Working group
OUTREACH of APPLICATION FOR SOCIETY
November, 2022

Invisible particles help to reveal invisible structures

We are accustomed to X-ray radiography to look inside the human body. A similar technique, called muon tomography (or radiography) uses invisible particles from the atmosphere to look into large structures of or on our earth.

"Who ordered that?"

This is the famous quote by Nobel laureate Isidor Isaac Rabi when, unexpectedly, the muon was discovered in the 1930s. At that time, scientists thought that they have figured out that matter was made of atoms and atoms were made of protons, neutrons and electrons.

The muon was discovered in 1936 by Carl D. Anderson and Seth Neddermeyer at Caltech while studying cosmic radiation. They discovered particles that bent differently in a magnetic field from what was expected for electrons and other known particles.

The new particle was identified as being very similar to an electron except for the mass – the muon is 207 times heavier.

Muons constantly fly through us because they can be created when cosmic rays – mostly protons from the sun hit the atmosphere with high energy at an altitude of about 10 km.

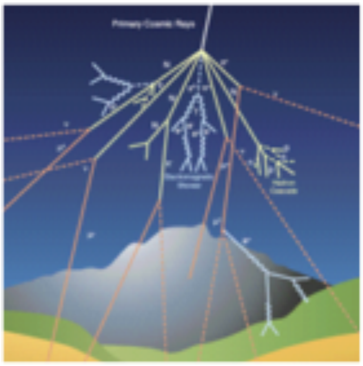
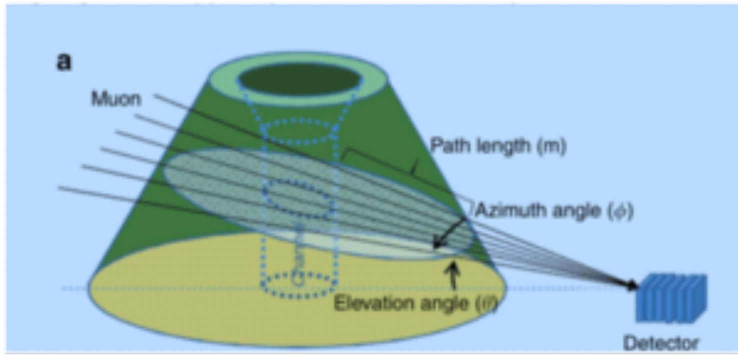
Muons have a very short lifetime of 0.000002 s and should therefore have decayed after 600 m in average. At sea level however about 100 muons are detected per second per square meter; typically one muon per second goes through a surface the size of our hand; 600 muons cross our body every minute.

The theory of special relativity explains that time passes more quickly in a moving object than in an object at rest which is why muons fly in average about 9 km through the atmosphere.

Principle of muon tomography

Muon tomography is a technique that uses information on the absorption of cosmic ray muons to measure the density of the materials crossed by the muons and thus construct three-dimensional models of the densities of obstructed objects or volumes.

In general this method can be used to determine the density of material of an object and learn about the internal structures. It is similar to imaging with X-rays but can survey much larger objects. Since muons are less likely to interact, stop and decay in low density matter than high density matter, a larger number of muons will travel through the low density regions of target objects in comparison to higher density regions.

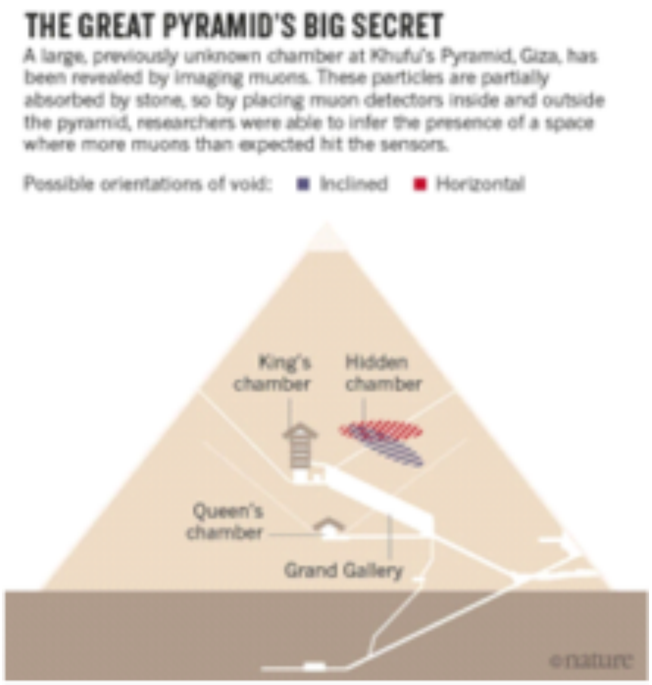
 

Applications

Muons can be used to study objects on earth, such as pyramids, for example. Researchers measure how many of the muons that are produced in the atmosphere, are absorbed in the pyramids and compare it to the expectation from expectation. From this, conclusions can be drawn about the existence of not yet discovered cavities.

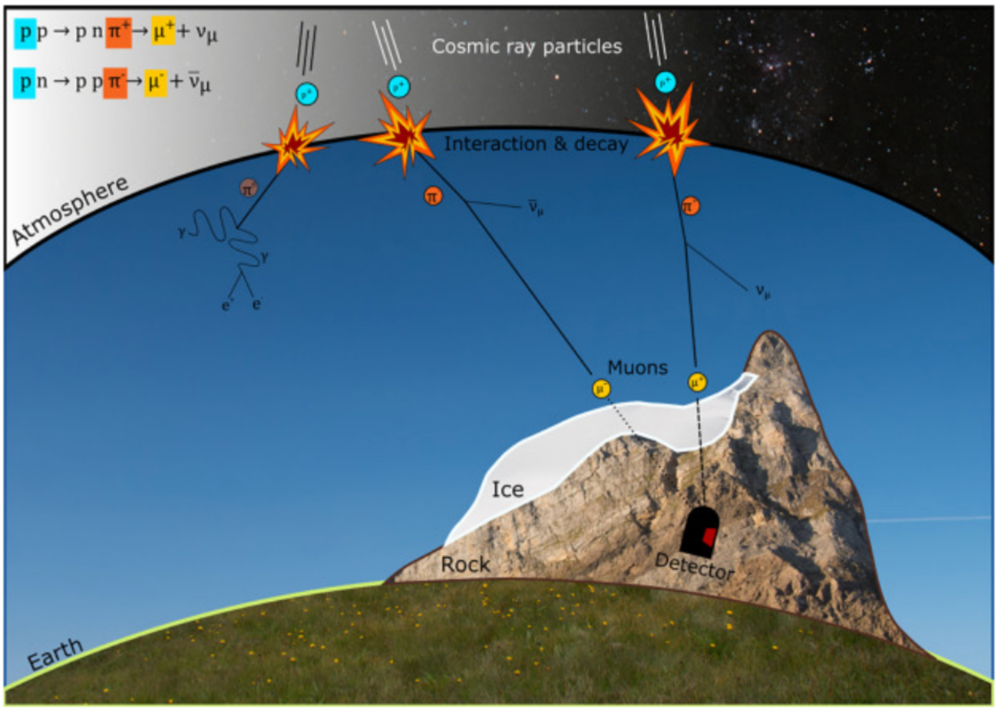
What's inside the pyramid?

Muon tomography was first used in 1971 to investigate the pyramid of Chefrten, in Giza, Egypt by Luis Alvarez. [Spark chambers](https://en.wikipedia.org/wiki/Spark_chamber)(https://en.wikipedia.org/wiki/Spark_chamber) were used. He found no evidence of a void.
The [ScanPyramid](http://www.scanpyramids.org/) (http://www.scanpyramids.org/) mission found a big void in the Great Pyramid (Khufu's Pyramid), above the Grand Gallery. It was observed inside the pyramid and reconfirmed with measurements outside the pyramid.



Other examples for muon tomography

- Monitoring the activity of volcanos
- Monitoring glaciers
- Exploring underground cavities
- Scanning civil structures such as dams, power plants or bridges for cracks or instabilities
- Scanning lorries to check the content of the freight



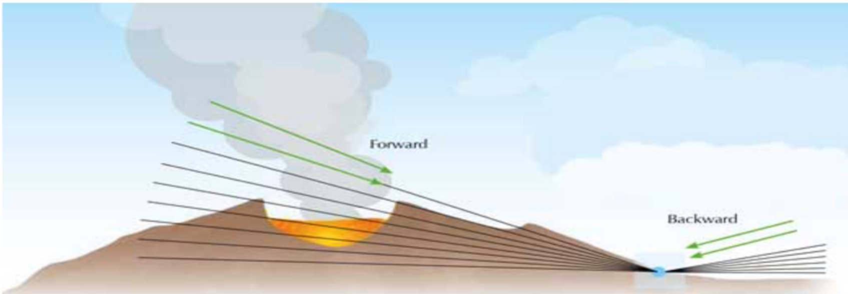
Going further: muon scattering tomography (link to separate page)

Special applications

Muon tomography has applications in many places

Volcanos

In 2007 Nagamine and Tanaka were the first to apply the technique for the study of volcanoes not only to gain structural information but also to monitor theit activity.
 Here a list of volcanoes that are presently under study are Vesuv (Italy), Etna (Italy), Stromboli (Italy), Soufrière (Antilles), Puy de Dôme (France) , Satsuma-Iwojima (Japan).



The principle of muon radiography. As they pass through the volcano, near-horizontal muons
are absorbed by the rock through which they are passing. The denser the rock, the
more muons are absorbed. Backward flux is used for normalisation.
Image courtesy of Nicola Graf

Monitoring glaciers

the measurement of the muon rate is used to investigate the thicknes of a glacier. The method is used for example to monitor the Eiger glacier in the Swiss alps with detectors installed in the tunnel of the railway that mounts to the Jungfrau. (link from SCNAT and LHEP with picture)

Exploring underground cavities

Thanks to the penetrating power of high energetic muons their measurement inside undergroud caverns may be used to explore unaccessable parts or determine the density of the rocks.

Scanning civil structures such as dams, power plants or bridges for cracks or instabilities
 It allows for example to control the spent nuclear fuel deposits without opening and no radiation risk for the people working.

Scanning lorries to check the content of the freight

Going further: muon scattering tomography

An extension of muon tomography, muon scattering tomography, is based on the multiple Coulomb scattering of muons crossing the volume under investigation. Muons are deflected and slow down when they interact with a material with high atomic number. Using tracking detectors that precisely measure the direction of the muons in front of and behind the volume under study the deflection is measured and thus objects with high atomic numbers can be localised.

Applications of muon scattering tomography

Security/Safety Cargo scanners to inspect the contents of trucks and containers

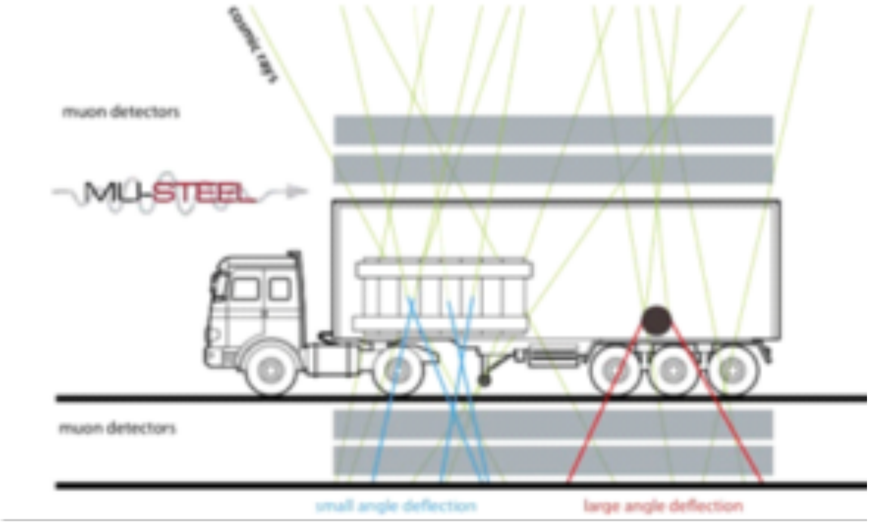
Control of spent nuclear fuel deposits (without opening, no radiation risk)

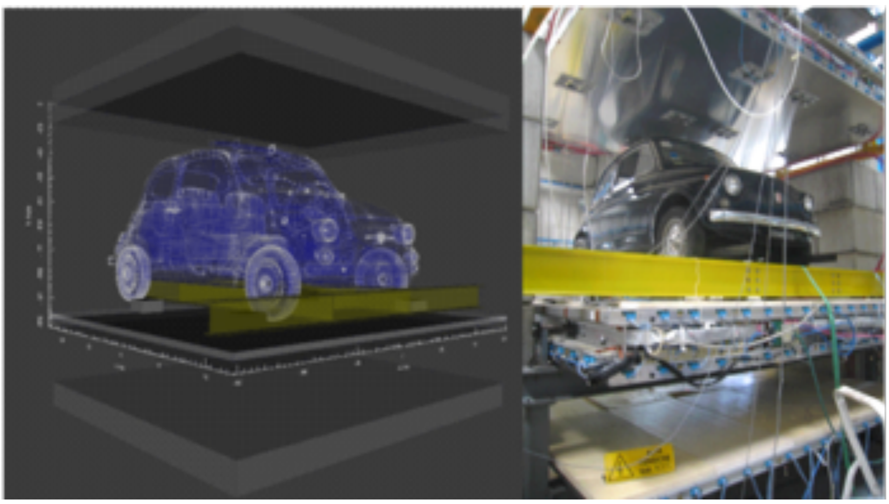
Study of the core of the Fukushima reactor plant

Industry: Control of trucks when entering steel foundries to detect hidden radioactive sources

Inspection of the inner structure of a blast furnace

Precision measurements : Measuring the alignment of structures / stability of buildings





Useful Links:

The examples mentioned here and the links given are just a selection and not an exhaustive list of all cases in each category

Muon tomography: https://cms.cern/content/muon-tomography
Cheops pyramids: movie on how researcher discover a new void
http://www.scanpyramids.org/#videos

General

https://en.wikipedia.org/wiki/Muography

https://en.wikipedia.org/wiki/Muon_tomography

https://journals.sagepub.com/doi/pdf/10.3184/003685015X14369499984303

https://indico.cern.ch/event/466934/contributions/2524834/attachments/1490162/2316412/progress_in_muon_tomography_EPS-2017.pdf

geoscience

https://www.sciencedirect.com/science/article/pii/S0012825221003433

Muography for the study of volcanoes

https://royalsocietypublishing.org/doi/10.1098/rsta.2018.0050

https://www.scienceinschool.org/article/2013/muons/
Muons reveal the interiors of volcanoes

https://cds.cern.ch/journal/CERNBulletin/2010/51/News%20Articles/1312698

The secret life of volcanoes: Using Muon Radiography

https://www.scienceinschool.org/2013/issue27/muons

Attraverso la roccia – la tecnologia della radiografia muonica

https://www.asimmetrie.it/attraverso-la-roccia

https://physicstoday.scitation.org/doi/abs/10.1063/PT.3.1829?journalCode=pto

The MU-RAY project :Volcano Radiography with cosmic-ray muons

https://www.sciencedirect.com/science/article/pii/S0168900210014890?via%3Dihub

STROMBOLI: REALIZZATA LA PRIMA RADIOGRAFIA MUONICA DEL VULCANO http://home.infn.it/it/comunicazione/comunicati-stampa/3536-stromboli-realizzata-la-prima-radiografia-muonica-del-vulcano based on emulsions (from the OPERA experiment)

First muography of the Stromboli Volcano

https://www.nature.com/articles/s41598-019-43131-8

1. The MEV project: design and testing of a new high-resolution telescope for Muography of Etna Volcano https://inspirehep.net/literature/1675335
2. http://wwwobs.univ-bpclermont.fr/tomuvol/presentation.php

Muography for the study of Pyramids

https://www.sciencesetavenir.fr/archeo-paleo/archeologie/egypte-de-l-infrarouge-et-des-muons-pour-sonder-le-coeur-des-pyramides_103836

http://www.scanpyramids.org

https://www.abc.net.au/news/science/2017-11-02/great-pyramid-giza-hidden-void-discovered-muons-cosmic-rays/9104608

kefren pyramid Luis Alvarez
http://www2.lns.mit.edu/fisherp/AlvarezPyramids.pdf
Teotihuacan Mexico
https://fr.wikipedia.org/wiki/Teotihuacan
https://www.youtube.com/watch?v=hJx0s_19Lrw

3. Cosmic-ray particles reveal secret chamber in Egypt's Great Pyramid

4. https://www.nature.com/news/cosmic-ray-particles-reveal-secret-chamber-in-egypt-s-great-pyramid-1.22939#/graphic

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons
https://www.nature.com/articles/nature24647.epdf?

Tunnels

Guthega–Munyang tunnel in Australia4,5 https://journals.sagepub.com/doi/pdf/10.3184/003685015X14369499984303

Muon Scattering Tomography

Progress in Muon Tomography (G. Bonomi, EPS conf.2017)

https://indico.cern.ch/event/466934/contributions/2524834/attachments/1490162/2316412/progress_in_muon_tomography_EPS-2017.pdf

https://cms.cern/content/muon-tomography

Cosmic Muon Tomography Project

http://mutomweb.pd.infn.it:5210

MUON CARGO INSPECTION

https://muon.systems/en/muoncargo

INSPECTION OF CIVIL STRUCTURES
https://www.mdpi.com/2410-390X/6/4/77

https://lingacom.com/solutions