Muography offers a new way to see inside a multitude of objects

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Five years ago, Japanese scientists working for the Tokyo Electric Power Company faced a daunting task: to peer inside one of the Fukushima nuclear reactors shattered in the 2011 earthquake and tsunami. The site was, of course, highly radioactive and extremely dangerous. Seeking a way to carefully inspect the site, the researchers turned to a technique that has grown in appeal across numerous scientific fields: muography.

Discovered in 1936, the subatomic muon particle is a heavy cousin of the electron. Muons don't serve any obvious purpose in the universe, and we still don't know why they exist. But physicists are now putting these mysterious particles to use: exploiting the natural rain of muons from the sky as a way to look deep inside an object. Muography offers many advantages over conventional scanning approaches. Muons penetrate much further than X-rays, they do essentially zero damage, and they are provided for free by the cosmos. These characteristics open up some extraordinary possibilities.

At Fukushima, the scientists set up two detectors, each weighing 20 tonnes and in a box with 10-cm-thick iron walls to protect the equipment from radiation. The detectors scanned the site between February and June 2015. The team did not see any sign of the nuclear fuel that should have been at the core of the reactor, so they concluded that the fuel had melted down and is now either collected among debris on the floor or has penetrated the reactor containment vessel (1). Finding where the fuel has gone will be vital to cleaning up and decommissioning the reactors (Spent fuel had been due to be removed this year, but the work has been delayed to 2022 because of the coronavirus disease 2019 [COVID-19] pandemic). Muography had served an important role, and it's likely to come in handy elsewhere.

A few years after the disastrous 2011 earthquake started a tsunami that devastated Japan's Fukushima nuclear power plant—shown here a few days after the tsunami struck—scientists set up two muography detectors to uncover signs of nuclear fuel at the core of the reactor. Image credit: Science Source/Digital Globe.

Muon Shadow

Muons are made high up in the atmosphere when cosmic rays (mostly protons) smash into the nuclei of oxygen, nitrogen, and other gases in the air. The collisions produce subatomic particles called pions, which are unstable and almost immediately decay into muons, particles with about 200 times the mass of an electron. The muons fly down through the atmosphere at close to the speed of light, and they strike Earth's surface at a rate of about 10,000 per square meter per minute.

Muography exploits the fact that muons lose energy to surrounding electrons as the muons pass through matter. When a muon loses most of its kinetic energy, it slows down and finally decays into electrons and neutrinos. The denser the matter muons pass through, the more quickly energy is lost, and the more muons are effectively absorbed. Therefore, muons can be used to construct an image based on the density contrast in the matter through which the muons have passed.

Detectors must be placed beneath the object of interest so that the detector can look through the object up at the sky, i.e., the source of muons. Detectors track the muons coming through the object, to form an image that is then compared with a muon image of the "free sky." This indicates how many muons have been blocked. The final picture is essentially a shadow of the object, in the light of cosmic muons.

In the 1950s, muography pioneer Eric George, a British physicist, used the technique to measure the depth of rock and ice above a tunnel in Australia's

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Muography is being used to explore the internal plumbing of volcanoes such as Vesuvius in Italy, pictured here with Pompeii ruins in the foreground. Image credit: Shutterstock/Boerescu.

Snowy Mountains, dug as part of an ambitious hydroelectric scheme (2). A decade later, Nobel Laureate and US experimental physicist Luis Alvarez, a veteran of the Manhattan Project, teamed up with Egyptologists to use muons to search for hidden rooms inside the Pyramid of Khafre, Giza (3).

The team didn't find any such rooms, but when modern archaeologists repeated the experiment on the nearby Great Pyramid in 2017, they made a major find. The group, led by Mehdi Tayoubi of the Heritage Innovation Preservation institute in Paris, France, used muon scanning to discover a previously unknown chamber at least 30 meters long—the first major inner structure found in the pyramid since the 19th century (4). The chamber has not yet been explored in person, but some experts speculate that it leads to a connected room that could have valuable items. Japanese muon scientists started rescanning the pyramid in 2020, but their project was put on hold because of the pandemic.

The Great Pyramid project is an example of what Giulio Saracino, a physicist at the University of Naples, Italy, calls a muography boom in the last decade, with the technique finding an increasing number of practical applications in research and industry.

Saracino notes that muography is better than other techniques, such as ground penetrating radar (GPR), for peering underground. For one thing, muography can be used to see further into apparently solid objects. Muography can comfortably scan objects through tens of meters of solid rock, whereas GPR often struggles to go beyond a few meters in many soils. And because muography is a passive technique—with no equipment needed to generate the signal to be analyzed—detectors can be installed and simply left to gather data. This reduces costs and makes projects logistically simpler.

The boom is being driven by better equipment. In the 1960s, Alvarez had to fill a chamber under the pyramid with bulky spark chambers: several meters of stacked metal plates sealed inside a box flooded with helium gas that ionized and flashed when a muon arrived.

Since then, physicists around the world have had a strong incentive to develop better devices to detect the muons released by massive particle accelerators such as the Large Hadron Collider at the European lab CERN in Geneva, Switzerland. As a result, modern muography equipment is lighter and more portable. It includes nuclear emulsion plates, which track muons in a similar way to traditional photographic film; and plastic scintillators, which build up a picture of each muon's trajectory from pulses of light that is generated in consecutive layers of plastic.

In 2019, Saracino's team used plastic scintillator detectors to produce underground maps of Mount Echia, the site of the earliest settlement in Naples, dating back to the sixth century BCE. Setting up several separate detectors to track muons arriving from different directions, the team combined two-dimensional snapshots to form detailed three-dimensional images. The team discovered a hidden underground cavity, which is yet to be explored (5).

The same technique is being used to explore the internal plumbing of volcanoes, including Vesuvius, to track magma movements and work out where water might seep in and cause an explosive eruption. Geologists already have a suite of methods to study volcanos—including seismology, satellite images, and gravity measurements—but muography can help fill in the gaps. Seismographs of the guts of a 1-kilometer-thick volcano usually have a resolution of a few hundred meters. Muon scanners can bring that down to a few tens of meters.

Scatter Scanners

After the terrorist attacks against the United States in 2001, the US government investigated whether muography could be used to search for smuggled nuclear material. Physicist Chris Morris of the Los Alamos National Laboratory, NM, and his team succeeded. Instead of counting muons blocked by an object, the physicists tracked those that were deflected by the dense concentration of charge in atomic nuclei. This change in trajectory can be spotted in a detector—actually, two detectors—to compare the paths of muons before and after they pass through the material of interest.

"We built a scanner that was big enough so that we put a little ramp up and drive a Jeep into it and examine the contents of the Jeep and pretty much showed it worked," Morris says. Revealing the technology in 2003, the team claimed its scanner could find "a block of uranium concealed inside a truck full of sheep" (6).

Tracking how muons scatter from an object gives more detailed information about its density than simply counting those that penetrate versus those that don't. The approach is much more sensitive to contrasts in material, because scattering depends strongly on the nuclear charge—for example, uranium scatters muons much more than iron. This scattering can speed up the production of images, especially for thin objects that don't absorb much. Tracking scattered muons has been shown to be about 10 times faster at imaging a lead brick than counting absorbed muons (7).

For some applications, Morris says the scattering technique can produce a useful signal in just a few minutes. That's enough time to detect a suspicious density difference inside a shipping container, such as concealed bales of drugs. Here, security officials have no need to wait for a fully resolved image—they just need the muon detector to indicate which containers deserve a more thorough search.

A commercial muon scanner based on scattering is already being used to screen cargo in this way at the Freeport Container Port in the Bahamas. Several governments around the world have them as well, and muography helps to monitor the US–Mexico border, Morris says. "There's a lot of money to be made at borders. If you can find people smuggling cigarettes or drugs into your country."

A Watchful Eye

Perhaps an even more important monitoring task for the scattering technique is examining nuclear waste. Working with industry experts at the Sellafield nuclear reprocessing plant in northwest England, David Mahon, a physicist at the University of Glasgow, UK, and colleagues have built and tested a muon detector that can find stray—and potentially dangerous—pellets of uranium in heavily shielded barrels filled with the cladding stripped from reactor fuel rods (8). Finding such contamination "was unheard of before with other techniques," says Mahon, noting that the barrels' radiation shielding also stops scanning radiation—i.e., X-rays—from getting in.

In the wake of the 2018 catastrophic collapse of a motorway bridge in Genoa, Italy, which killed 43 people, the Glasgow group has also investigated whether scattering muography could help scan vital infrastructure for weaknesses. In a new preprint paper, they show that the technique can be used to reveal the interior of a reinforced concrete block, showing the internal structure with more resolution and less distortion than either ultrasound and radar imaging (9). (Although muography took significantly longer—about 1,200 hours compared with less than two hours for the other methods.)

Mahon says it's probably not realistic to use muography to scan an entire bridge for defects, but the technique could be used in a more limited way when the investigation is less urgent—perhaps to check original design drawings and confirm, say, the number of reinforced cables within a section.

Morris envisages uses in healthcare too. In unpublished data, his group has shown that muon scattering can offer continuous imaging of human chest cavities. That would be impractical with existing scanning methods—no hospital has the resources to let its patients spend hour after hour in active MRI scanners, and being constantly X-rayed would be highly dangerous. With scattering muography, you can simply leave detectors above and below the patient's bed to produce a usable image in about an hour, to reveal whether the lungs are filling with fluid, for example—a potentially useful tool in the era of COVID-19. The patient, though, would have to be quite still (as in the case of those in the ICU); so far Morris has only tested the approach on dummies.

But Morris says they do encounter skepticism that such images can seemingly be pulled out of thin air. Because physicists have spent so long dealing with muons as annoying background noise, he suggests that they're surprised the mysterious subatomic particles can be useful. "I think for a long time people just didn't believe it," he says. "So it's slow, but I think it's catching on." Like muons striking a detector, the constant stream of new data and findings is steadily forming a reliable picture of muography itself.

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