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Exploring Muon Imaging: Principles, Applications, and Techniques

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Abstract: ***The first scanning of Chephren's pyramid using muon imaging was carried out by L. W. Alvarez in 1970. Since then, Muography based on penetrating probes and detectors has found wider application in different fields. Muon imaging is conducted using two modes (i) absorption and transmission modes (ii) deviation modes of muon. Utilizing both the modes structure of variable size and different densities are imaged. In the present paper after a brief review of cosmic ray muon, the various applications of muon have been classified and discussed under three specific categories: muon radiography, muon metrology, and muon tomography. The basic ideas of all three categories have been explained to realize the principle and significance of the muon imaging applications.***

Keywords: Muon Radiography, Muon Metrology, Muon tomography

1. Introduction

In the last few decades, the variety of radiations and particles has opened up numerous possibilities in imaging. Recently muon imaging has experienced an impressive development due to the advancement of experimental equipment, and techniques employed in High Energy Physics. L.W Alvarez, a great expert in particle detectors and Nobel Prize winner first explored the internal structure of Chephren's pyramid at Giza in 1970, searching for unseen chambers their using muon imaging based on muon absorption.

In the first period, the application exploited mostly the attenuation of cosmic-ray muon during their crossing over the region under observation. For designing new application strategies recently the deflection characteristics of muon has been considered. All these early periods of applications are based on the measurements of attenuation of the cosmic ray muon flux. In this process, the total number of muons existing under the volume of consideration is counted, and then the thickness of the specimen is assessed by assuming the chemical composition of the material through which the muon flux has passed. Based on the principle of absorption/ transmission of muons, the technique is named muon radiography or muon absorption radiography. It is very similar to common x-rays and popularly in brief is called muography.

Apart from the absorption of muons due to its continuous energy loss while crossing the material, using existed muons scattering angle the properties of crossed material can be studied. This ingenious idea was first proposed by research group from Los Alamos in 2003. In such a case, the trajectories of both incoming and outgoing muon are mapped to obtain a 3D representation of the volume under studied. This novel method has opened up many other opportunities for new applications. Based on this effect, the method is classified as muon tomography or muon scattering tomography or muon multiple scattering tomography (MCS).

Besides muon radiography and muon tomography, one more technique called muon metrology has been suggested for civil applications to use cosmic rays muons. The principle involved here is the simple fact that the total scattering angles of muons traveling through a sample of many particle systems is zero. It is similar to the phenomenon done with laser positioning systems. The positioning of different parts of a given structure can be evaluated using this technique. For decades this technique has been commonly employed for calibration and alignment of the apparatuses and devices in particle and nuclear physics.

The above-mentioned cosmic ray muon applications use a detector to track and reconstruct the propagation of muons inside the sample. Based on the requirements, the detectors with specific characteristics are used for each application.

Recently the overall research field of applications of cosmic ray muons has experienced distinguishable growth. The ensemble of these applications has been discussed extensively in the following sections.

2. Muon Radiography

Muon radiography (Muography) works on measuring the attenuation of muon flux intensity due to the absorption by a heavy object when passed through it. As muons are less interacting particles, they are less likely to be stopped and decayed by a less dense material than a denser. By this process, the number of muons passing through the target volume is measured to get an idea of the material density. The schematic picture of muon radiography is shown in **Figure 1**.

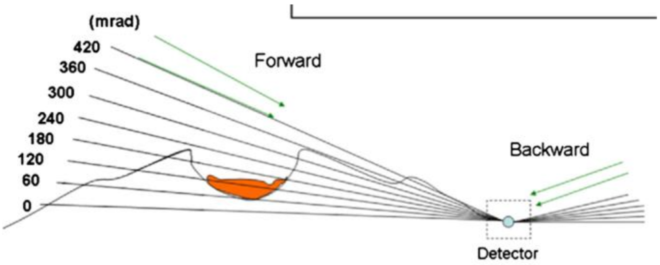

Figure 1: Schematic view of principle of muonic radiography [2]

Only the downstream muons that have crossed the object are measured in this process. If one wants to increase the detection area, then more detectors will be used, but all in downstream positions. Firstly, the incoming muon flux is measured without any objects between the detector and the sky. Then the attenuation of the flux is calculated. This technique is helpful where MCS cannot be used, which uses two detectors (one for upstream and another for downstream). For this process, the detector is to be point-sized (~ $1m^3$) as compared to the size and distance of the object under investigation.

A 2D projection is usually provided for a certain position. So, by gathering several measurements, one can get a 3D projection of the internal structure of the material under investigation. This process is being used for several activities like volcanic activity study, pyramid cavities study, etc.

2.1 Applications

- **Study of Volcanoes –** Muography has a great application in volcanic studies. Many countries have adopted this technique for their volcanic studies like Japan, Italy, and France. In 1994, a simple tracking system using the magnitude of the intensity of muon flux across Mt. Tsukuba was used to predict some volcanic eruptions **[1]**.

  In Italy there are active volcanoes such as Etna, Vesuvius, and Stromboli were investigated in these couple of years by this muon radiography technique. During the period 2009-2012, the Vesuvius was studied by the INFN, in collaboration with the INGV using the MU-RAY and MURAY2 **[2]**. Another example is the Stromboli volcano, which is a large strato-volcano in south Italy. Here emulsion films were used **[3]** to study the internal structure of the summit crater area. It was performed for about 5 months with a detector area of 0.96~m^2 with an altitude of 640~m above sea level. **Figure 2** shows the time variations of the muons flux across different domains of the Ontake volcano in Japan.

  Also in France, two main collaborations i.e., the DAFNE group and TOMUVOL are active in these studies on volcanoes.

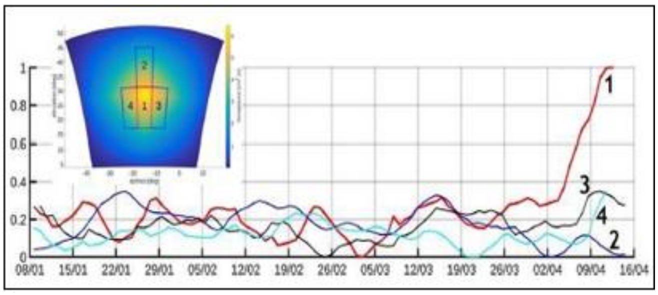

Figure 2: The muons flux variation with time versus various regions of the lava dome **[13].**

- **Mineral Exploration –** The muon radiographic technique is being used in the mining geophysics field. In the year 1979, this was used to detect the density anomalies **[1].** This can be far more useful for massive sulfide and iron exploration. This technique was also used at the McArthur River mine, in Canada, for detecting the presence of uranium ore. Several other ore deposits were also reported by this use **[4]** such as the Nyrstar Myra Falls mine, in Canada.
- **Monitoring of CO_2 geo-storage –** Muon radiography has another application in the monitoring of CO_2 trapped in deep underground. The storage sites should be at least 1 km deep and the monitoring to be done for decades. For this kind of measurement, large area detectors (~1000 m^2) **[5]** should be used. The use of arrays of detectors placed in horizontal boreholes beneath the storage site is taken to be the only practical application.
- **Glaciers bedrock profiles –** It is difficult to study the active curving by glaciers as the thickness and bedrock shape under the glaciers are unknown quantities. Some parts of the Aletsch glacier were mapped using a nuclear emulsion detector and Jungfraubahn railway tunnel under the Eiger glacier was studied using a three detectors system in the years 2015 and 2017 respectively. The density difference between the rock and the ice is the cause for the reconstruction of the bedrock shape.
- **Chamber detection in Pyramids–** After the famous experiment done by Alvarez to find some hidden chambers or cavities inside a pyramid, the second one to be tested was the Pyramid of the Sun, Teotihuacan, Mexico. This examination was carried out by a group at the National Autonomous University of Mexico (UNAM), which used this muographic technique to explore the internal body of the pyramid. After about a decade from the start day, the most significant result was that there was a less dense portion from the rest of the structure.
- **Underground cavities and tunnels –** Radiography is also very helpful in the survey of underground tunnels and cavities. The first one was considered to be carried out near Trieste, Italy, inside the GrottaGigantenatural cave **[6]**. Installation of muon detectors is not always possible as galleries could not be made available, so a borehole could be constructed to place the detector deep inside **[7]**. Mt. Echia, Naples in Italy is one of the recent places for the void detection study to be carried out. A scintillator-based detector made up of plastic and having a sensitive area of 1 m^2 was used as radio detector **[8]**. Ancient Temperino mine in Italy is another example of underground case study conducted using radiography.
- **Industrial Application –** Radiography has also been in use for some industrial purposes. This method is used for

degradation monitoring of the furnace. For iron making in a blast furnace **[12]**, two 2 x 1 m^2 plastic scintillator detectors at a separation of 15 m were used. The testing was carried out for 45 days. Also to distinguish between high-Z and low-Z material, they used muons for the study of the blast surface **[13]**. Another application is the use of two layers of scintillating fibers with an area of 140 x 140 mm^2 and separation of 100 mm, with 8 msrd of solid angle resolution, connected to SiPMs for the infrastructure degradation investigation **[14].**

3. Muon Metrology

Its basic principle based on the estimation of relative alignment of a system of detectors evolves over a while. These changes will show the movements or deformations in the structure under study. By this method, one can get the position and orientation of different detectors by precise assessment of the alignment parameters. Thus, by having a better geometrical knowledge of the system, one can reconstruct track by knowing the change in the values of alignment parameters with time, so able to monitor the stability of the structures.

3.1 Applications

Alignment of tracking detectors - When a charged particle crosses a tracking detector, energy gets deposited in some sensitive elements of the detector, resulting in the collection of position measurements. These measurements have to be located in space so that we get to know the accurate relative position of all the detector elements for the reconstruction of particle trajectory. But because of some bias on measured position which results in degradation of tracking performances, we need alignment parameters precise assessment. For example, a track-based alignment system is used, to measure the amount of misalignment, by reconstructing charged particle tracks using potentially misaligned detector. This technique is superior to that of intrinsic detector resolutions working at smaller levels.

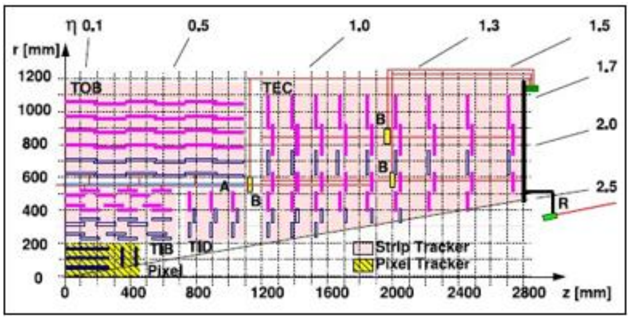

Figure 3: Alignment of the CMS tracking detectors by muon metrology method **[16]**

Stability monitoring of historical buildings - This is another example of large structures stability monitoring. The limiting factor in this technique is that it takes a few days for the collection of proper data. But in this case, it will not be a problem. This method has been used at the vaulted roof of the Palazzo della Loggia, Brescia, Italy. Its idea is that, for a set of tracking detectors, to study the structural changes of the whole building, relative change in their alignment over time can be used. It uses the highly penetrating nature of the muons. To study the resolution of the parameters of interest for a given sample, the estimation was repeated several times.

4. Muon Tomography

The muon tomography technique was proposed by a Los Alamos group in 2003. They observed that cosmic muons like all other charged particles get deflected while crossing a given material. For a particle having momentum (p), the scattering angle (σ_θ) is given by,

$$\sigma_\theta \simeq \frac{13.6\ MeV}{pc}\sqrt{\frac{X}{X_0}} \qquad (1)$$

Where X is the thickness, X_0 is the radiation length and σ is the width of the distribution.

By measuring the scattering angle one can reconstruct linear scattering density (LSD) of unknown material, which is the product of atomic number (z) and density (ρ). For cosmic muons the scattering angle distribution is not Gaussian because of its non-monochromatic nature.

The distribution when taking the momentum spectrum of cosmic muons into account,

$$\frac{dN}{d\theta} = \frac{1}{b\sqrt{2\pi x}\,\lambda} \qquad (2)$$

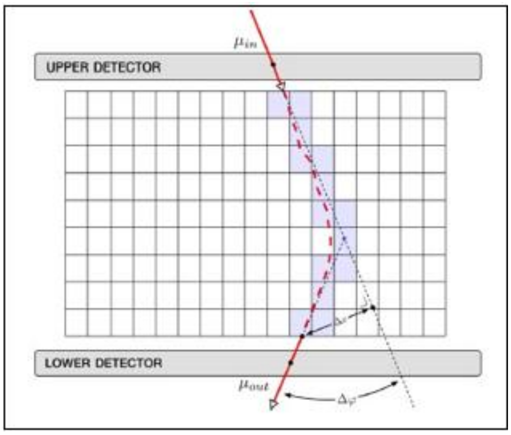

Figure 4: Principle of muon tomography **[2]**

4.1 Applications

Transport Control – The first application of MCS tomography was proposed by the Los Alamos group to contrast nuclear contraband by detecting heavy metals in containers and trucks. A famous portal is in operation in Freeport (Bahamas) which is based on drift tube technology. Some others are under construction in Catania, Italy **[13]**. Once a container is placed inside the portal, the controls must provide a reliable response in a very short time without delaying the transport chain.

Figure 5: Large area detectors for scanning of commercial trucks **[17]**

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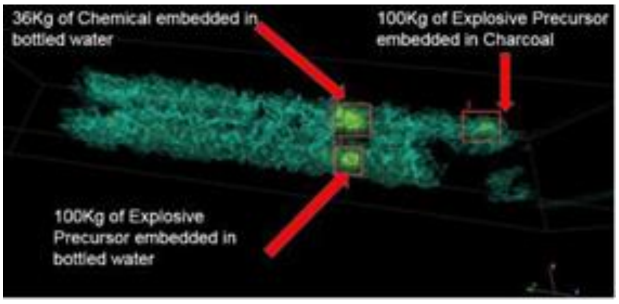

Figure 6: Three-dimensional image of scanned materials inside it **[17]**

- **Nuclear waste –** The inspection of dry storage containers involves plenty of activities **[14]**. Till now we haven't found any perfect method to probe the storage content without opening it. By placing cylindrical detectors around the lateral end, information about the direction and position of the particles entering the container can be obtained. The position and direction of the exiting muons crossing the lateral surface of the container can be measured by the detectors.
- **Monitoring of building stability** – The historical building can use tracking detectors for static monitoring of buildings deformation with long scale time. Using a specific measurement system, the wooden vault of "Palazzo della Loggia" in Brescia has been monitored. The target detector shipment relative to the muonic telescope is monitored continuously by the cosmic muons traversing both detectors. The expected precision in this way is of the order of a few millimeters with a couple of weeks for observation, for simulation purposes. To see seasonal deformation and to detect general deformation trends, the precision should be good enough.
- **Plenoptic Assisted Tomography –** In this method MMTs (Mini-muon trackers) are used in time coincidence with the object and the scattering angles of the incoming and outgoing muons are measured. This process can be used to create high-resolution images as compared to traditional tomography by binning the muon in 1 cm increments after projecting the depth value of a muon's position to a certain plane that is parallel with the detector faces.
- **Barrel Testing -** Done by the University of New Mexico, in which a concrete-filled barrel is kept between two MMTs. Having been unsure about the exact content of the barrel, they decided to measure and see if they could identify the contents. A rotation approach was used for imaging that consisted of rotation post-projection. In practice, for the traditional muon tomography technique, we need many angles to fully reconstruct a cylindrical object. But using depth projections in this plenoptic method, we get a significant amount of resolution with less data.

5. Summary

Even if cosmic ray muons were discovered a century ago, their incredible properties remain helpful in exploring our knowledge of nature and the universe. They have been used as probes to identify many new particles and establish their properties. Usually, various particle detectors and experimental devices dedicated for nuclear and particle physics get calibrated using muon beams. But in the last decade, the recently emerged fields like muon radiography, muon tomography, and muon metrology have added new dimensions to the areas of research related to muon technology.

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Author Profile

Dr. Nitali Dash has been an Assistant Professor at the Shailabala Women's Autonomous College (SBWC), Cuttack since February 2023. She obtained her PhD from Bhabha Atomic Research Centre (BARC) in 2016 and did Post-Doctoral work at the Institute of High Energy Physics (IHEP), Beijing; CETMS, SOAU, and HRI, Allahabad. She has in collaboration with neutrino experiments INO, India; Daya Bay Reactor Neutrino Experiment, China; Deep Underground Neutrino Experiment (DUNE), Fermilab; Hyper Kamiokandae Neutrino Experiment (HK), Japan at the national and international level respectively. She has published more than 20 articles in peer-reviewed Journals, among them 2 in PRL with a total of citations more than 600. Her areas of interest include neutrino physics, dark matter, and Astro-particle Physics.

Prof. Manasi Goswami, is currently a Senior Professor in Physics at the Department of Physics, Regional Institute of Education (NCERT), Bhubaneswar. After getting a PhD degree from the University of Delhi in Nuclear Physics she is engaged in teaching and research at NCERT. She has published near about 20 research papers in Physics and 5 research papers in Science Education in Internal Journals. She is also a popular science writer and has received a National Award from DST, Govt of India for her popular writing in. 2019. She has written a few text books and reference books in Physics. At present, she is the Dean of Instructions at RIE Bhubaneswar.