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Exploration of Lunar In Situ Resources Can Be Conducted by Applying Density-Sensitive Cosmic-Ray-Based Geophysical Muon Imaging Method Called Muography

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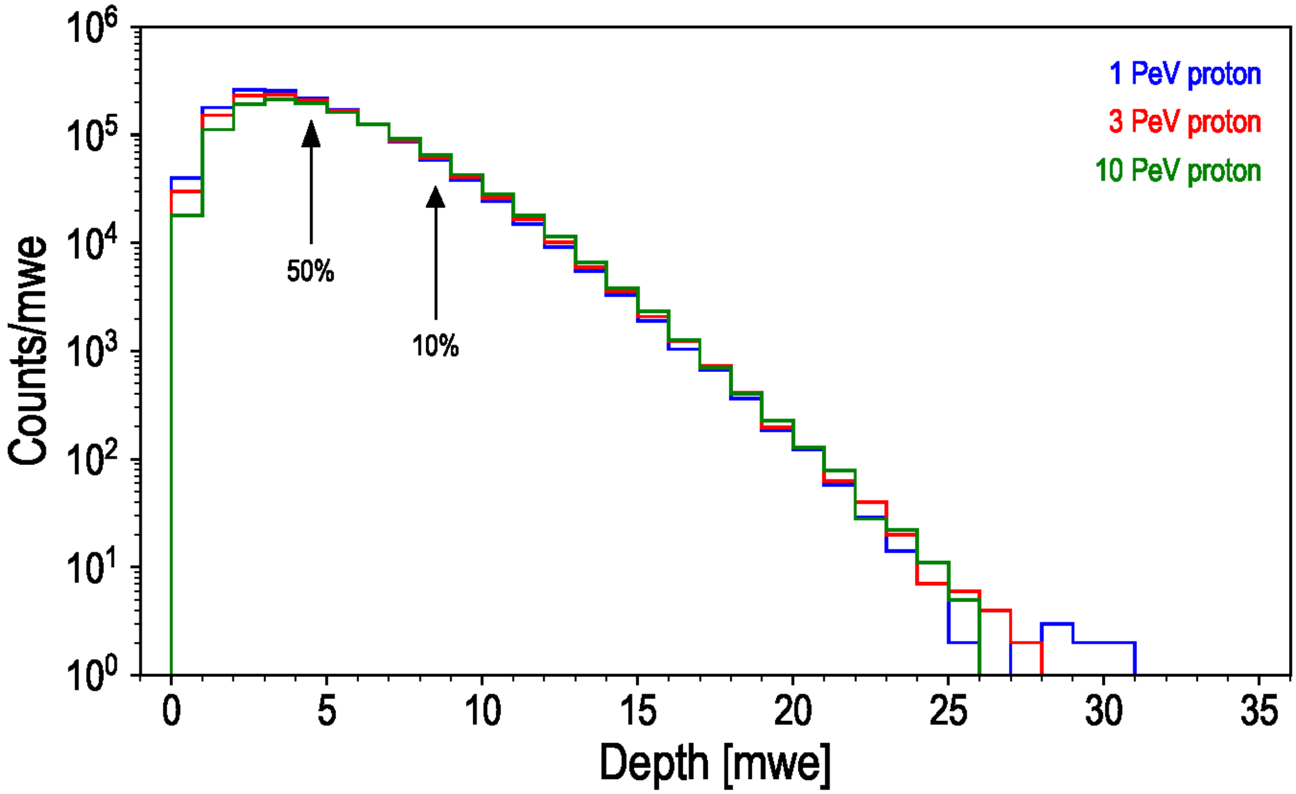
In the future, the mining industry becomes increasingly challenged by the need for applying its state-of-the-art techniques off the Earth. A permanent human presence on the Moon, for example, requires effective new technologies that will enable the in situ resource utilization (ISRU). On the Moon, the ISRU concept targets for developing methods for the exploration and characterization of a wide range of local resources, including water ice, helium-3, oxygen, regolith, and metals. We propose that many of these essential resources are related to density anomalies (e.g., high water content, high porosity) and can possibly be detected and mapped by a novel geophysical density imaging method called muography.

On Earth, muography is based on the detection of muons that are constantly produced in the interactions between air molecules and primary cosmic rays. The attenuation of muon flux is measured after the particles have passed the object, such as a volcano or a large body of rock (e.g., measurements are performed in caves or tunnels). The measured muon fluxes from different directions are finally translated to 2D or 3D density models based on the fact that high average densities reduce the flux faster than those of low. However, as the Moon has no atmosphere, lunar muography requires that muons are produced in the interactions between primary cosmic-ray particles and the uppermost parts of the lunar soil. Our preliminary results suggest that muons are indeed generated in the uppermost lunar soil. Hence, muography would work on the Moon.

Furthermore, and perhaps surprisingly, the energy appears to have only a small impact in the production depth of muons. This is illustrated in the figure, which shows the muon production depth distributions for three different selected primary cosmic-ray particle energies in petaelectron volts (PeV). Note the logarithmic scale in the vertical axis. The unit of the horizontal axis is mwe (meter water equivalent), which is a common reference in these types of particle physical simulations (1 mwe equals 1-m-thick column of water). For other materials, such as for high-porosity lunar regolith, the absolute depth is obtained by dividing the mwe depth with the density of the material (i.e., for the density of 2.65 g/cm^3, the depth of 5.0 mwe corresponds to 1.89 m). The differences in muon counts/mwe in the first meters can also be due to statistical uncertainties. The two arrows indicate the approximative depths where a half (50%) and every 10th (10%) of the produced muons are able to penetrate.

Our next aim is to determine the absolute muon flux as a function of the depth on the Moon. This is work in progress, and as the first step we have used, as shown, protons as primary cosmic-ray particles, water as the target material, and simulated three different primary energies: 1 PeV, 3 PeV, and 10 PeV. The number of simulated primaries were 1,000, 375, and 125, respectively. The zenith angle of incoming protons was selected to be uniform and limited to 75°. Simulations were carried out using the Fluka simulation package.



1 PeV proton
3 PeV proton
10 PeV proton
50%
10%
Counts/mwe
Depth [mwe]