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**Muon Imaging: Seeing Through**

Muons, omnipresent and ever-penetrating, are seen as particles of knowledge, allowing us to perceive impenetrable objects. Providing insights into matter, their applications span well beyond particle physics and have the potential to further expand into use in other scientific fields. One highly prospective field is civil engineering where these particles have the ability to “look into walls” to monitor structures for damage. By incorporating predictions of muon prevalence, scientists will be able to develop muon applications in civil engineering in order to monitor the integrity of structures to protect cultural heritages and ensure the safety of occupants.

In 1936, Caltech researchers Carl Anderson and Seth Neddermeyer, were researching cosmic radiation, when they first identified muon particles (Kaiser, 2019, par. 2). However, it was not until the late 1950’s that scientists would realize the applicability of these particles. Muons reach us through streaks of high speed particle groupings called Cosmic rays which tear apart carbon molecules in the atmosphere into muons. A common occurrence, muons rain down on every inch of the earth’s surface (Gibney, 2018, par. 4 ). Moreover, these particles are known for their penetrating power. They pass through hundreds of meters of solid material before they are absorbed (Gibney, 2018, par. 3). This combination of “omnipresence and penetrating power makes muons perfect for imaging large, dense objects without damaging them,” says Cristina Cârloganu, a physicist at the Clermont-Ferrand Physics Laboratory in France. In imaging, scientists use particle detectors to measure muon prevalence and energy levels at different levels around an object. The muon, an agent in the process, will pass through open space but will decompose, ricochet off, or change the energy level of when it interacts with materials depending on the composition of the material. These interactions with material space, allow scientists to use changes in muon count and energy levels to image objects.

Over the last half a century, Muography (“muon imaging”) has seen an expanding application across multiple scientific disciplines. The first use of muons for imaging dates back to the 1950’s when scientists started to use muons in research. The particles allow for the research of superconductivity, magnetism, and other molecules such as electrons. In the Paul Scherrer Institut in Switzerland, researchers are able to generate muons in physics accelerators (Paul Scherrer Institut., 2021, par. 3). They then guide these particles with the aid of magnets through structures to image them (Paul Scherrer Institut., 2021, par. 1).

In the past decade, muons have seen an introduction into nuclear engineering. These particles have a versatile property in that when they interact with a dense material such as uranium, they are scattered and absorbed in characteristic ways, depending on the atomic number of the material (Jarman, 2021, par. 3). This allows muon detector systems to identify nuclear material within objects. The main application of this property is in cargo shipping when detector systems are used to scan for potentially dangerous nuclear material in order to prevent illegal transport. As the technology continues to grow, so will the widespread use of these systems in nuclear engineering and subsequently, the increase in nuclear security.

Muons have also seen an introduction into Archaeology and Geology. At Egypt’s Great pyramid, muons allowed scientists to discover hidden tomb’s that went unfound for years (Morishima, 2017, par. 1). As muon detector systems cause no harm to the sites they image, they are an ideal technology for archaeology. Following the discovery in the Great Pyramid, other scientists have used muography to map cavities under Naples that have existed since the eight century B.C. (Giney, 2018, par. 9). Moreover, “Giulio Saracino, a physicist at the University of Naples Federico II in Italy . . . [plans to use muography to] look for a rumored aqueduct beneath the nearby ancient city of Cumae” (Giney, 2018, par. 9).

Italy, home to an active volcanic region, has found use of the imaging capabilities of muons to ensure public safety (D’Allesandro, 2019, par 2-3.). Muons detectors are used in conjunction with other instruments to better predict volcanic eruptions in Italy. The detectors allow for scanning of rock density that scientists use to identify vulnerabilities that will first breakthrough in an eruption (D'Alessandro, 2019, par 1.). With this information, scientists pinpoint and attempt to understand eruption mechanisms that pose a threat to the civilian populace living nearby.

It is primarily the presence, absence, and scattering of muon particles that allow for the imaging of objects. Yet there are different detector systems, each with their own advantages and drawbacks. Absorption radiography uses imaging detector planes in the bottom to define the tracks of muons and detect if there is an object above (Kaiser, 2019, par. 11). It relies only on the levels of presence of muons. With reliance on prevalence and absence, absorption radiography is much less accurate than other detector systems but is useful for nuclear engineering since it uses mostly prevalence levels. Muon tomography utilizes layers of detectors that look at the prevalence, absence, and scattering of muons particles. With the use of two detectors, the system compares the levels of muon counts between the different detectors. This allows for higher accuracy. Borehole detectors utilize borehole drills to dig 100-250 meter feet tunnels in the ground which borehole detectors will be placed in. This detection system is the most useful for underground events which are hard to image since they go deep into the ground.

Muon detectors have the potential to be used in civil engineering to detect cracks in structures in order to protect occupants and structural integrity. As buildings age and face weather conditions, their foundation begins to dwindle and there lies a danger in there being potential for cracks to form. As muon detector systems have the capability to image structures, they have a use in detecting cracks in buildings. There lie three structures which serve to benefit the most from muon detector systems. The first is bridges, which carry massive amounts of volume, cause disastrous accidents, and are essential for transportation. Bridges are expansive and will require absorption radiography systems to operate since a top detector will be harder to place. The second is historical sites, which often use old architecture styles that are out of date. The maintenance should be non-invasive in that it doesn’t vandalize or harm the heritage site. Muon detectors systems utilize the current flow of muon detectors and are able to image sites in a non-invasive manner. Historical buildings are a lot harder to install muon detector systems in since their architecture is variant, and therefore will need convenient to place detectors and a convenient system. The third is smart homes which are self-aware home technology. Through muon technology, smart homes can monitor their building for any damage and can alert the homeowner when there is damage. Smart homes will use layers of muon tomography systems which will need to incorporate other factors that can potentially change muon count (temperature, seasons, and pressure) and also detectors that are portable and easy to fit in tight spots.

Muon detectors placed at the structures will be monitored overtime to detect subtle changes in the structure density in order to detect cracks. Average levels taken in other days can help detect subtle changes (Vandenbroucke, 2021). Yet, through the use of scientific prediction, the error bound for average level can be accounted for. Through my detections and the data of the Distributed Electronic Cosmic Observatory, I found that the higher the atmospheric pressure, the lower the muon count. The line of reasoning is that dense air is harder to travel through so higher pressure leads to less muons making the trip (Cheng, Mok, 2001, par. 2). In addition to this correlation, scientists at NASA have found that higher altitude levels leads to higher muon count. At higher altitudes, muons don’t have to travel as far so muons that would have decayed before reaching ground level drive up the numbers at higher altitudes. Moreover changes in season also lead to difference in muon count. In the summer, there are higher levels of muons as compared to the winter (Mendoca, 2016, par. 3). With changes in the seasons correlating with changes in distance from the sun, it can be concluded that closer to the earth, the higher the count. In the summer the earth is closer so there is a higher count and vice-versa for the winter. Through the use of these predictions, scientists can further develop muon applications. In scenarios, where muon systems need to be dynamic, the use of predictions in replacement of an upper detector in muon tomography leading to higher accurate results as opposed to absorption radiography. Using prediction of muon prevalence will allow for better imaging without using another muon detector at top. This will help in scenarios where placement is difficult like bridges and it'll allow for more applications for muon imaging technology.

Muons have recently come into the mainstream in the scientific community due to their numerous potential applications. Through the use of prediction of muon prevalence, taking into account atmospheric pressure, season, and altitude, the uses of this innovative technology can be further expanded into other disciplines, specifically civil engineering. In civil engineering, the use of muon predictions will allow scientists to better monitor the integrity of bridges, smart homes, and historical buildings, in order to protect inhabitants and cultural heritage.

**References**

D’Alessandro R et al. 2019 Volcanoes in Italy and the role of muon radiography. Phil. Trans. R.Soc. A 377, 20180050. (doi:10.1098/rsta.2018.0050)

De Mendonça, R. R. S., Braga, C. R., Echer, E., Dal Lago, A., Munakata, K., Kuwabara, T., Sabbah, I. (2016). The temperature effect in secondary cosmic rays (muons) observed at the ground: analysis of the global muon detector network data. The Astrophysical Journal, 830(2), 88.

Giney E. (n.d.). Muons: The little-known particles helping to probe the impenetrable. Nature, 557, 620-621. https://doi.org/10.1038/ d41586-018-05254-2

Hong Kong Special Administrative Region Government Radiation Health Unit, Saiwanho Health Centre. (2001, May 2). The day-night variations of cosmic rays intensity at sea level under the influence of meteorological fronts and troughs (K. M. Cheng & H. M. Mok, Authors). ArXiv.

Jarman S. (n.d.). Prototype detector uses cosmic muons to scan shipping containers. In Imaging. https://physicsworld.com/a/ prototype-detector-uses-cosmic-muons-to-scan-shipping-containers/ (Reprinted from Physics World, 2021, February 22)

Johnson-Groh, M. (2017, January 27). NASA studies cosmic radiation to protect high-altitude travelers. NASA Blogs. https://www.nasa.gov/feature/goddard/ 2017/nasa-studies-cosmic-radiation-to-protect-high-altitude-travelers

Kaiser R. 2019 Muography: overview and future directions.Phil. Trans. R. Soc. A 377: 20180049. http://dx.doi.org/10.1098/rsta.2018.0049

Morishima, K. et al. Nature 552, 386–390 (2017).

The SμS muon source. (n.d.). Paul Scherrer Institut. Retrieved March 24, 2021, from https://www.psi.ch/en/media/the-sms-muon-source

Vandenbroucke, J. (n.d.). Distributed electronic cosmic-ray observatory data

[Data set]. DECO. https://wipac.wisc.edu/deco/data