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Muon Tomography:

Minuscule Particles vs. Objects Larger than Life

BY: MADELINE GREEN

Muons, a sort of "cousin" of the electron, act as a natural and continuous radiation source.

First discovered in 1936 by Carl D. Anderson, muons have the same charge as the electron but are about 200 times as massive. The true magic of muons, however, lies in its applications to reconstruct the insides of large objects, such as pyramids, volcanoes, shipping containers, and even nuclear reactors.[1] Though what muons reveal about an object is otherwise straightforward, how muons are created and the physics of how muons are shot and traced through large bodies leaves much to be understood. Muon radiography and muon scattering tomography are two specialized methods that allow different types of imaging, with the former relying on muon absorption as they pass through an object and the latter on how muons reflect off atoms in materials it encounters. While geological and homeland security applications of muons have been popular experimentally, future research looks toward using muons on an other-worldly scale.

THE BIRTH AND EFFECT OF COSMIC PARTICLES

Muons are formed from cosmic rays by high-energy protons striking the nuclei of lighter elements in Earth's upper atmosphere. By typical Newtonian physics, muons should not be able to reach the Earth due to the speed of its decay. However, due to principles of special relativity, time dilation and the length contraction of particles moving at nearly the speed of light, the muons can actually reach Earth with such high speeds that it can penetrate thick rock, including Earth's surface. Muons are a naturally occurring radiation source and work similarly to X-rays by interacting strongly with the materials it travels through to reveal its internal properties. Unlike X-ray radiation though, muons do not pose any health hazards.

While particles such as lone electrons, positrons, and protons are also created in the cosmic showers occurring in the upper atmosphere, muons are the most abundant at sea level. These "background" particles are a result of decay interactions that continuously birth muons, but these are filtered out by the atmosphere as they travel and lose energy due to stronger interactions with matter.[2] Due to Bremsstrahlung, or braking radiation that depends on inverse mass of the particle, the much heavier mass of the muon makes this interaction's effect 40,000 times smaller.

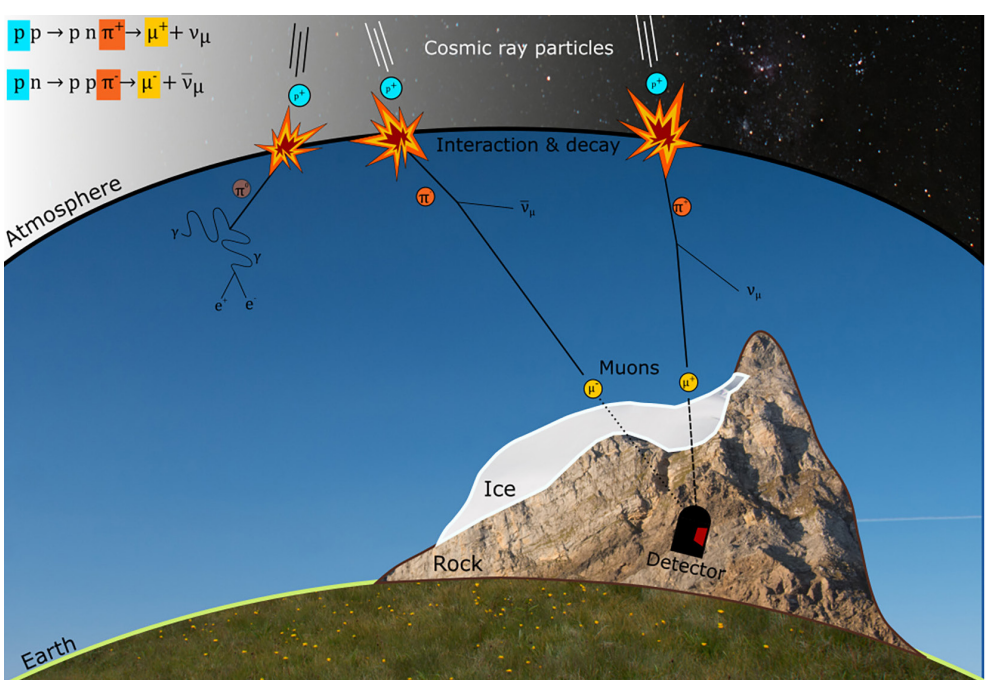


Figure 1: Illustration of the origin of cosmic-ray muons and their interactions with geologic materials. Cosmic-rays made of primarily protons (p^+) collide with nuclei in Earth's upper atmosphere, beginning a cascade of particle decays, including neutrons (n), pions (π^+/π^-), muons (μ^+/μ^-), and muon neutrinos (ν_μ). Muons possess such immense energy and mass that it can penetrate into dense materials, such as ice and rock, and still reach a detector.

When researchers need muons, they can either build them in a lab using particle accelerators or "harvest" them from cosmic rays. Despite the term, atmospheric muons are not actually physically caught and shot through an object. These particles are constantly raining down from the atmosphere and physicists simply measure their flux, or the rate at which they pass through a specific area over time. The type of muon needed is completely dependent on the nature of the job. Cosmic-ray muons have much higher energy than accelerator-made ones, with a range of energies on the scale of GeV (10^9 electron volts) to TeV (10^{12}). This makes natural muons much harder to stop and perfect for penetrating deep into materials. On the other hand, accelerator muons are mainly in the MeV (10^6) range to the low GeV range, stopping sooner when interacting with a material. Because of this extra precision, accelerator-made muons are more often used for biomedical applications.[3]

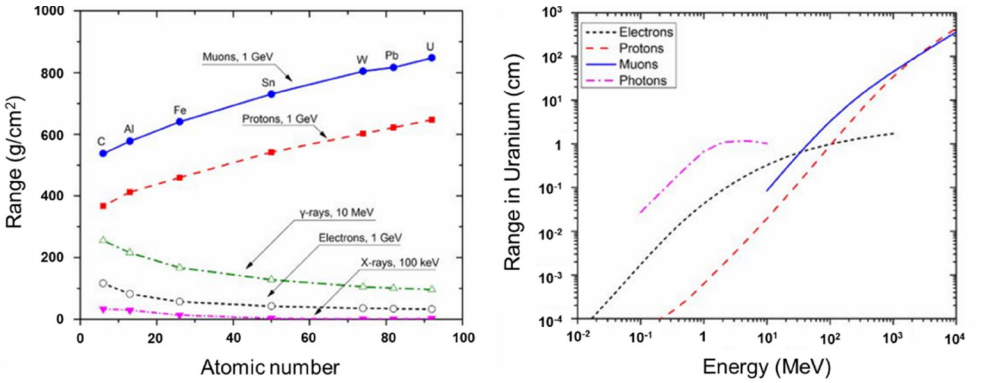


Figure 2: Comparative particle ranges and material penetration depths. Muons are superior in penetration power compared to other common particles used in imaging probe experiments. (Left) Particle range at a constant energy is plotted against the atomic number (Z) of various materials. At a constant energy, muons (dark blue line) maintain a much higher range from lighter to heavier materials. (Right) The penetration range of Uranium is plotted as a function of energy. Electrons (black dashed line) and photons (pink dashed line) begin to plateau in range, where increasing the energy no longer increases its penetration depth. The muon range (dark blue line) continues to scale linearly at high energies.

FROM PARTICLE TO PULSE: PHYSICS & INSTRUMENTATION OF MUON IMAGING

There are two main types of interactions muons have with atoms in a material, underlying the different methods of imaging an object. These two interactions are muon absorption and scattering, which physically occur simultaneously while a muon travels through a material. While both methods allow scientists to discover more about the innings of structures, the difference in techniques arises from what is chosen to be measured.

Muon absorption, otherwise known as muon radiography, has been used since the 1950s to determine depths of ice and to image pyramids and magma chambers.[1] Muons are transmitted or "absorbed" through any material it passes through and loses energy as it travels, resulting in a probability of crossing through completely. The fraction of muons that cross or don't cross through a material depends on the density and the distance the muons travel.[4] Experimentally, the number of muons sent through an object is usually known. By measuring the number of muons received after transmission, the density of a material is solved for. Additionally, by sending enough muons through, there is enough information to build a 2D density map of an object without ever having to physically probe it.

On the other hand, muon scattering tomography relies on the difference in trajectories of muons before and after they collide with atoms of a material. Changes in the muon angle happen thousands of times over the path of an object, resulting in the need for an overall average of angular change.

This change is given by the equation:

$$\theta_{MS} = \frac{13.6\ MeV}{\beta cp} Q \sqrt{\frac{x}{X_0}} \left(1 + 0.038\ ln\left(\frac{x}{X_0}\right)\right)$$

In this scattering angle equation, β is the relativistic velocity, c is the speed of light, p is the momentum (velocity times mass) of a muon, x is the distance travelled, and X_0 is dependent on atomic number and the mass of the material the muon is traveling through.[4] From this, it can be seen that muons scatter at larger angles when interacting with heavier atoms, and faster muons tend to scatter at smaller angles.

However, although the physics of the muon is well understood, it is still important to consider how these muons are actually counted and how its measurements are extracted. Different imaging methods and detectors exist for specific applications of each measured structure. There are three main types of detectors that are most commonly used for muon detection: plastic scintillators, nuclear emulsions, and gaseous detectors. Scintillators use the excitation and de-excitation of atoms that interact with muons. As these muons pass through an object, photons from the excitations are collected, converted into electrons, and then amplified into a signal. Nuclear emulsion detectors are coated with a gelatin that is sensitive to ionizing radiation and leaves a 3D trail when

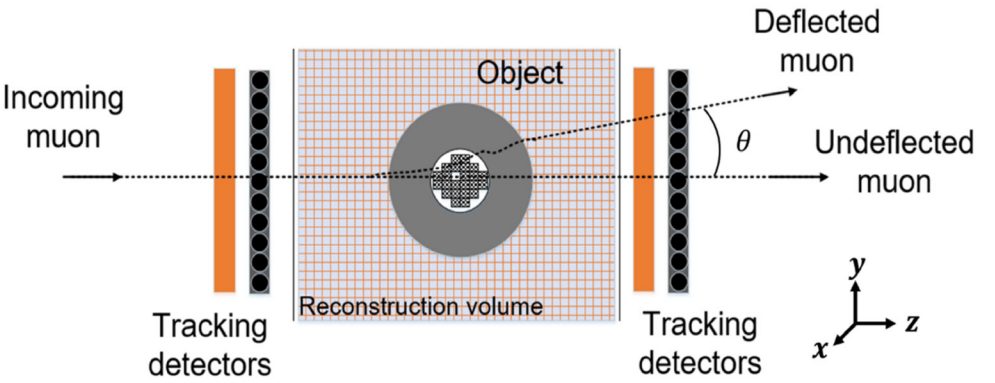


Figure 3: Schematic of a Muon Scattering Tomography system. The schematic illustrates the experimental setup used to image an object within a designated reconstruction volume. Incoming muons trajectories are measured before being sent through a volume. As muons pass through the object, interactions with nuclei cause scattering from original trajectories. A second set of detectors measures the exiting muon position and angle, which allows researchers to then calculate the scattering angle. Because the magnitude and direction of the muons is dependent on the traversed material, scientists use this information to reconstruct a 3D map of the volume.

a muon strikes it. These detectors are left in place until enough muons travel through to be able to chemically reconstruct the trajectories of all of the muons. Finally, gaseous detectors rely on muon-induced ionization of gas molecules—high-voltage electrodes pull the freed electrons toward an anode, where the signal is amplified into an electrical pulse.[4]

REAL-WORLD APPLICATIONS: REVEALING THE UNSEEN

Muon absorption was experimentally used to image two craters of the Sakurajima volcano before and after an eruption. By measuring the flux rate of muons as they pass through the volcano, more muons are absorbed by the thick rock than the less-dense surrounding air. Then, scientists measured the average density of the volcanic cone and saw an increase in its density after an eruption. This signified that magma hardened into a "plug." The observatory that measured the muons was 150 meters above sea level and approximately three kilometers away from the craters. Detectors were oriented both backwards and forwards, allowing researchers to compare muon flux from the volcano with background muons from the surrounding atmosphere. This confirmed that the forward muon flux reflected density changes in the volcanic material.[5]

In application to muon scattering tomography, cargo scanners are used in national security to identify any nuclear weapons or nuclear materials carried within vehicles entering the United States. Six planes of gaseous detectors were each placed above and below the scanning area in order to calculate the scattering angle caused by the objects inside. In order to additionally simulate the cluttered inside of vehicles, researchers placed a led cube along a full automobile engine and transmission. It was found that the led cube stood out dramatically, even in the presence of other metal materials, and it was identified in as little as four minutes; however, scientists concluded that if the experiment was performed closer to sea level, where there is a higher concentration of muon flux, the time to identify these heavier atomic elements could be reduced.[6]

THE NEXT DECADES OF DETECTION

It is clear that muons have and will continue to be used for important geophysical applications, but characteristics of this particle also suggest applications in other scientific fields. In astronomy and cosmology, it is suggested that muon telescopes could be used to scan beneath the surface of Mars or other planets with sufficient muon flux similar to or stronger than Earth's surface.[1] There are also proposed theories on how muons could be used to experimentally validate the existence of dark matter.[7] As seen from its numerous and varied applications, muon technology is a field that is continuously advancing. While there is much more to anticipate from its impacts, muons have successfully been used to explore the previously undiscovered.

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IMAGE REFERENCES

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