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Experiments on muon radiography with emulsion track detectors

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Abstract. Muon radiography is a method of study the internal structure of large natural and industrial objects based on sensing an object with a flux of cosmic muons with their subsequent registration and analysis of the pattern of their dispersion, or conplete (or partial) absorption.The Lebedev Physical Institute of the Russian Academy of Sciences and the Skobeltsyn Institute of Nuclear Physics of Moscow State University have started a series of muon radiography experiments with nuclear emulsion detectors. As a result, the optimal conditions for experiment arrangement have been determined, algorithms of data processing have been worked out, and peculiarities of the method have been ultimately investigated.

1 The muon radiography method applications

Interest to the application of muon radiography (MR) for the purposes of the Earth sciences arose soon after the discovery of cosmic rays and, in particular, the cosmic muons. It is conditioned by the fact that the comic muon flux is sufficiently significant and stable in the cosmic radiation, and in addition, the cross section of the particle interactions at typical energies makes them the perfect agent for the tomography method, as they are able to cross hundreds of meters of rock with the absorption proportional to the traversed substance thickness [1]. Muon radiography applies the same basic principles as medical radiography, namely absorption of the beam (muon instead of an x-ray) crossing matter (rock or constructional material instead of living tissue) and registration with a sensitive device (detector). Advantages of this method are its non-invasiveness, i.e. no damage of the object material, and the natural source of radiation. Since muon is a charged particle, its detection occurs directly and is not associated with additional technical difficulties. Muons of cosmic rays with an energy of 1 TeV has path of 8.6 km water equivalent, what makes muon radiography applicable to the objects even a kilometer in size, with the prerequisite of their location above the detection level, because of the experiment specificity.

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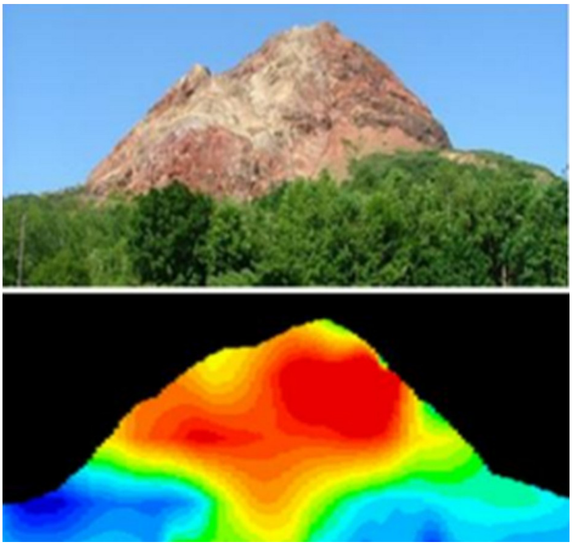

Figure 1. Radiographic image of the volcano Showa-Shinzan (Japan) below a volcanic crater floor. Top – the volcano external appearance; bottom – the density distribution of the breed in a vertical plane passing through the peak. Height of the object is about 1 km; size of detector is 0.4 m^2; exposure time is 60 days; resolution is about 50 mrad [6]

The most actual applications of muon radiography are geosciences [2, 3], geological exploration and mining research [4], alternative method of seismic research [5] and volcanology [6–10] (information about volcanic orifice and lava movement, see Fig. 1).

In addition, the method of muon radiography can be applied for nondestructive testing of massive industrial structures (bridges, dams, blast furnaces, etc.) [11] and for imaging of large archaeological objects. The first archaeological application on the method was performed in the 70-ies of the last century in an attempt to detect a hidden camera inside the body of one of the Egyptian pyramids (pyramid of Khafre) [12] and proved its feasibility and applicability, although the studies didn't show any presence of additional cameras. Using the similar approach with special emulsion photographic plates, in 2016 the international team of scientists received the first "muonographic" picture of the internal structure of the so-called "broken" pyramid of Sneferu (Bent Pyramid), the oldest pyramid of Ancient Egypt, and found in its body previously unknown secondary camera (camera 2 on Fig. 2) [13]. Located at the royal necropolis of Dahshur (around 26 miles from Cairo), this particular structure may be older than even the Great Pyramid, and is believed to be constructed by Old Kingdom Pharaoh Sneferu (circa 2600 BC).

Lately, the capabilities of muon radiography for nuclear reactor monitoring were actively developed [14, 15]. The need for such a research became apparent after the devastating accident at the Fukushima-1 nuclear power plant in Japan [16, 17] (see Fig. 3).

The muon radiography method modification can also be used for control over nuclear materials hidden in luggage or vehicles [18, 19].

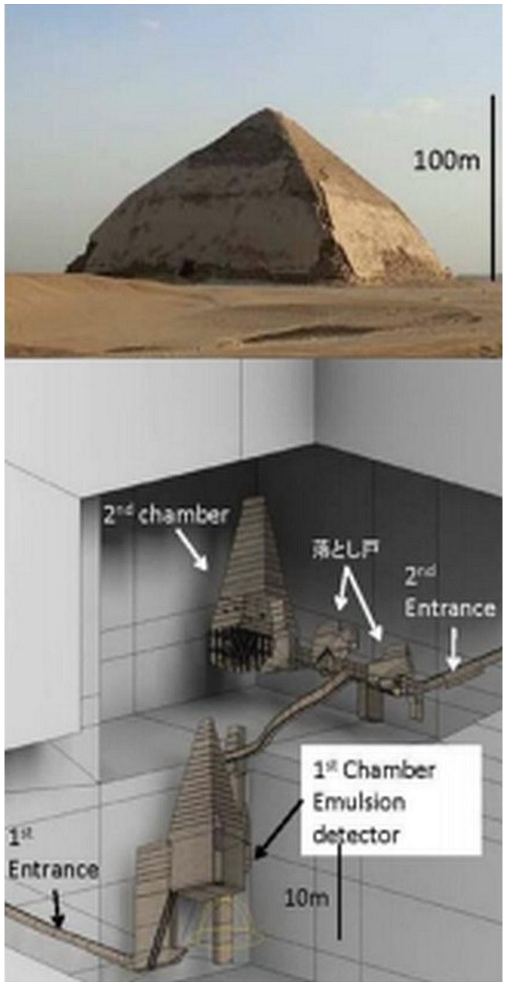

Figure 2. Observation of Bent Pyramid (2015-2016). General view and the scheme of muon detector inside the pyramid

2 Application of the emulsion track detectors in the muon radiography

In the world practice, studies of the internal structure of large objects by the muon radiography method is carried out either with electronic instrument, [21–24], or with track detectors on base of nuclear emulsions [25–27] (see Fig. 4). Electronic devices used for MR are typically rather bulky and difficult to operate. In contrast, emulsion track detectors are of small dimensions and simple construction, and currently have the high spatial (<1 μm) and angular (~ 1 MDA) resolution, large information capacity, ease of transportation and application in complex conditions (such as volcanoes or nuclear reactors). In addition, the most important advantages of nuclear emulsions are their independence from power supply sources and no need for on-line electronic reading systems. The detector size and number of emulsion layers are determined by the desired sensitivity of the experiment depending on the expected angular and linear dimensions of the studied object.

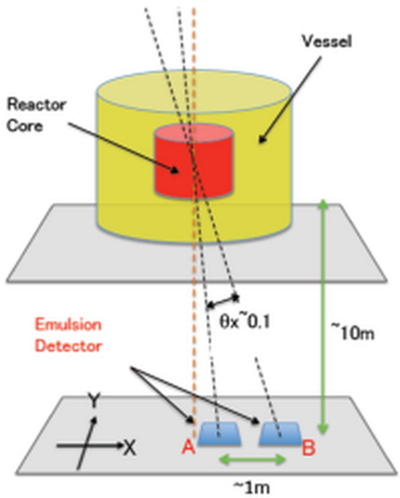

Figure 3. Scheme of the successfully implemented experiment with the "muonographic" inspection of a nuclear reactor Joyo (Japan). The diagram shows the placement of emulsion detectors to inspect the condition of an operational reactor using muon radiography [20]

In previous ten years in many countries (Japan, Italy, Switzerland, Canada, etc.) a significant number of projects for different massive object study with muon radiography method with the use of emulsion track detectors were performed. This approach became possible due to development of automated methods for emulsion data processing and the creation of high-speed scanning apparatus [28–31]. In Russia, the experiments of this type were not carried out up to date, in particular, because of the lack of a reliable manufacturer of nuclear emulsions. However, in the last years, the production of nuclear emulsions with characteristics required for the registration of relativistic particles was established in the Russian company "AVK Slavich" in Pereslavl-Zalessky, Yaroslavl region. It allowed the researches from Lebedev Physical Institute of the Russian Academy of Sciences (LPI) and the Skobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU) to carry out the test experiments on the method application.

3 Test experiments in Russia on muon radiography method with the use of emulsion detectors

The LPI and SINP MSU research groups have carried out a number of test experiments with the aim of implementation of muon radiography method on base of emulsion track detectors. The object of the first study was a steel column of 23 tons (magnet yoke of SINP MSU cyclotron) used as a massive absorber of atmospheric muons creating a "shadow" in the particle flux (Fig. 5). In the experiment there were used emulsions of two types: the emulsions produced by Russian company "AVK Slavich" and the ones of Japanese company Fuji Photo Film analogous to those applied for the international experiment OPERA [32]. Detectors installed in the body of the steel column and outcide were exposed for 49 days.

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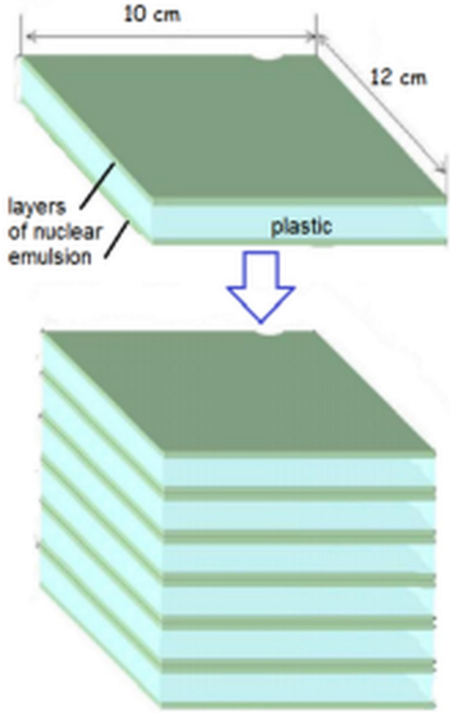

Figure 4. Scheme of a nuclear emulsion track detector

The exposed emulsions were analysed on automated measuring facilities available in LPI [33] and SINP MSU [34] equipped with optical tables of high accuracy and digital high-resolution cameras for recording and digitizing optical images and providing a high scanning speed of nuclear emulsions.

Result of each emulsion plate processing was a data array defining trajectory of each particle registered in the detector by its zenith and azimuthal angles applied in this technique. The data obtained in the automatic processing are subsequently subjected to the procedure of subtraction of the background tracks accumulated in the emulsion storage and transportation. The angular distribution of the registered muons obtained in the first test experiment demonstrated variations of muon fluxes coming to the detector in the different selected angle ranges, corresponding to the different path length in the iron absorber (column).

The second test experiment was held in the Institute of the tire industry in Moscow, the exposition of detectors was 135 days. The monitoring objects were the 40 tone steel wheels of a tire dino rollers (Fig. 6). The scheme of the emulsion track detector assembling was identical to the previous experiment, one detector included three packs with two emulsion layers in each.

Fig. 7 shows the experimental angular distribution of muons obtained in the detector located directly under the steel wheel surface. The result presentation was performed with the tangents of track angle projections

$$t_x = \frac{dx}{dz} = tg\,(\theta)\cos(\varphi)$$

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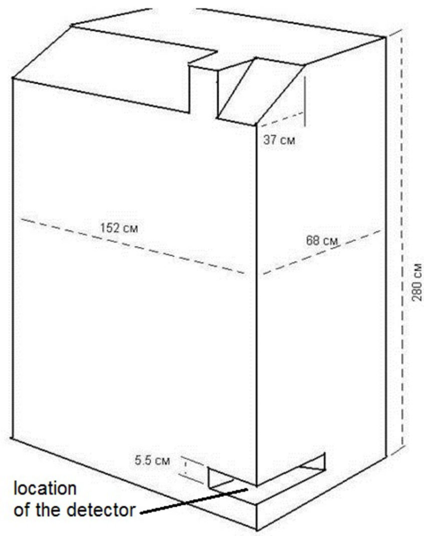

Figure 5. Steel column (part of a cyclotron) as a muon flux absorber. Location of the detector inside the column is shown

Figure 6. The object of study by MR method – a massive steel wheels of a tire dino rollers (40 tonnes, 3m in diameter). Arrows indicate the location of emulsion track detectors

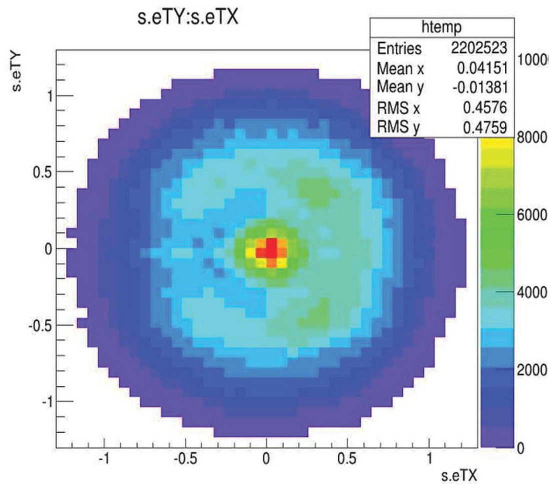

Figure 7. The angular distribution of muons registered in one of the nuclear emulsion detectors after their passage through the object (steel wheels of a tire dino rollers)

and

$$t_y = \frac{dy}{dz} = tg\,(\theta)\sin(\varphi)$$

the on the planes xz and yz, respectively. In this coordinates the obtained picture becomes close of the object photo image in "muon beams". The distribution presented on Fig. 7 clearly shows the "shadow" from the steel wheels.

The third experiment on the muon radiography method was set up at a depth of 30 m in the underground mine located on the territory of the Geophysical service of Russian Academy of Sciences in Obninsk. The experiment was aimed at registration of attenuation of the atmospheric muon flux by comparing the readings of detectors on the earth level and at a depth in the mine after muon passing through the soil layer. In the number of the experiment tasks there was included the possibility of the detection of a hollow in the surrounding soil (vertical elevator shaft) with a help of detector located at a depth of 30 m. In the direction to the elevator shaft (angles $\theta \sim 25°$ and $\varphi \sim 135°$ in the coordinate system indicated in Fig. 8) the absorption of muons is weakened by the presence of the cavity, and hence the flux of muons coming to the detector from this direction should significantly exceed the incoming one from other directions.

In order to determine the optimal exposure time sufficient to obtain the necessary information the detectors were exposed for different periods (2 and 4 months). The obtained experimental distributions of muons traversing the detector exhibited at the depth of 30 m within 4 months is shown in Fig. 9a. For comparison, Fig. 9b shows similar distribution obtained in the model calculations using GEANT4 toolkit [35].

To select signal muon tracks accumulated in the emulsion during the experiment from background ones, the background averaged over the azimuthal angle φ was subtracted from the original distribution (tx, ty). This method gives a better presentation for the difference in track density. The distribution in Fig. 9a clearly shows the signal from the elevator shaft (highlighted with a white frame). As well, the signals from other inhomogeneities in the soil layers above the detector are clearly seen in the picture. Peculiarities in the center of the distribution are associated with the presence of a lense of

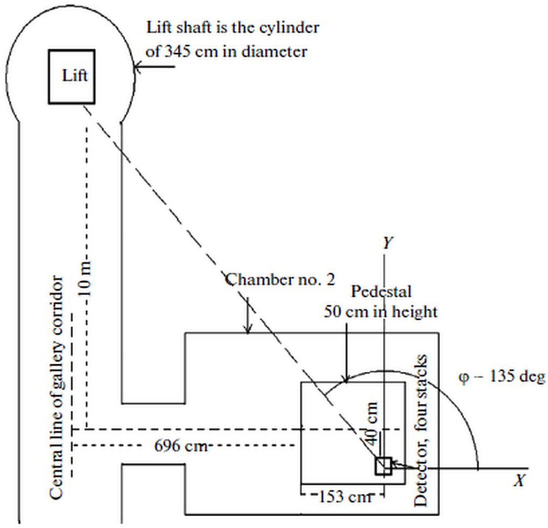

Figure 8. Scheme of relative location of elevator shaft and underground detectors (top view). Orientation of x and y axes in the detector system and the direction to the elevator shaft are shown

marble-like limestone around the geophysical mine. In the model calculations the specificity of the surrounding soil was also taken into account, as sown in Fig. 9b.

4 Conclusions

The analysis of the results obtained in muon radiography test experiments indicates that the emulsion track technique allows to obtain reliable data on the structure of investigated objects. The experimental data are in accordance with the predictions of the model calculations. The possibility of development of muon radiography in Russia is demonstrated using the emulsion track detectors of the proposed design and emulsion data processing facilities available at Russian institutes.

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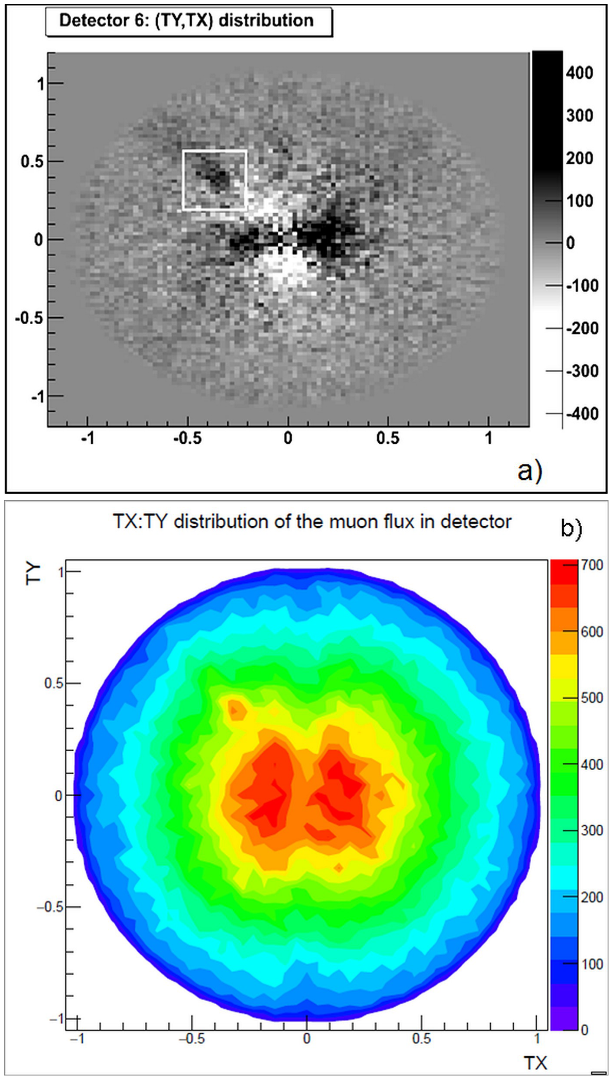

Figure 9. (a) 2D distribution (tx, ty) of muon flux at a depth of 30 m after subtracting of background, averaged by angle φ; the white square frame marks out the imprint of elevator shaft. (b) The same distribution, obtained in model calculation.

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