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Theoretical analysis for better understanding Muography

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التحليل النظري للتصوير بالميونات

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Abstract:
Utilizing muons in geoscience has been increase over the last decade. Radiographic imaging using muons, also termed Muography, is relied on the measurement of the muon's absorption, created by the interaction of cosmic rays with the earth's atmosphere, in matter. Muons are considered elementary particles with potent penetrating activity, a privilege that allows them able to cross bodies of dimensions of the order for hundreds of meters. Earlier researches throw a light on practical side for muon particle. Therefore, the current work places an emphasis on establishing a scientific theoretical base for better understanding the mechanism for muography. Accordingly, it will participate in innovating tools for accurate, safe, and professional muography. Herein, we aim to clarify the physical characteristics for muon particle, and how it is preferable compared to other techniques. The theoretical analysis has been performed to elucidate the interaction between the substance and muon from the physics' point of view. Moreover, systems and principles of muon imaging innovation, explanation of muon's creation, lifetime, distance, interaction, physical characteristics, and applications of muons in Geoscience are explained. Taken together, we aim to realize the basic mechanisms to get clear muon radiography with focusing on theoretical advantages for muography in comparison to traditional radiations.

Keywords: Muography ,Muon ,Cosmic Rays, Geoscience ,Muon Imaging

الملخص
شهد استخدام جسيمات الميون في علوم الارض تطورا ملحوظا خلال العقد الاخير . ويعتمد التصوير بالميونات (Muography) علي قياس امتصاص جسيمات الميون الناتجة عن تفاعل الأشعة الكونية مع الغلاف الجوي للأرض أثناء مرورها خلال المادة. وتتميز جسيمات الميون بقدرتها العالية علي اختراق الاجسام الكثيفة، مما يجعلها وسيله فعاله للتصوير غير الاتلافي .يهدف هذا البحث الي تقديم تحليل نظري يوضح الخصائص الفيزيائية لجسيم الميون والية تكوينه وتفاعله مع المادة، اضافه الي توضيح المبادئ الأساسية لتقنية الميوغرافيا ومقارنتها بوسائل التصوير التقليدية مع استعراض اهم تطبيقاتها في علوم الارض.
ويسهم هذا العمل في توفير أساس علمي يساعد في فهم هذه التقنية ودعم تطوير تطبيقاتها المستقبلية.

الكلمات المفتاحية: التصوير الميوني، الميون، الأشعة الكونية، علوم الأرض، تصوير الميون.

Introduction

Muon imaging is an eminent non-invasive practice manipulating cosmic ray muons to explore dense objects' internal structure. Muons are elementary particles formed by interaction of cosmic rays with atoms in the atmospheric earth, producing hundreds of secondary particles which can travel at closely the swiftness of light, reaching the ground, and then crossing broad thicknesses of matter. This continuous release muonic particles remarks them extremely effective for penetrating dense materials, usually impermeable compared to other kinds of radiation, like X-rays (Zhang et al., 2020; Pezzotti et al., 2025; Zhou et al., 2025).

Such novel technique, muon imaging, named “muography” is used for safe imaging of internal structures and applied for a range of fields involving geophysics to archaeology to nuclear safety (Giammanco et al., 2025). Muography is a pioneer geophysical protocol that permits the evaluation of density distribution inside large objects via monitoring the travelling of flux of cosmic muons which precisely detect density abnormalities that might show cavities (Rábóczki et al., 2025). The muographic practice is designed for imaging the central of a body, releasing the highest penetration bulk of cosmic muons (Zhang et al., 2020; Lechmann et al., 2021). There are two diverse techniques are presently stated to as Muography and have a function of computing the density of the target object including absorption Muography and deviation Muography. In absorption Muography, the reduction of the muon flux is accustomed to calculate the muons’ absorption into matter. The calculated number of muons is used to get scatter plot with two-dimensions of the density of a target capacity. Deviation Muography is generally aimed to recognition of high-density materials in small-sized objects and is predicted on the numerous Coulomb scatterings practiced by muons when crossing through matter (Mahon et al., 2019; Vanini et al., 2019).

Muography grants a recent way to understand inside objects’ multitude (Adam 2021). This study clarifies that muons are created higher in the atmosphere when cosmic rays (almost protons) crash into the oxygen’ nuclei, nitrogen, and other air gases. Such collisions yield subatomic unstable particles named pions, which mostly immediately degenerate into muons (200 times the mass of an electron). The muons pounce within the atmosphere like the speed of light, and attack Earth’s surface at a speed of 10,000 per square meter per minute.

From physical point of view, muons lose energy to adjacent electrons when the muons penetrate through matter. Once a muon loses majority of its kinetic energy, it decelerates and lastly degenerates into electrons and neutrinos. The denser the matter when muons pass through dense matter, it results in swift loss of its energy, and more efficient absorption of muons. Consequently, muons can be utilized to construct an image depending on the density contrast inside the matter over which the muons have conceded (Georgadze, 2024; Autran and Munteanu, 2024).

Imaging of cosmic ray muon signifies a non-intrusive geophysical discovery practice initiated upon the penetration characteristics of ordinary high-energy muons. Muons are species of leptons, display diverse properties: large mass (approximately 207 times that of an electron), notable penetrability (permitting them to cross kilometer-scale rock developments), and widespread normal origins (being the harvests of cosmic rays that interact with the Earth’s atmosphere (Hivert et al., 2017; Oláh et al., 2019; Beni et al., 2023). In the land of mineral detection, via the statistical investigation of the flux diminution of muons consequent to their dispersion through the target matter, by mixing inversion algorithms with Monte Carlo simulation, this permits to construct high-resolution 2D to 4D (involving the temporal dimension) density profiles. This, sequentially permits for the accurate recognition of subsurface voids, fault zones, ore bodies, and other structural differences. Imaging of cosmic ray muon offers numerous privileges when compared with old geophysical approaches (such as seismic protocols and gravity). These involve a deep-detection capacity which discover dense rock masses situated over 1000 m below the surface), eco-friendly, the disappearance of non-natural radiation sources, and the power to carry out dynamic monitoring (Malmqvist et al., 1979; Gosse et al., 2025).

Research Problem

Despite the rapid development of muography and its increasing applications in geoscience, most published studies have focused on practical applications, while limited attention has been given to presenting a comprehensive theoretical explanation of the physical principles governing muon generation, propagation, interaction with matter, and imaging mechanisms. Therefore, this study aims to establish a theoretical framework that provides a better understanding of muography and highlights its scientific advantages over conventional imaging techniques.

Muography in comparison to other techniques

Muons are characterized by more potency compared to than to other particles such as electrons owing to existing constraints (Accettura et al., 2023). Saracino records that muography is better related to other methods, like ground penetrating radar (GPR), for scrutinizing underground, as muography can be utilized to explore more into speciously solid objects. Muography can easily scan substances over tens of meters of solid rock, while GPR frequently scuffles to search beyond a limited meters in numerous soils. Also, it is muography is a passive practice with no required equipment to create the sign to be examined. Detectors can be connected and directly kept to collect data, this in turn lessens costs (Cimmino, 2019).

Gaisser protocol is considered the most basic theoretical model, which does not take into consideration the curvature of earth and the diminution of the muon flux along the atmosphere (Gaisser, 1990 and Zyla, 2020) and articulated in terms of the Equation (Lechmann et al., 2021).

Systems and principles of muon imaging innovation:

A recent study clarifies the systems and principles of muon imaging technology. Such report reveals that imaging of cosmic ray muon is a practice that influences obviously going on cosmic ray muons to recreate subsurface density structures, with specific appropriateness for discovering dense ore bodies contrary to lower-density host rocks. This is for the reason that muons can pierce deep sub-surfaces to travel numerous kilometers with expectable attenuation (Zhou et al., 2025). Muons are produced by occurrence of interactions between atmospheric nuclei and primary cosmic rays to reach sea level with well-distinguished characteristics: a flux of around $I \approx 1$ muon/ (cm2 · min), a relative spectrum of energy and a consistent angular dispersal (peaking at vertical incidence, resulting a $\propto \cos2\ \theta$ trend). When crossing materials, muons interrelate via two chef mechanisms that summarize imaging:

• Based on the Lambert–Beer law Intensity attenuation through ionization: this generates a calculable link between material density and muon flux reduction.

• Coulomb scattering for trajectory deflection: Deflection angles is based on the material's the muon's momentum p and atomic number Z, coding differences in structural density. Specific detection systems involving nuclear emulsion detectors, scintillator detectors, Cherenkov detectors or gas detectors organized in multi-layer "telescope" structures attain data on muon trajectories, loss of energy, and timestamps. Following preprocessing including trajectory reform, standardization, and background deduction, the data are handled using any of the following:

• Transmission tomography: Overturning density evidence by explaining the linear system $A\rho = L$;

• Scattering tomography: Deriving density gradients from estimated deflection angles. This work produces 3D density disseminations of targets and related ambiguity maps.

Explanation of muon's creation, lifetime, distance, interaction, and physical characteristics

Creation of muons derives from pions. Pions ($\pi +$ and $\pi -$) comprise of a quark and an antiquark and consequently, a meson. Pions are the lightest mesons and the lightest hadrons. They are formed from the collision of particles and cosmic rays in the upper atmosphere. Pions are unbalanced and have a lifetime around $2.6 \times 10-8$ s. They will primarily decay into muon and antimuon using this equation (Vasiliev, 2019).

$$\pi + -\longrightarrow \mu + + \nu\mu \qquad (1)$$

$$\pi - -\longrightarrow \mu - + \bar{\nu}\mu \qquad (2)$$

Muons are created by pions in the atmosphere at about 15km from the surface of the earth and such phenomenon is named "The Muon Paradox (Rauniyar and Agrawal, 2023). They are characterized by a lifetime of $\tau \approx 2.197 \times 10-6$ s (Wang et al., 2025). The lightest and most firm particles create the primary generation; however, the heavier and less firm ones fit to the secondary and tertiary generations. All the constant matter we can detect in the world is made from particles that is related to the initial generation, meanwhile the heavier particles will rapidly decay to a more stable type. The muons are considered parts of the secondary generation.

The distinct relativity and calculation the muon's distance are based on Haboury and Galantay, (2020). It includes the initial method to estimate the distance that the muon travels to the ground using the Newtonian dynamic. Considering the theoretical lifetime τ and the speediness of the muon is the speed of light. This study detected the distance d by which the muon travels: $d=c\tau \approx 660$ m. Muons are formed in the atmosphere at about 15km from the earth. Regarding special relativity, this report considered the dilatation of time and the notion of contraction of space.

The chief physical procedures of the interaction in-between muons, considering them charged particles, and substance involve the energy degeneracy because of interactions of particle with extranuclear electrons of the substance. Such process has been defined in Equation (Bouteille et al., 2016). Also, it contains Multiple Coulomb scattering induced by the interaction with the matter's atomic nuclei. Multiple Coulomb scattering is the key reason for the muons' deflection once they cross material media. When muons circulate through matter, every interaction with the matter's atomic nucleus will induce muons' small-angle deflection. This deflection induces the occasion muons to scatter and travel along haphazard paths. As a collective impact, it finally renders the muons to create a haphazard net deflection from the initial incident way following travelling through the matter. This is also the key reason of the array trailing and energy straying of muons. This physical method can be statistically handled and mathematically defined as a possibility distribution purpose where the deflection angle relies on the traversed material thickness. The angular deflection distribution tracks a nearly Gaussian form by feature of the Central Limit Theorem, with its RMS width detailed in Equation explained by Tanaka (2016). The radiation length could be computed by Equation explained by Schouten and Ledru, (2018).

Muons can identify the dynamic and static magnetic fields within materials to disclose data about their characteristics (Hillier et al., 2022). This can be utilized for noticeable application to magnetic substances, from ionic signal in battery materials (Pérez et al., 2023) via liquid crystals (McKenzie et al., 2013) to chemical responses inside solution (McKenzie and Roduner, 2009). The limited lifetime of the muon (2.2 μs) is considered beneficial in experiments as the resultant β particle is frequently expected to be produced in the muon spin' direction at the immediate of decay (https://www.isis.stfc.ac.uk/Pages/muon_flyer_general.pdf#search=muon%20flyer).

The magnetic fields within the sample can be contingent from the alteration in spin-polarization from muon implantation to muon decay. Nowadays, majority of muon experiments utilize spin polarized beams with positive antimuons to quantity the magnetic fields in bulk samples (100 mg or more). These beams originate from positive pions decaying at rest in the production target surface, and named "surface muons". The advantages of using the positive muons because they are considered >95% spin-polarized, with a slight momentum spread and normally cease within 0.1–1 mm in utmost materials. Beams originating from pions decaying in flight are termed "decay muons", permitting for lower and higher energies and negative muons as well. Decay muons could be utilized in pressure cells in conditions that a negative muon has a stronger interaction with the sample, or to take the benefit of the X-rays produced by nuclear capture of negative muons to assess the elements the sample comprises. This could be useful for understanding the objects of cultural heritage (Lagrange et al., 2025). All these methods labor with bulk samples, however beams of positive muons can also be qualified to distant lower energies, named "slow muons" with keV before MeV energies (used to explain reedy film materials with a range of 10–200 nm thicknesses) (Alberto et al., 2022).

Application of muons in Geoscience

Creation of muons derives from pions. Pions ($\pi +$ and $\pi -$) comprise of a quark and an antiquark and consequently, a meson. Pions are the lightest mesons and the lightest hadrons. They are formed from the collision of particles and cosmic rays in the upper atmosphere. Pions are unbalanced and have a lifetime around $2.6 \times 10{-}8$ s. They will primarily decay into muon and antimuon using this equation (Vasiliev, 2019).

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Conclusion

This study presented a theoretical analysis of muography by explaining the origin of cosmic-ray muons, their physical characteristics, interaction with matter, imaging principles, and major applications in geoscience. The study demonstrated that muography is a safe, non-destructive, and highly penetrating imaging technique suitable for investigating large and dense structures. Furthermore, it provides a comprehensive theoretical basis that supports future research and contributes to the development of muography applications in geoscience and related disciplines.

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