectors. Both types require readout electronics, trigger system, data acquisition and analysis software. Typical sizes of the cargo containers will require large detector surfaces. This may rule out scintillator detectors due to their cost.

Multiwire chamber consists of thin, parallel and equally spaced anode wires symmetrically sandwiched between two cathode planes. Cathode can consist either of a plane of thin equally spaced wires or a conductor plane. Cathodes are connected to negative voltage. Anode wires are grounded. This creates homogeneous electric

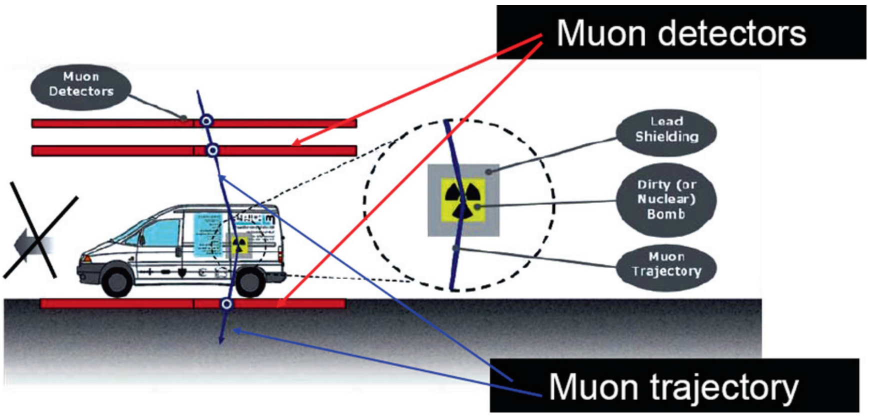


Fig. 2 Muon screening principle [2]

field in most regions of the chamber. Electric field increases rapidly around anode wires. A charged particle passing through the detector ionizes gas, liberated electrons follow electric field lines towards anode wires. Strong field very close to wire acts as a multiplication region: energy of electrons increases, they ionize gas and such created avalanche of electrons reaches the anode wire. Electrical pulses are read out from the anode wires. Pulse height depends on the composition of the gas, its temperature and pressure, applied voltage, geometry of the chamber.

Multiple plane wire chambers with different wire inclination angles allow reconstruction of particle trajectories in space.

Space resolution of detector is mostly defined by the distance between wires ("pitch"), lever arm of track measurement, alignment of the chambers.

Muon chambers of the HERMES experiment [3] may be used as an example of the muon detection system. Active area of the modules are between 263×996 mm^2 and 347×1424 mm^2. Sense and cathode wires are spaced by 2 mm and 0.5 mm respectively. Anode wires are made of 25 μm gold plated tungsten while cathode wires are of 90 μm gold plated bronze. Nonflammable gas mixture of Ar(65%), CO_2(30%) and CF_4(5%) at atmospheric pressure is used.

6 State of the art of muon radiography in cargo monitoring

We are not aware of any commercial cargo inspection equipment based on the muon radiography (see Fig. 3). Here we will present some pioneering work in this filed.

6.1 Images of tungsten cylinder

The work of K.N. Borozdin et al. [4] presents the results (4 on the reconstruction of the shape of tungsten cylinder (radius 5.5 cm, length 5.7 cm). It was supported by a plastic plate laying on two steel support rails. The wire chambers (60×60 cm^2) with two coordinates readout were placed at the distance of 27 cm, two chambers above and two chambers below the cylinder. It is clearly visible. It is not clear to us how long the measurement lasted to obtain this image.

6.2 Proposal to use LHC CMS muon chambers

M. Benettoni et al. [5] proposed to use for muon radiography muon chambers designed for the CMS experiment at CERN LHC accelerator. Detectors with active area of 7 m^2 have angular resolution of the order of 1mrad in one direction and 10 mrad in the other. Sandwich of chambers and iron layers is used for muon momentum estimation. Experiment in Padova is under way.

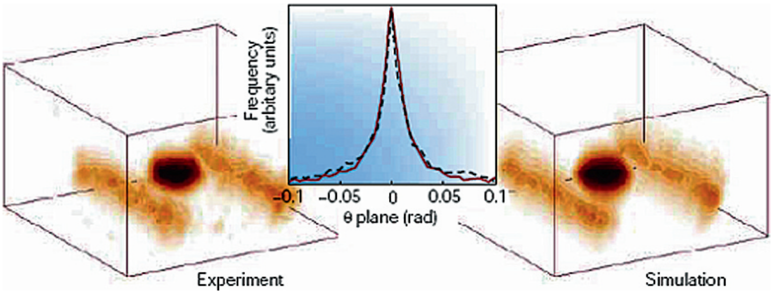


Fig. 3 Muon radiography experiment and Monte Carlo simulation of [4]

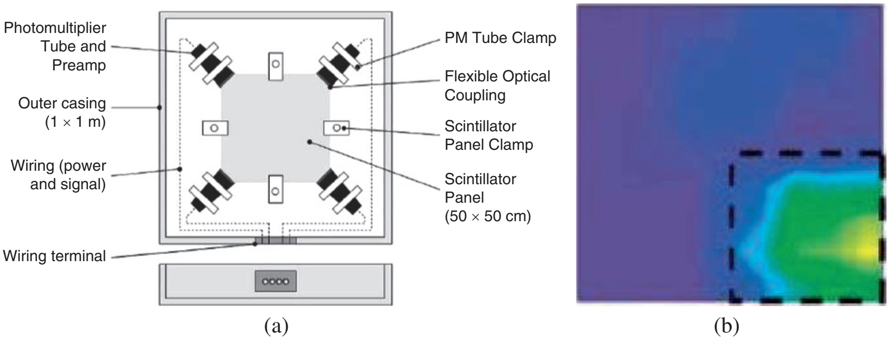


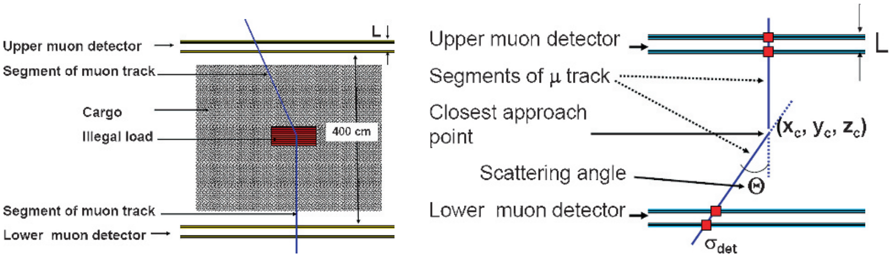
Fig. 4 (a) Muon detector of [2] (b) image of 15 cm thick lead brick seen with it

6.3 Two dimensional muon based density mapping

S.J.Stanley et al. [2] constructed detector (Fig. 4a) with plastic scintillator readout with four photomultipliers. Muon position is reconstructed through the center of gravity of photomultipliers' signals. Photomultipliers are calibrated with light emitting diodes. After 6 h of data taking and some image processing piece of lead 15 cm thick is clearly seen in Fig. 4b.

7 Present work – feasibility of the full scale muon cargo screening detector

We aim at the estimation of the measurement time and the detector parameters necessary for obtaining an information about the presence of a suspicious load in the cargo. For this purpose a GEANT4 [6] based Monte Carlo simulation is used. The geometry(shown in Fig. 5a) consists of two sets of chambers placed above and below the cargo. Each chamber measures two coordinates in the horizontal plane. Only events with one hit in each of the chambers are analyzed.



(a) Geometry (b) Observables related to the muon trajectory

Fig. 5 Simulation used in the current work

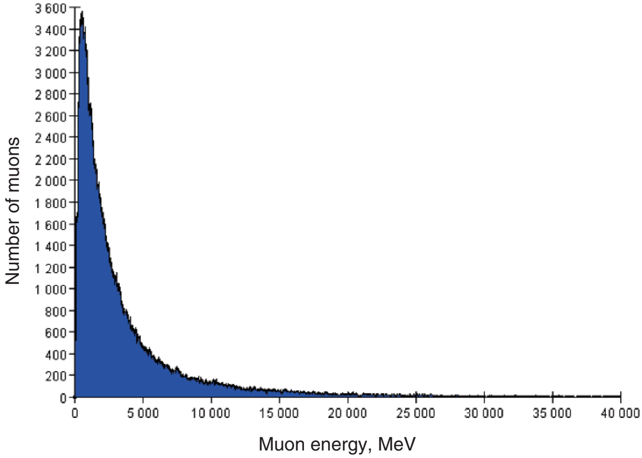


Fig. 6 Muon energy distribution used in the realistic version of the muon generator

We use observables related to the change of the muon direction due to the multiple scattering (Fig. 5b). From the measurements of the two points on the muon trajectory above and below the cargo we determine:

- The scattering angle Θ
- The distance of closest approach of the upper and lower track segments δ
- The coordinates of the region of the closest approach of the upper and lower track segments

Two effects are studied: dependence of the observables on cargo material and on the detector parameters. Two versions of muon generators are used. In the simplified version vertical muons with fixed momentum are generated. In the realistic version zenithal angle (θ) distribution proportional to $\cos^2\theta$ and energy distribution according to [7] (shown in Fig. 6) are used.

Table 3 Mean scattering angle Θ for various materials - Monte Carlo results

Material	Mean scattering angle Θ
400 cm air	0.04
395 cm air + 5 cm Al	0.4
395 cm air + 5 cm Pb	2

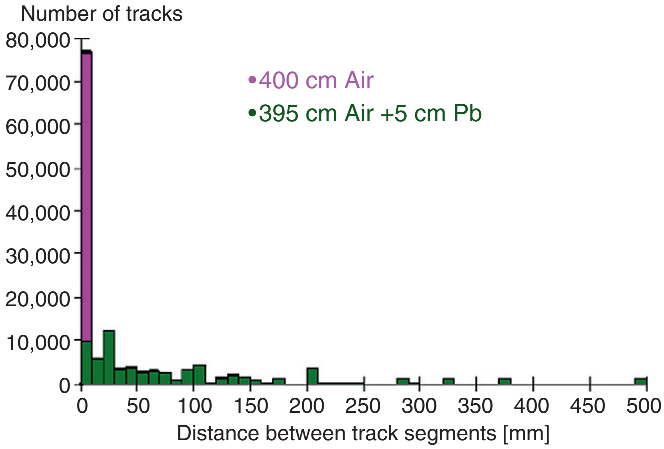


Fig. 7 Distributions of distance between track segments for muons traversing 400 cm of air, as well as 5 cm of lead and 395 cm of air

7.1 Dependence of observables on the cargo material

For various materials we present in Table 3 the mean scattering angle Θ for 30 GeV muons and the ideal detectors. The distributions of δ for 400 cm of air (395 cm of air and 5 cm of lead) are presented in Fig. 7.

Change of the muon generator from simplified to realistic results in change of the mean scattering angle from 0.04 mrad to 3.4 mrad for 400 cm air.

7.2 Dependence of the observables on the detector parameters

The spacial resolution σ_{det} is assumed to be the same for all the chambers in both horizontal directions. The vertical coordinate is measured perfectly well. Dependence of the scattering angle Θ on σ_{det} is presented in Table 4. The effect of the finite position resolution may be compensated by increasing the distance L between the chambers within upper (lower) detector. Summary of results is presented in Fig. 8.

Table 4 Dependence of the mean muon scattering angle Θ as a function of the detector spacial resolution σ_{det}. Simplified muon generator and 400 cm air

σ_{det} [mm]	Θ [mrad]
0.	0.04
0.3	3.4
3.0	34.

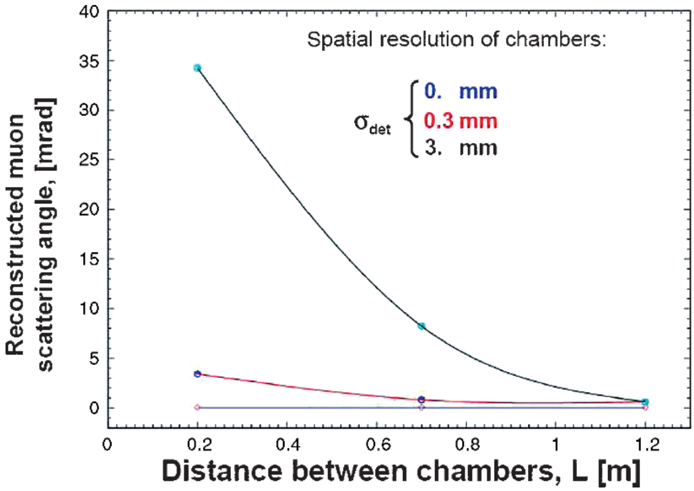


Fig. 8 Mean reconstructed muon scattering angle Θ as a function of the distance between the chambers L and chambers' spacial resolution σ_{det}

8 Conclusions

When designing the muon radiography system for cargo inspection one should keep in mind that detector performance may "shadow" the difference between various materials. The necessary irradiation time should be estimated and is one of the key performance figures of the system. The MC simulation with realistic momentum and angular distributions of muons is essential. The work is in progress.

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References

1. T. Kochanski, "A Novel Method of Detecting Shielded Nuclear Weapons and Voids in Cargo" (Revised Feb 28, 2008)
2. S.J. Stanley et al. in: Proceedings of an International Conference on Illicit Nuclear Trafficking: Collective Experience and the Way Forward. (Edinburgh, 2007), p. 571

3. K. Ackerstaff et al., Nucl. Instr. and Meth. A**417** (1998) 230
4. K.N. Borozdin et al., Rev. Sci. Instr. **74** (2003) 4294
5. M.Benettoni et al. in IEEE NSS Conference Record vol. 2 (2007) 1021
6. S. Agostinelli et al., Nucl. Instr. and Meth. A**506** (2003) 250, J.Allison et al., IEEE Trans. Nucl. Sci. **53** No. 1 (2006) 270
7. J. Kremer et al., Phys. Rev. Lett. **83** (1999) 4241