IL NUOVO CIMENTO **46 C** (2023) 45
DOI 10.1393/ncc/i2023-23045-6

COLLOQUIA: SOGIN 2023

Muon radiography for the safety and safeguarding of nuclear material

GIULIO SARACINO([1])([2])([3])

([1]) *Dipartimento di Fisica, Università di Napoli Federico II - Napoli, Italy*
([2]) *INFN, Sezione di Napoli - Napoli, Italy*
([3]) *MuonX SRL - Napoli, Italy*

received 7 March 2023

Summary. — Muon radiography is an imaging technology based on the detection of muons of cosmic origin. Muons are able to penetrate deeply into matter and are a free source available 24h. They can be used for security and safeguards in the management of nuclear material. An example is the inspection of heavily shielded containers, such as nuclear fuel storage casks, to verify their contents in case of loss of continuity of knowledge or to image their contents if it is unknown. Muons can also be applied for subsurface investigation, providing a competitive or alternative methodology to classical prospecting methods. They can be used to study the geologic conditions of a deposit area (before construction and over time), to map empty underground structures (tunnels, shafts) or to monitor any unauthorized excavations for illegal access. This article will give a brief review of the state of the art, with some key examples.

1. – Introduction

Muons are elementary particles with the same electric charge as electrons and a rest mass about 200 times greater. Cosmic muons are produced by the interaction of so-called primary cosmic radiation (composed mainly of protons and heavier nuclei) with Earth's atmosphere. The energy spectrum of muons is continuous and ranges from a few MeV to several TeV. Although they are unstable particles, most muons produced in the atmosphere reach the Earth's surface, passing through buildings and penetrating hundreds of meters into the crust. This ability to pass through matter is the basis of two imaging techniques that are briefly introduced in the next sections.

2. – The physics of muon radiography

Passing through matter, muons interact electromagnetically with electrons and nuclei of atoms, losing energy and scattering from the initial direction. Energy loss is the basis of muon radiography by absorption, some time called *muography*, while multiple scattering is the basis of muon tomography, also called muon radiography by scattering. The two effects are briefly described below, while a more detailed description can be found in [1] and the bibliographical references therein.

The average energy loss of a muon crossing a thickness x of homogeneous material with mass density ρ is proportional to the *opacity* $X = x\rho$ and can be described by the following equation:

$$\left\langle -\frac{dE}{dX} \right\rangle = a(E) + b(E)E \tag{1}$$

If the density is not constant along the path, the opacity can be written in terms of the average density $< \rho >$:

$$X = \int \rho(x)dx = x < \rho > \tag{2}$$

In general the parameters a and b depend on the muon energy and on the atomic composition of rock through the average of the ratio Z/A and Z^2/A, where Z is the atomic number and A the mass number of the elements composing the rock [2]. At first order the main dependence from the material is trough the mass density, *i.e.*, apart from very low and very high atomic number materials, the energy loss is the same for many materials once normalized to the opacity and a muon crossing materials with different atomic number Z but same opacity loses approximatively the same amount of energy.

In addition to energy loss, muons undergo deflections due to the electromagnetic interactions with the nuclei of the matter passed through. The cumulative effect of many interactions randomly change the initial direction of the muons. For a fixed energy the angle of exit after a certain thickness of material x follows, approximatively, a gaussian distribution with average zero and standard deviation given by:

$$\sigma_\theta = \approx \frac{13.6MeV}{pc}\sqrt{x\lambda}. \tag{3}$$

where p is the momentum of the muons and $\lambda = 1/X_0$ is the linear scattering density, defined as the reciprocal of X_0, the material radiation length. The radiation length is usually approximated as:

$$X_0 = 716.4\ g/cm^2 \frac{A}{Z(Z+1)\ln(287/\sqrt{Z})} \tag{4}$$

Since cosmic muon energy spectrum is continuum, the measured deflection angle distribution is given by the convolution of the gaussian distribution with the momentum spectrum. Taking in account this effect it can be shown [1] that the variance of the distribution $\langle \theta^2 \rangle$ can be approximated by:

$$\langle \theta^2 \rangle \propto x\lambda \underset{\sim}{\propto} xZ\rho \tag{5}$$

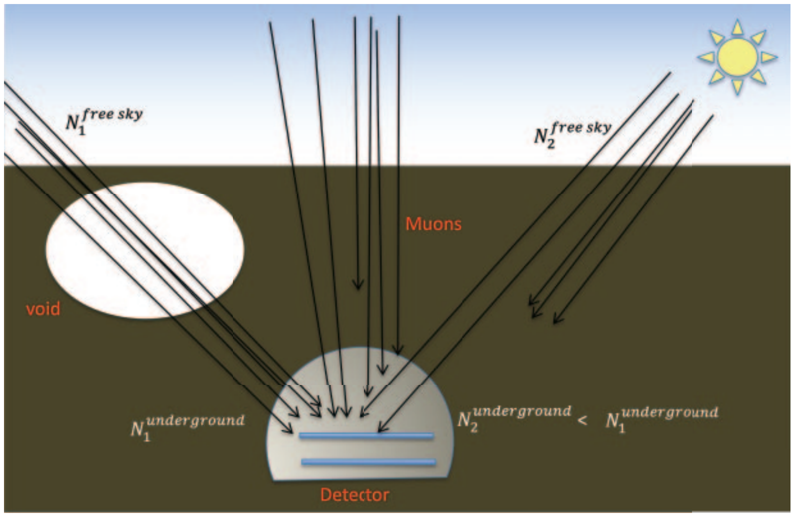

Fig. 1. – Principle of muon radiography by absorption. A detector, placed in an underground tunnel, measures muon flux as a function of direction. The attenuation of the flux depends on the amount of matter traversed by muons. In particular, the presence of a cavity corresponds to an excess of muons.

This measured variance is therefore sensitive to the atomic number Z of the matter crossed. Since it is also depending on the opacity X, a combination of the two technique, absorption and scattering, allows to discriminate between different materials.

Muons are revealed with detectors called trackers, which provide the direction of flight of muons passing through them. Several technologies are in use, the most common of which include gas-based and scintillator-based detectors, typically made of sensitive planes that provide the coordinates of the point of impact of the muon with the detector. The direction is then calculated from these measurements, with an error that depends on the spatial resolution of the detector and the distance between planes. For more details see [1,3].

2˙1. *Muon radiography by absorption.* – Energy loss is the physical process behind muon radiography by absorption. A muon detector measures the muon flux downstream of the volume under investigation (InVo). The attenuation of the flux depends on the opacity of the InVo, which is why this technique resembles common X-ray radiography. Muon absorption radiography allows the study of large InVo, such as volcanoes, mines and underground cavities. For such measurements, a single *small* detector with a sensitive area of 1 m^2 or less is sufficient, although increasing the surface area gives the results in a shorter time.

A single tracker usually provides 2D information, such as average density as a function of direction, allowing for the detection of cavities or other bulk discontinuities. By combining measurements from different observation points, 3D images can be obtained. The principle of muon radiography by absorption is illustrated in fig. 1, where a sketch of a detector positioned in a tunnel is shown. Along the direction that intercepts the

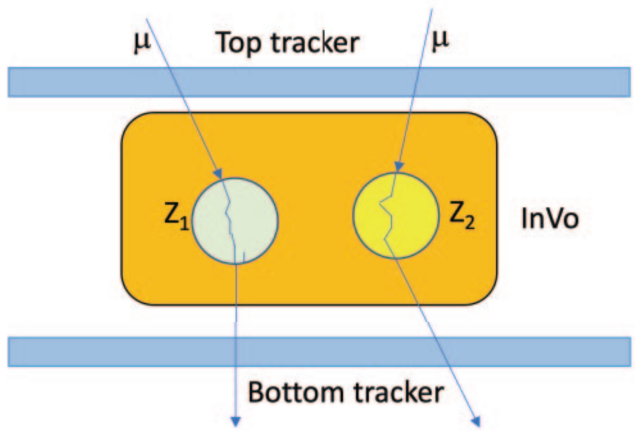

Fig. 2. – Principle of muon radiography by multiple scattering. Two detectors, placed below and above the investigated volume, respectively, measure the entry and exit directions of muons. High-Z material (Z_2) tends to scatter muons more than low-Z materials (Z_1).

cavity, fewer muons are stopped than in the case where there are no cavities. As a result, the detector will measure a higher muon flux in that direction. To be more quantitative, the relative transmission $R(\theta, \phi)$ can be used. R is defined as the ratio, for each direction (θ, ϕ), between the measured transmission and that obtained from simulations. The latter quantity is based on the hypothetical model of InVo made on the basis of all available data. The measured transmission is obtained by the ratio between the muons flux measured in the underground and the one observed in *open sky*. Values of $R(\theta, \phi) \sim 1$ correspond to directions where the measurement values are in agreement with the InVo model. Value of $R(\theta, \phi) > 1$ correspond to an excess of muons with respect to the model, that could imply the presence of a cavity in the direction (θ, ϕ) not included in the model. An example of a measurement of cavities is presented in sect. **3**.

2·2. *Muon radiography by scattering*. – The electromagnetic multiple scattering of muons is the physical process at the base of the muon tomography (MT). The deflection of the muon depends on the material inside the InVo: high Z material produce a greater scattering with respect to low Z material. This is schematically sketched in fig. 2. To measure the muon deflection two trackers are needed, one measuring the muon before entering the InVo and the second after. Cosmic muons comes from all the zenith angles θ between the horizon ($\theta = 90$) and the zenith ($\theta = 0$), but the flux is not isotropic and is approximatively proportional to $cos^2\theta$, therefore is maximum at the vertical, decreasing with θ, till to become zero at the horizon. Thus, in principle the maximum number of muons useful for the MT could be obtained surrounding completely the InVo. In practice, the preferred geometries are either with one tracker at the top and one at the bottom or two or more trackers positioned sideways. In any case the area of the trackers is proportional to the size of the InVo. In addition, the greater the distance between the trackers and the InVo, the better their spatial resolution must be. Area and spatial resolution have a major impact on the cost and complexity of the equipment, limiting the practical size of the InVo to tens of m^3.

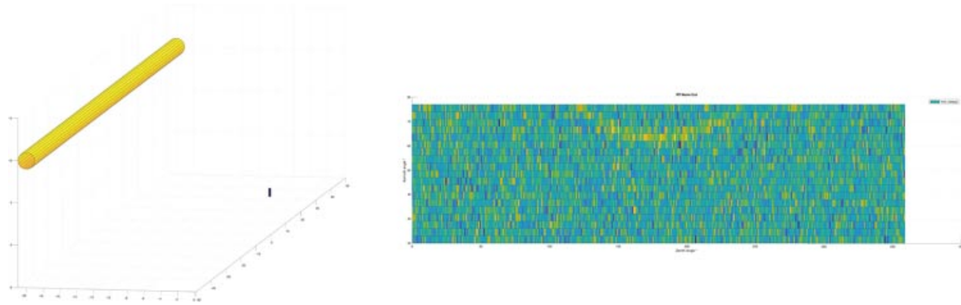

Fig. 3. – Left: the model of a tunnel of 100 m length, 2 m in diameter and located at a depth of 5 m. The borehole detector is placed ad a depth of 15 m and at a lateral distance of 20 m. Right; the expected relative transmission after 20 days of data acquisition. The yellow arc shape at the top angular region is the signature of the tunnel.

Regarding imaging algorithms, many procedures have been and are being developed. One of the simplest is based on Point Of Closest Approach (POCA) reconstruction, while Maximum Likelihood Expectation Maximization (MLEM) allows for better results at the cost of increased computational time. These algorithms are typically based on subdividing the InVo into cubes (voxels) and provide a three-dimensional representation of the contents of the InVo. For more details, see [1,4]. Two examples of MS applications will be presented in sect. **4**.

3. – An application of muon radiography by absorption: detection of tunnels with borehole detectors

The mapping of all existing cavities, tunnels, wells and, in general, the geophysical characterization of a long-term storage facility located underground are of utmost importance for safety and security purposes. Muography can be an alternative, cost-competitive method to traditional geological survey methods. In some cases, for some soil types, it can provide better performance in terms of spatial resolution. In addition, in order to prevent illegal access to the site, the ability to monitor any tunneling or shaft excavation over time can be critical for safeguarding purposes. To this end, the installation of one or more detectors in the subsurface enables a real-time and remote monitoring of any excavation work with minimal human interaction.

Muon radiography has already demonstrated the ability to detect voids in the subsurface using planar scintillator-based detectors with a volume of about 1m^3 volume [6-8]. In this case, a tunnel, at a depth greater than that of the InVo, where the detector can be installed is required . The possible use of a compact detector, with good angular resolution and geometric acceptance, which can be placed in special boreholes, is an interesting alternative, especially for monitoring possible tunnel excavations for illegal access. An example of this type of detector is described in detail in [9, 10]. This detector can be inserted into a borehole 25 cm in diameter and has a length of 1.3 meters. The acceptance of the detector is optimized for the cylindrical geometry, being based on arc-shaped scintillators. The angular resolution is on the order of 0.7 and 3 degrees in azimuth and zenith, respectively. An example of the application to tunnel detection, obtained by simulation, is shown in fig. 3. In this particular case, the signal of tunnel presence is evident after about 20 days of data acquisition.

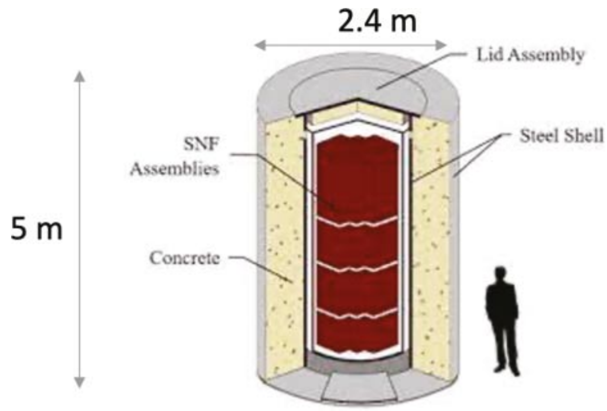

Fig. 4. – A sketch of a typical dry storage cask (DSC). Picture from [5].

4. – Applications of multiple scattering muography for imaging nuclear material

4·1. *Dry storage cask inspection ad the Idaho Laboratory and the MUTOMCA project.* – Dry storage casks (DSCs) are currently the main option for storing spent nuclear fuel in a repository. Examples of DSCs are the CASTOR®V or the Westinghouse MC-10, which have a typical height of about 5 m, an outer diameter of 2.4 m and a mass of about 100 tons or more (see fig. 4). They are heavily shielded with concrete and steel to reduce radioactivity in their vicinity. Characterization of their nuclear contents prior to permanent storage, for routine verifications or for re-verifications in case of loss of continuity of knowledge, is currently based on visual inspection, which is possible only if the fuel assembly is placed in dedicated water pools. Active imaging with X-rays or gamma rays is difficult, again because of shielding. Techniques based on measuring residual radioactivity are made difficult by both the shielding of the casks and of the external fuel rods, which tend to shield the internal ones. In addition, the presence of the other casks, usually present in the storage facility, represents a nontrivial background.

Cosmic muons have been proposed for imaging the nuclear content of DSC, using multiple scattering or a combination of multiple scattering and absorption [4]. An interesting test performed at the Idaho National Laboratory in the United States is reported in [11]. Two gas detectors, about 1.2 m $\times$ 1.2 m in area, were placed around a MC-10 cask partially filled with nuclear fuel rods (see fig. 5). The two detectors could not cover the entire volume of the cask, so different data acquisitions, each of about 10 days, were made, moving one of the two detectors to achieve the maximum coverage of the cask. Unfortunately, one of the data sample was compromised by a storm that shifted the position of the detector, preventing an accurate reconstruction of the muons tracks. Despite these limitations, the test demonstrated the capacity to detect the missing fuel assemblies, as shown in fig. 5, where comparison between data and Monte Carlo simulations is presented. This test is particularly significant because it showed that even an undersized detector is capable of detecting missing fuel assemblies in a reasonable time. In addition, it showed that the residual radiation (order 10 μSv/hr) near the container does not significantly degrade the detector efficiency.

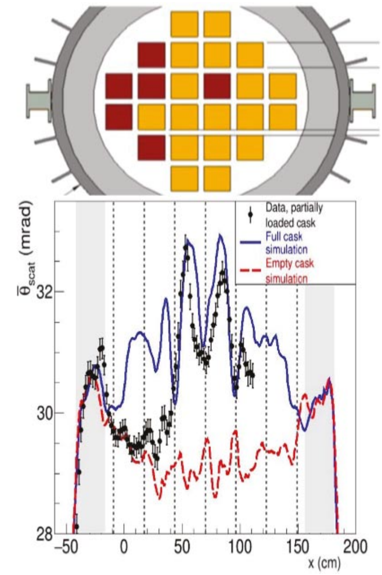

Fig. 5. – Results from the a test on a MC-10 cask, partially filled with fuel assemblies. On the top the sketch of the positions of the fuel assemblies (yellow) and of missing fuel (red). In the bottom the scattering angle measured as a function of the position. The geometrical correspondence of the fuel columns is shown with the dashed lines. Expected result in case of a full and an empty cask are shown as well. Pictures from [11].

A similar measurement is the goal of MUTOMCA (MUon TOmography for CAsks), a collaboration between Forschungszentrum Jülich GmbH (FZJ, DE) and INFN with the participation of EUROATOM and BGZ Company for Interim Storage (DE). They designed a muon detector made of two trackers modules, each formed by 183 drift tubes of 4,5 m of length and 5 cm in diameter, displaced vertically in 6 layers. The two detectors can be rotated around the cask in order to obtain a 360° coverage (see fig. 6). A preliminary test with a small prototype showed that the residual radioactivity doesn't compromise the tracking capability [12]. A full prototype was installed, in January 2023, and is under test at the fuel storage facility at Grafenrheinfeld site in Germany. It should be pointed out that, in order to contain the cost and complexity, this detector measure the

Fig. 6. – (A) Detector segment obtained by adding the INFN Muon Detector (upper part) to the drift tube module (lower part). (B) Detector positions. (C) Top view drawing of a six-layer drift tube muon detector module. Pictures from [15].

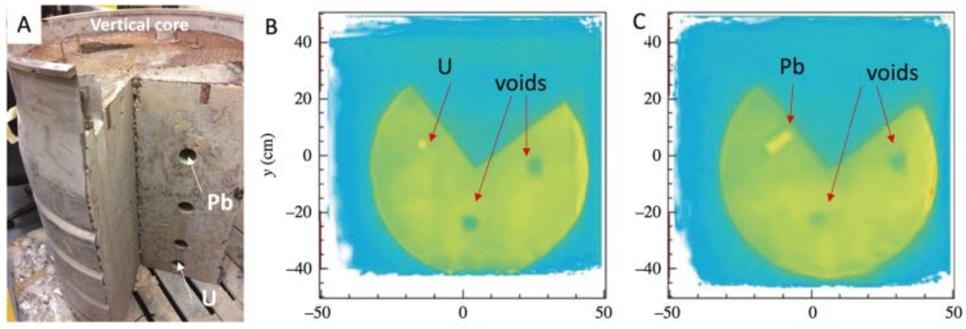

Fig. 7. – (A) The surrogate drum with a 20 mm-diameter, 30 mm-long cylinder of uranium and a lead pieces, measuring approximately 90 mm × 40 mm × 20 mm. (B) and (C): slices of 10 cm thickness obtained of the 3D muon tomography in the region of the uranium (A) and in the region of lead (C). The presence of the two materials as well as the voids are clearly visible. For this analysis 24.7 million muons were collected, for a total acquisition time of about one month. Pictures from [17].

horizontal coordinate with a spatial resolution much better than the vertical one and, as already mentioned, it cover only partially the DSC volume. This choice was supported by extensive Monte Carlo simulations [12,4], that showed that this configuration can provide very precise information about the number of fuel assemblies present in the DCS. For the test at Grafenrheinfeld a second tracker, realized by INFN, is installed on the side of the drift tubes detector, in order to measure also the horizontal coordinate with good precision and validate the expected performances.

4˙2. *Inspection of legacy barrels at Sellafield*. – Characterization of shielded waste containers, the contents of which are unknown, is a widespread problem, especially in those countries that began their nuclear plans long ago and have accumulated a lot of nuclear waste from the past. The barrel shielding limits the use of active X-ray and gamma-ray imaging, while muon tomography allows for clean images of their content. The Nuclear Physics group at the University of Glasgow, working alongside the UK National Nuclear Laboratory (NNL), has development a technology, based on scintillator fiber detectors, to produce high-resolution images for the identification of small fragments of uranium within 500-litre intermediate level waste containers. This project focuses especially on the case of legacy barrels in the Sellafield Nuclear site, in UK. Extended Monte Carlo simulations have been performed in order to demonstrate the feasibility of the method, as reported in [16]. An interesting experimental test is reported in [17]. As it is possible to see in fig. 7, a surrogate 500 l drum was prepared for the purposes of this validation. Uranium and lead samples were placed in some cores. In the same picture two slices obtained by a 3D reconstruction of the drum are shown, where it is possible to see clearly the presence of the samples as well as the empty cores. This system was commercialized by Lynkeos Technology, a SPIN-OFF of this research activity.

Muon tomography for the characterization on nuclear waste is also one of the goals of the INFN contribution to the PREDIS project, (Pre-Disposal Management of Radioactive Waste, EURATOM NFRP-2019-2020-10 RIA call) started in 2020 and with 4 years of duration. PREDIS project intend to increases the Technological Readiness Level of treatment and conditioning methodologies for wastes for which no adequate or industrially mature solutions are currently available.

5. – Conclusions

The two main physical processes of muon interaction with matter, energy loss and multiple scattering, can be used to obtain detailed images of subsurface and nuclear material inside shielded containers. The high penetration capacity of cosmic muons allows this technology to be used competitively with traditional geological survey methods or X-ray and gamma tomography. It also offers the advantages of a free and natural source, available 24h, that can be used without radiation protection concerns. Once installed, muon detectors can be remotely controlled and the data transmitted for analysis with minimal human intervention. Research activities are ongoing in many countries, and new start-ups have sprung up to introduce this technology to potential markets, including one related to safety and safeguard in nuclear waste management.

REFERENCES

[1] Bonomi G., Checchia P., D'Errico M., Pagano D. and Saracino G., *Prog. Part. Nucl. Phys.*, **112** (2020) 103768.
[2] Groom D. E., Mokhov N. V. and Striganov S., *At. Data Nucl. Data Tables*, **78** (2001) 183.
[3] Ambrosino F. and Saracino G., *Real Time Detectors for Muography*, Chapt. 5 of *Cosmic Ray Muography* (World Scientific Publishing Company) 2023, https://doi.org/10.1142/9789811264917_0005.
[4] Vanini S. *et al.*, *Philos. Trans. R. Soc. A*, **377** (2018) 20180051.
[5] Hanifehzadeh M. and Gencturk B., *Ann. Nucl. Energy*, **155** (2021) 108155.
[6] Saracino G. *et al.*, *Sci. Rep.*, **7** (2017) 1181.
[7] Cimmino L. *et al.*, *Sci. Rep.*, **9** (2019) 2974.
[8] Borselli D. *et al.*, *Sci. Rep.*, **12** (2022) 22329.
[9] Saracino G. *et al.*, *Nucl. Instrum. Methods Phys. Res. Sect. A*, **1048** (2023) 167995.
[10] Cimmino L. *et al.*, *Sci. Rep.*, **11** (2021) 17425.
[11] Durham J. M. *et al.*, *Phys. Rev. Appl.*, **9** (2018) 044013.
[12] Ancius D. *et al.*, *ESARDA Modelling of safeguards verification of spent fuel dry storage casks using muon trackers*, *41st Annual Meeting, Symposium on Safeguards and Nuclear Material Management, 14–16 May 2019, Stresa (Italy)*, p. 142.
[13] Poulson D. *et al.*, *Nucl. Instrum. Methods A*, **842** (2017) 48.
[14] Checchia P. *et al.*, *IAEA Symposium on International Safeguards CN267-048* (2018).
[15] Bonomi G. *et al.*, *MUTOMCA: An experiment to investigate spent fuel casks with muon tomography*, IAEA CN-303, in press.
[16] Yang G. *et al.*, *Philos. Trans. R. Soc. A*, **377** (2019) 20180062.
[17] Mahon D. *et al.*, *Philos. Trans. R. Soc. A*, **377** (2019) 20180048.