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Portable tracking detector for cosmic background measurements

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A precision measurement of underground cosmic muon flux has relevance in various applications. It may reveal underground structures such as ores of increased density or an empty cavern, and it is a key quantity for proposing underground low-radiation experiments. As an example of the latter, the cosmic muon flux has been determined at a new experimental facility under construction in Felsenkeller, Dresden, Germany. Concerning the former applications, we investigate the required precision of cosmic muon flux measurements. A Monte Carlo simulation has been applied to quantify the multiple scattering of muons in standard rock and the required angular resolution of tracking detectors. We found that a typical 20 mrad angular resolution is sufficient to study structures of cavities smaller than 8 m diameter, and smaller cavities or corresponding high density accumulations, will be even more smeared. To verify the simulations, measurements have been performed with the a portable tracking detector at 7.5 meter-soil-equivalent depth in an artificial tunnel system in Budapest, Hungary.

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1. Introduction

The investigation of the reactions of stable and radioactive nuclei require low-radiation background, therefore these experiments are usually located deep underground. An accelerator-based experimental facility is under construction at shallow (50 meter-rock-equivalent) depth underground in Felsenkeller, Dresden, Germany [1–3]. The knowledge of the cosmic background (mostly atmospheric muons) is a key element of the design of the experiment.

Cosmic background measurements have been performed by a Close Cathode Chamber-based [5, 6] tracking device [7–10] at the beginning of 2013. The cosmic muon flux measurements covered the full 2π solid angle of the upper hemisphere. The muon telescope was reliably operated and 477k muon track have been collected during the measurement period of 44 days. The cosmic muon flux is plotted in Fig. 1 and its maximum value was found below 2.2 m^{-2} sr^{-1} s^{-1}. The higher flux were measured in the direction of zenith and the entrance of the tunnel to West. The description of the first prototype of the detector and our measurements in Felsenkeller underground laboratory are presented in Ref. [4].

In this paper, we are focusing on the quantification of the angular resolution limit of tracking detectors to be used for underground cosmic background measurements. Practical uncertainties of angular distribution are originated from the multiple scattering of cosmic particles across the rock. The effect has been quantified by Monte Carlo simulation and verified by our measurements. The results provide information for the design of tracking detectors which are dedicated for cosmic background measurements in underground laboratories.

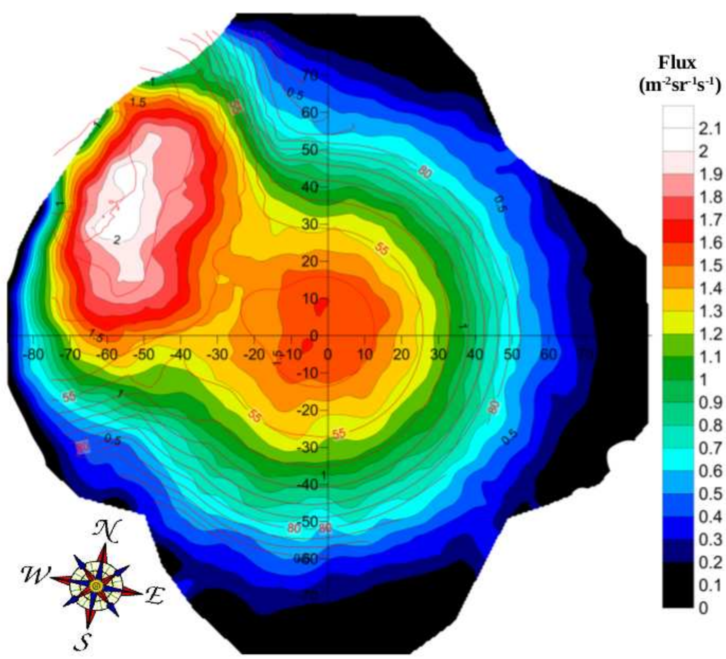

Figure 1: Cosmic background measurements cover the full 2π of the upper hemisphere at the proposed site for the underground experiment in Felsenkeller, Dresden, Germany [4]. *Red level lines* show the rock thickness which has been obtained by geodesical measurements.

2. Multiple scattering of atmospheric muons in rock

Atmospheric muons are charged particles, as they penetrate into the soil they suffer multiple scattering from the nuclei of the material. The distribution of the scattering angles is approximately Gaussian with the following standard deviation:

$$\sigma = \frac{13.6\,\mathrm{MeV}}{\beta \cdot c \cdot p} \cdot \sqrt{\frac{X}{X_0}} \cdot \left[1 + 0.038 \cdot \ln\left(\frac{X}{X_0}\right)\right] \qquad (2.1)$$

where $\beta \cdot c$ is the velocity of the muon and p is the momentum of the muon, X is the rock thickness, and $X_0 = 10$ cm is the radiation length of rock. Equation (2.1) shows that the slower muons scatters, and more and multiple scattering mainly occurs at the end of the muons' trajectory. Those penetrating particles scatter most which are stopped closely behind the detector.

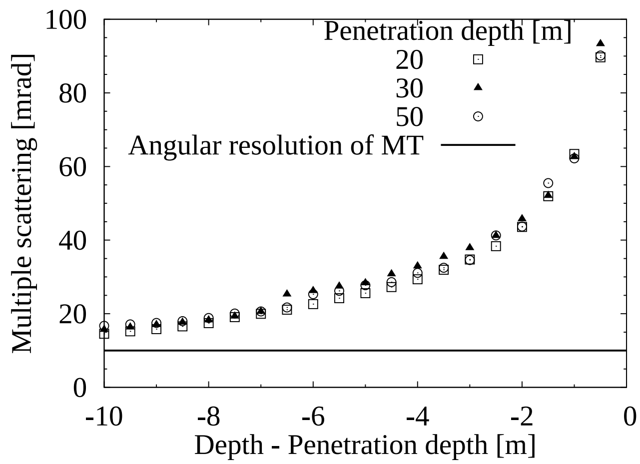

Figure 2: The evolution of multiple scattering of cosmic particles which are stopped at the depth of 20 m (*empty rectangles*), 30 m (*filled triangles*) and 50 m (*empty circles*). The angular resolution of the REGARD Muontomograph (MT) of 10 mrad is well below of the smearing effects which are caused by small size cavities in the detector angle of view.

To quantify the effect, a GEANT4 [11] code has been developed to simulate the penetration of atmospheric muons across the rock. In our case, the CRY [12] cosmic ray generator provides the particle showers ($\mu^{\pm}$ and $e^{\pm}$) as the input for our detector simulations. The CRY can reproduce the measured muon and electron spectra at sea level [12].

Muon and electron showers have been generated within a 300 m $\times$ 300 m area at sea level. Standard rock (Z=11, A=22, and ρ = 2.65 g cm^{-3}) based on Ref. [13] has been implemented in GEANT4 with the thickness of 100 m. The angular scattering has been calculated at each half meter for those muons which could penetrate a certain thickness (penetration depth).

The requirement of a specific "penetration depth" can be translated to a narrow region in muon energy. Evidently low energy muons will scatter more; however they can not penetrate deeper. An interesting result arises if we measure the mean scattering angle as a function of the *difference* between penetration depth and actual depth. Figure 2 shows the evolution of multiple scattering for those particles which are stopped at the depth of 20 m, 30 m and 50 m. The angular resolution

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of the detector should be below the smearing effect of multiple scattering to adequately detect rock inhomogeneities. The angular smearing of 20 mrad corresponds to 8 meter in difference between detector depth and penetration depth; in other words, an 8 m diameter cavity will appear with this image smearing on the cosmic muon flux map. In case of searching for smaller cavities or correspondingly large increases in soil density, it is not relevant to design a detector with much better angular resolution.

3. Direct verification of absorption

To verify the results of Monte Carlo simulation, measurements have been performed by the REGARD muon telescope at 7.5 meter-soil-equivalent with the density of 2.2$\pm$0.2 gcm^{-3} in the Jánossy Pit at the KFKI Campus in Budapest. Concrete absorbers have been deposited on ground level with the density of 2.4 gcm^{-3} and with the size of 6 m^3 and 2 m^3. Data have been taken with/without the concrete absorbers. For each setup, 1.4 M tracks have been collected during 7 days of data taking.

These measurements have also been implemented in GEANT4. To minimize the effect of multiple scattering, the muon tracks have been generated from the detector with the energy of 10 GeV (can penetrate 15 meter-soil-equivalent with the probability of 100 %) and with uniform angular distribution up to $\pm$ 45°.

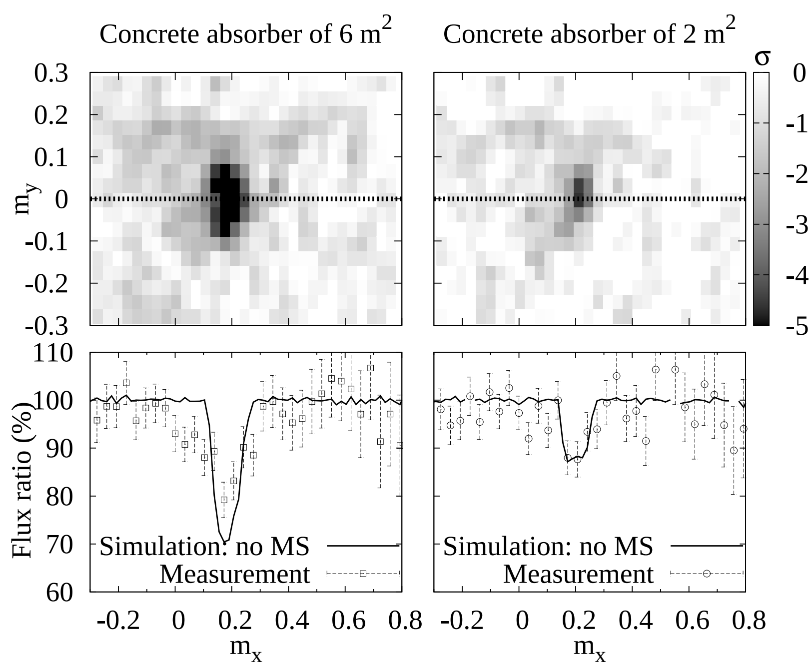

Figure 3: Upper panels: bin by bin difference of the measured fluxes (with and without concrete absorbers) in σ-units shown on grayscale. Lower panels: The ratio of the measured muon flux without absorber and with the absorber of 6 m^2 (*left*) and the absorber of 2 m^2 (*right*) as well as estimated flux change (lines) assuming no multiple scattering.

Figure 3 shows the bin-by-bin difference of the fluxes (with and without concrete absorbers) divided by the statistical error σ-units on grayscale as the function of the slope of track projections, m_x and m_y (*upper panels*) for the absorber of 6 m^2 (*left*) and the absorber of 2 m^2 (*right*) as well as the middle slice (*dashed lines in the upper panels*) of the ratio of the angular distributions are plotted in the *lower panels*. The absorption of muons are well predicted by the simulation and the small broadening is caused by the above-mentioned multiple scattering.

4. Summary and conclusions

Precision on-site measurement of the cosmic muon flux in the full 2π upper hemisphere has been demonstrated at the 50 meter deep Felsenkeller site. The multiple scattering of atmospheric muons have been quantified by GEANT4 simulations. We found that the multiple scattering depends on the size of density inhomogeneity above the tracking detector. The simulations are verified by the measurements which have been performed at shallow depth underground with special well known absorbers. From the presented results, one can conclude for example that if an underground cavity is smaller than 8 m diameter, then due to multiple scattering the absorption image will be smeared by more than 20 mrad.

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