PROCEEDINGS OF SCIENCE

Cosmic ray imaging with nuclear emulsion plates for investigation of archaeological ruins

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We are developing a technique for the investigation of archaeological ruins using cosmic ray imaging (muography), a nondestructive imaging technique that utilizes muons in cosmic ray air showers. We use nuclear emulsion plates as muon detectors. The features of being electric power supply-free, lightweight, and compact are highly advantageous for installing the detector in narrow structures inside archaeological ruins such as pyramids and catacombs for the observation of cosmic ray muons. In 2016 and 2017, in ScanPyramids, cosmic ray imaging with nuclear emulsion plates revealed two unknown voids named SP-NFC and SP-BV inside the Khufu's Pyramid in Egypt. To analyze the more detailed geometry of these voids, we have installed multiple nuclear emulsion plates inside the Pyramid of Khufu in 2019. Through these observations, we successfully revealed the position and shape of SP-NFC with high precision, leading to the direct imaging of the space using a fiberscope. This achievement not only represents the first instance of directly confirming a void discovered through cosmic ray imaging but also has a significant impact on archaeology. Furthermore, in 2022, we started to search for the hidden inner structure of the Pyramid of Khafre's Pyramid. Our technology has been used not only for pyramids in Egypt, but also in the investigation of the temple pyramid at the Copan ruins in Honduras of the ancient Mayan civilization, and the underground ruins in Naples, Italy. Cosmic ray imaging is expected to become a new method for archaeological site surveys in the future.

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1. Introduction

Cosmic-ray imaging is a non-destructive imaging technique that leverages the high penetration power of muons, which are subatomic particles produced in secondary cosmic rays generated when high-energy primary cosmic rays collide with the Earth's atmosphere. This method visualizes density contrasts within objects up to several kilometers thick. As muons travel through matter, they lose energy, allowing higher-energy muons to penetrate thicker materials. For example, a 10 GeV muon can penetrate approximately 20 meters of rock, while a 1 TeV muon, with 100 times more energy, can penetrate even 1 kilometer of rock. Although the directional bias in the incidence of cosmic-ray muons reaching the Earth's surface, they fall at a constant rate of about one per square centimeter per minute, making them usable worldwide.

In cosmic-ray imaging, detectors capable of measuring the direction of muons are placed inside or near the target object. By measuring the angular distribution of muons that pass through the target and reach the detectors, we can infer the integrated density within the object. Only muons with sufficient energy to penetrate the target reach the detectors. This energy threshold is determined by the type and amount of material along the muon's path. By considering the energy distribution of muons from different directions, we can estimate the integrated density within the target. By performing this estimation within the detector's measurable angle range, we can obtain a two-dimensional distribution of integrated density for the target. If prior information on the shape and internal uniformity of the object is available, we can estimate the average density within the target by determining the path length of muons through each direction.

This technique, which utilizes the absorption of cosmic-ray muons by matter, began in the 1950s when E. P. George and colleagues installed a Geiger counter inside a tunnel to measure the thickness of rock by comparing the detection rates of cosmic ray muons inside and outside the tunnel [1]. In 1967, L. W. Alvarez and colleagues attempted to explore unknown chambers within Khafre's Pyramid in Giza by installing a spark chamber in a biggest chamber called Belzoni Chamber in the pyramid and measuring the incoming directions of muons passing through the pyramid's masonry (Fig. 1) [2]. The pyramid is a stone structure built using millions of limestone blocks, each weighing several tons and cut into approximately 1 to 2 meter cubes. However, no design plans of the pyramid remain, leaving its construction methods and internal structure a mystery. This experiment was the first to create a two-dimensional cosmic-ray transmission image, comparing it with simulated results based on known structures of the pyramid, though no unknown chambers were discovered.

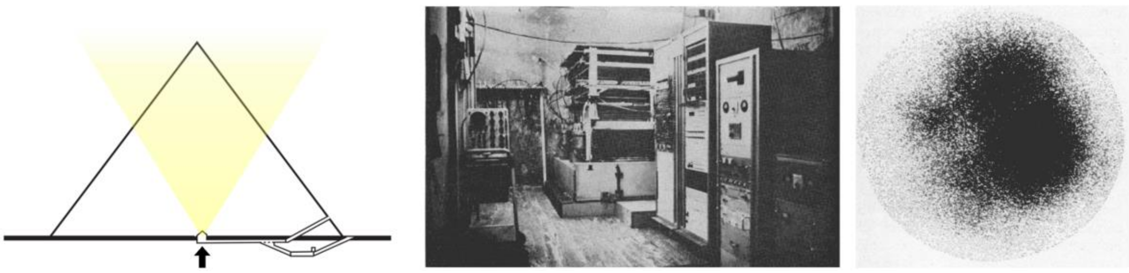

Figure 1: Left: A cross-section diagram of Khafre's Pyramid : the visualization range is marked with yellow areas and the Belzoni Chamber is indicated with an arrow. Center: Detector installed in the Belzoni Chamber [2]. Right: Angle distribution of detected muons [2].

Subsequently, muons arriving from horizontal directions to image volcanoes and blast furnaces, among other applications. In recent years, cosmic-ray imaging is applied to various targets using various detectors. In this paper, our ongoing investigation of ancient ruins using cosmic ray imaging with nuclear emulsion is described.

2. Nuclear emulsion plate

The nuclear emulsion plate is a solid-state track detector that uses silver halide photographic technology to record the trajectories of charged particles in three dimensions with submicron spatial resolution, represented as strings of silver grains (Fig. 2) [3].

We have been advancing the development of this technology as a detector for cosmic-ray muons. The nuclear emulsion plate consists of an 80 micron thick emulsion layer as detection part on both sides of a transparent plastic plate, which ranges from 200 to 500 microns thick. The total thickness of this plate-like detector is less than 1 mm. The emulsion layer is composed of a gelatin membrane with three-dimensionally dispersed silver bromide crystals about 200 nm in diameter. When charged particles such as muons pass through these silver bromide crystals, latent images consisting of a few silver atoms are formed on the crystal surfaces. These latent images grow into silver grains observable under an optical microscope through photographic chemical development. The developed nuclear emulsion plate records the muon's path as a three-dimensional chain of silver grains. By digitizing these tracks with a submicron precision using an automated nuclear emulsion scanning system equipped with a microscope imaging optical system, a large amount of track information can be processed. In addition to muons from cosmic rays, the nuclear emulsion plate also records tracks of other charged particles such as electrons from environmental radiation. However, differences in mass, energy, and charge among these particles result in variations in track shape, length, and the density of silver grains on track. By analyzing this information, we can distinguish muons from other particles.

Using nuclear emulsion plate as a detector for cosmic ray imaging has several advantages. The high resolution of the nuclear emulsion plate allows for the construction of very compact and lightweight detectors. Furthermore, since the nuclear emulsion plate does not require power for measurements, there are fewer restrictions on where it can be installed. These characteristics provide significant advantages when deploying detectors for cosmic ray imaging of natural and artificial structures.

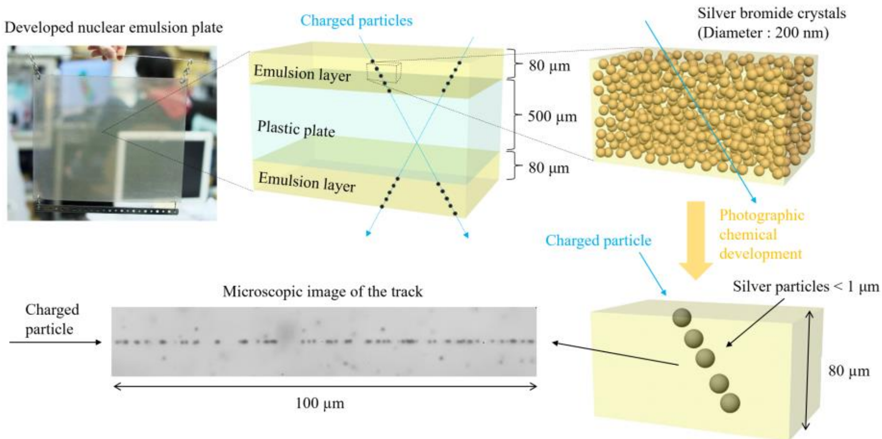

Figure 2: Overview of nuclear emulsion plates

3.ScanPyramids

In 2015, an international collaborative research project named "ScanPyramids" was launched to investigate the pyramids of Egypt using advanced non-destructive technologies such as cosmic ray imaging. The project is managed by the Egyptian Ministry of Antiquities and focuses on the three Great Pyramids of Giza (King Khufu, King Khafre, and King Menkaure) and two pyramids in Dahshur (the Red Pyramid and the Bent Pyramid), which were built during the Old Kingdom, the peak of pyramid building. Participating from Japan are Nagoya University and KEK, from France CEA and INRIA, from Canada Université Laval, and from Germany Technical University of Munich. Nagoya University, KEK, and CEA, which are in responsible charge of cosmic ray imaging, have developed and are using detectors with different characteristics, such as a nuclear emulsion plate, a scintillation detector, and a micro-pattern gas detector, respectively (Fig. 3). Other technologies, such as infrared imaging by Laval University, and ground-penetrating radar and ultrasonic surveys by Technical University of Munich and Cairo University, are being used in combination for the survey.

Figure 3: Left: A nuclear emulsion plate. Center: A scintillation detector. Right: A micro-pattern gas detector

3.1Khufu's Pyramid

The Pyramid of Khufu is the largest man-made structure ever built by mankind (Fig. 4, 5). The entrance on the north face of the pyramid was built at the time of its construction and leads to the Descending Corridor that leads to the interior. Above the entrance is a gabled structure, called a Chevron, constructed of high-quality limestone slabs. The gable structure is an innovative construction method first used in the Khufu's Pyramid, and is a roofed structure that distributes the weight of the upper part of the structure to prevent the lower space from collapsing. This entrance is now closed and inaccessible without special permission. Tourists can enter through the horizontal corridor dug by al-Ma'mun in the 9th century. The Descending Corridor and the the al-Ma'mun Corridor meet in the interior, and at the junction they diverge in an upward and downward direction. The Descending Corridor, with a cross section of about 1 m in length and width, is about 100 m long and leads to an underground chamber (8 m wide, 14 m deep, and 5 m high) beyond it. After climbing up the Ascending Corridor from this junction, a huge space called the Grand Gallery (40 m long with a trapezoidal cross section of approximately 1 m on the upper side, 2 m on the lower side, and 9 m high) unfolds. Entering the Grand Gallery and passing through a horizontal corridor, visitors reach the Queen's Chamber (5 m wide, 5 m deep, and 6 m high), which has a gabled ceiling. Going up the Grand Gallery, we reach the King's Chamber (5 m wide, 10 m deep, 6 m high), the only granite chamber in Khufu's Pyramid.

Among these internal structures, the Descending Corridor, the Subterranean Chamber, the Queen's Chamber, and the Relieving Chambers are not open to the public. Therefore, at the beginning of ScanPyramids, the detectors were installed in the Descending Corridor and the Queen's Chamber. Nuclear emulsion plates and a scintillation detector were installed in the Queen's Chamber for observations. In addition only nuclear emulsion plates could be installed in the narrow Descending Corridor, while micro-pattern gas detectors were observed from outside the pyramid due to gas leakage problems.

Figure 4: Khufu's Pyramid from the north and the Chevron (top right)

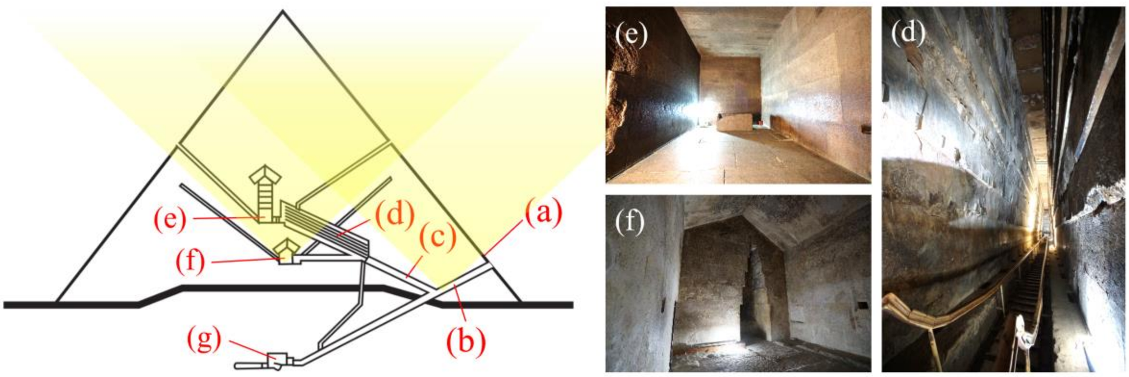

Figure 5: A north-south cross-section diagram of Khafre's Pyramid: (a) the Chevron, (b) the Descending Corridor, (c) the Ascending Corridor, (d) the Grand Gallery, (e) the King’s Chamber, (f) the Queen’s Chamber, (g). The visualization range of cosmic ray imaging using nuclear emulsion detectors installed at two locations in the Descending Corridor and the Queen's Chamber from 2015 to 2016 marked with yellow areas.

3.2 Discovery of two voids by cosmic ray imaging using nuclear emulsion plates

In 2016, we installed three nuclear emulsion detectors with size of 25 cm × 30 cm in the Descending Corridor for 67 days and observed 6.3 million cosmic-ray muons within an angular range of ±45° relative to the detectors (Fig. 5). The nuclear emulsion plates were developed in Giza, Egypt and read out using the nuclear emulsion scanning system called Hyper Track Selector at Nagoya University in Japan [4]. Using a model of the internal structure of Khufu's Pyramid constructed through photogrammetry and laser scanning, we conducted simulations and compared them with these observation results. As a result, we discovered a region with a muon excess of more than 5 sigma, extending in the north-south direction, which could not be explained by the known structures (Fig. 6) [5]. This indicates the presence of a low-density region in this direction compared to the surrounding areas, suggesting the existence of an unknown void within Khufu's Pyramid for the first time. This void, located just above the Descending Corridor and extending a void in the north-south direction, was named the ScanPyramids North Face Corridor (SP-NFC). This void is potentially related to the Chevron on the north face of the pyramid, making it an archaeologically significant finding. However, the two-dimensional images obtained from this observation did not provide depth information, and the precision was insufficient to accurately determine the detailed three-dimensional position and shape of the SP-NFC.

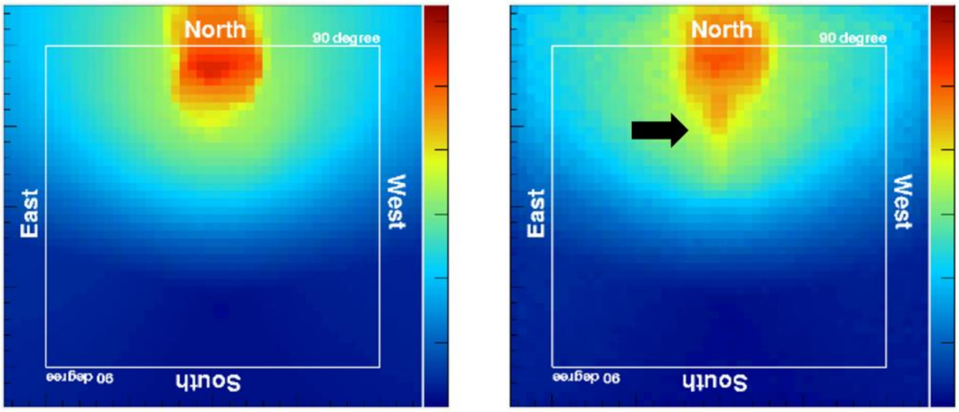

Figure 6: Left: a simulation result. Right: An observation result, and the muon excess region is indicated with an arrow [5].

In parallel, nuclear emulsion plates were installed at two locations in the Queen's Chamber. One was placed on the floor of the Queen's Chamber, and the other was placed inside a narrow niche, approximately 1 meter in width and height, located on the east side of the Queen's Chamber (Fig. 7) [6]. It was expected that the Grand Gallery and the King's Chamber, located above the Queen's Chamber, would be detected from the observation results of these two detectors. The nuclear emulsion plates were replaced every few months for continuous observation, and the observation data obtained over different periods were integrated and analyzed. The detector area for analysis was 0.45 square meters each. The detector installed in the niche recorded 4.4 million muon tracks over 98 days of observation, while the detector on the floor of the Queen's Chamber recorded 6.2 million muon tracks over 140 days of observation. Comparing these observation results with Monte Carlo simulations using Geant4 corresponding to 1000 days of observation, we confirmed that the Grand Gallery and the King's Chamber matched between the observation results and the simulations. Additionally, we discovered muon excess regions with a significance of more than 10 sigma in both detectors (Fig. 8). Since the excess regions were detected in different directions relative to each detector, triangulation was used to estimate the three-dimensional position of the excess region (Fig. 9). It was confirmed that the void causing the muon excess was located 40 meters above the Queen's Chamber, just above the Grand Gallery. Furthermore, it was revealed that this void has a cross-sectional area comparable to that of the Grand Gallery and a length of more than 30 meters, indicating a large void.

Figure 7: Left: nuclear emulsion detectors in the niche of the Queen’s Chamber. Right: nuclear emulsion detectors placed on the floor of the Queen’s Chamber [6].

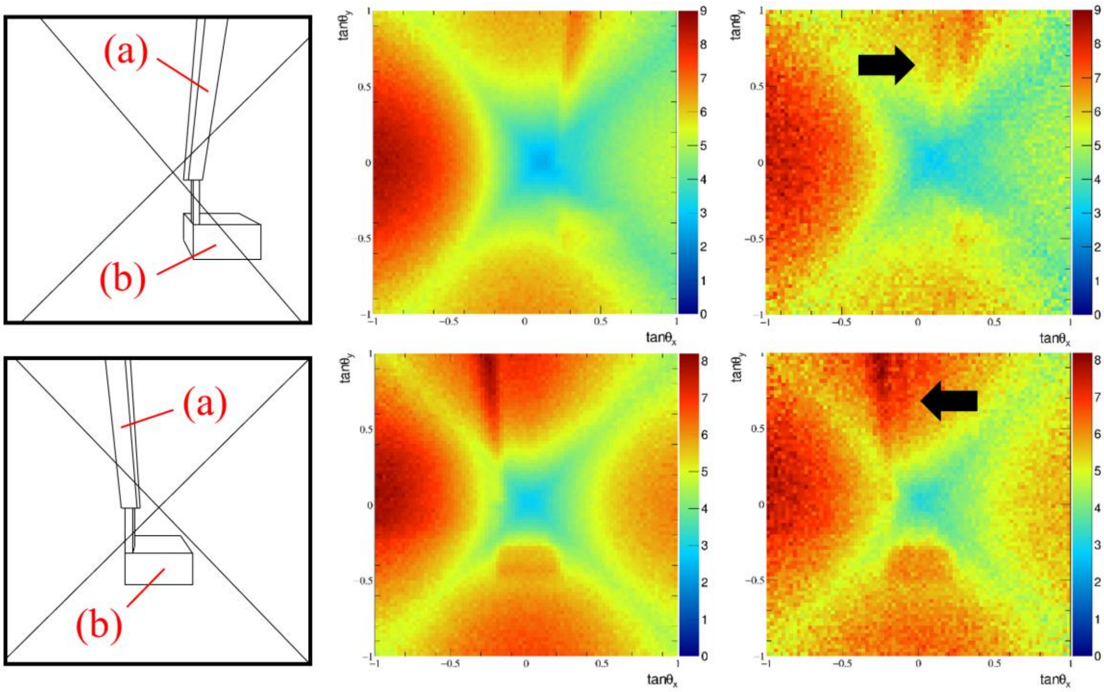

Figure 8: Analysis results from the detectors installed in the Queen's Chamber. The top row shows results from the detector installed in the niche, while the bottom row shows results from the detector installed on the floor. Left: The internal structure of the pyramid within the analysis range of each detector, (a) the Grand Gallery, (b) the King's Chamber. Center: Simulation results [6]. Right: Observation results [6]. The muon excess regions are indicated with arrows.

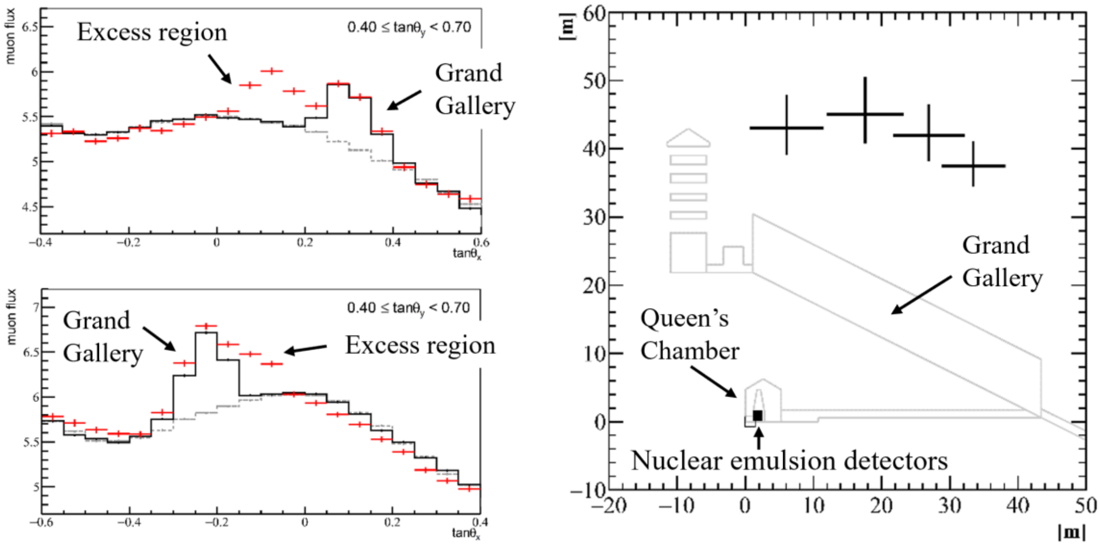

Figure 9: Analysis results from the detectors installed in the Queen's. Left: Muon flux cross-section in the east-west direction, including the muon excess region and the Grand Gallery. The top row shows data from the detector installed in the niche, while the bottom row shows data from the detector installed on the floor. The red line represents observation data, the black line represents simulations, and the gray line represents simulations assuming no known internal structures [6]. Right: The position of the large void is indicated with a cross on the north-south cross-section diagram of the pyramid [6].

3.3 Confirmation with two different detectors

Observations using the scintillation detectors by KEK were conducted at two locations on the east and west sides of the Queen's Chamber. On the east side, 4.8 million events were detected over a five-month period, and on the west side, 12.9 million events were detected over an eight-month period. The analysis comparing the observation results with the simulation results was conducted. The results also confirmed the void discovered by analysis with nuclear emulsion plates. Furthermore, two Micromegas detectors were installed outside the pyramid in the direction of the discovered void and detected a total of 12.9 million tracks over two months. The analysis results showed an excess of muons caused by the discovered void, located in the center of Khufu's Pyramid, along with the Grand Gallery. The new void discovered in the center of the pyramid through independently observation and data analysis from these three detectors was named the ScanPyramids Big Void (SP-BV) (Fig. 10) [6].

3.43D shape estimation for SP-NFC

To elucidate the three-dimensional positions and shapes of SP-NFC and SP-BV, a large-scale observation was conducted in 2019. In this section, SP-NFC, for which the analysis has already been completed, is described [7].

To simultaneously observe SP-NFC, located directly above the Descending Corridor, from multiple points, nuclear emulsion plates were installed at four locations in the Descending Corridor and three locations in the al-Ma'mun Corridor (Fig. 11). In the Descending Corridor, nuclear emulsion detectors with an area of 0.225 m² were installed for a maximum of 211 days.

From these positions, SP-NFC could be imaged from directly below and at a close range, allowing for precise determination of its cross-sectional size, as well as its northern and southern ends. Meanwhile, nuclear emulsion detectors with an area of 0.075 m² were installed for 272 days in the the al-Ma'mun Corridor, located to the west of the Descending Corridor. From these positions, SP-NFC could be imaged from the side, strongly constraining its tilt and length.

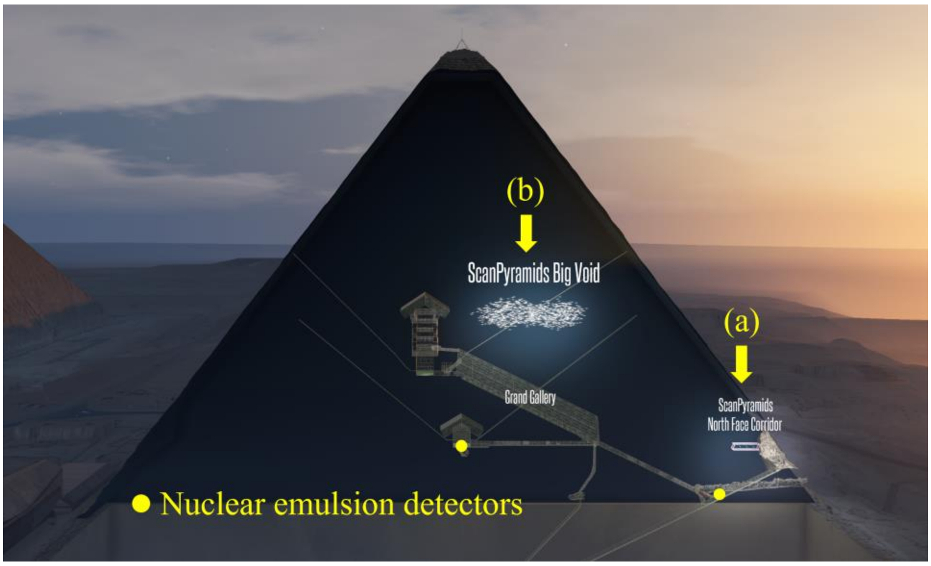

Figure 10: Two voids discovered inside Khufu's Pyramid: (a) ScanPyramids North Face Corridor (SP-NFC), (b) ScanPyramids Big Void (SP-BV).

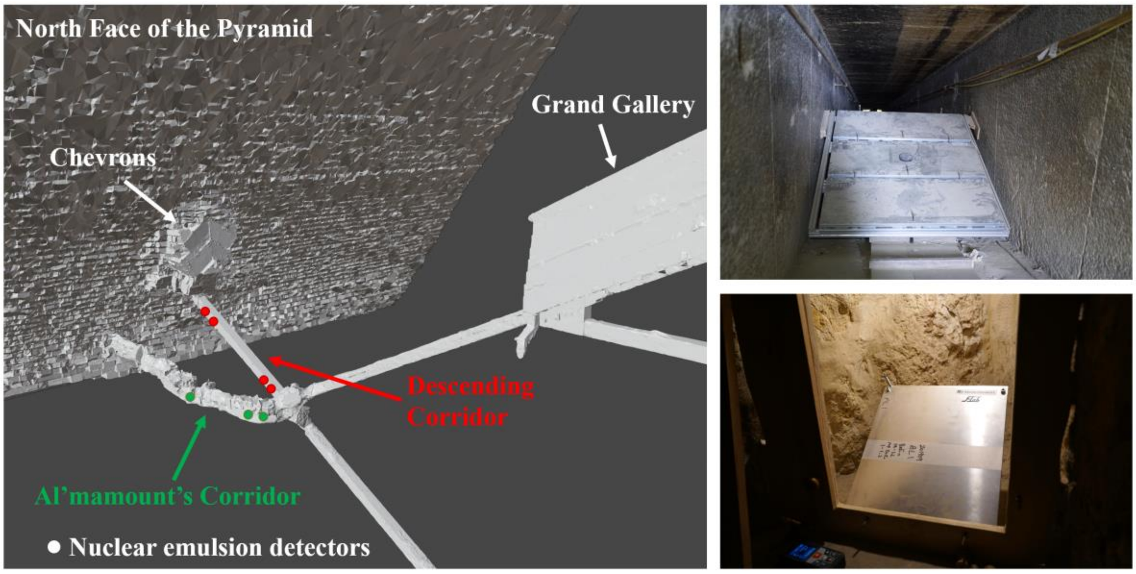

Figure 11: Left: The positions of the nuclear emulsion detectors installed are shown in the 3D model viewed from the south. Detectors were installed at four locations in the Descending Corridor and three locations in the al-Ma'mun Corridor. Right: The top photo shows the detectors installed in the Descending Corridor, and the bottom photo shows the detectors installed in the al-Ma'mun Corridor [7].

The shape estimation of SP-NFC significantly relies on the accuracy of the 3D model used for simulation and the precision in determining the positions and angles of the detectors within the model. For this analysis, simulations were conducted based on a detailed 3D model of the inside and outside of the pyramid created from laser survey conducted by Cairo University. By comparing the simulation results with the observation data, the positions and angles of the nuclear emulsion plates within the 3D model were determined with an accuracy of less than 5 cm and less than 1 degree, respectively. Using this highly precise 3D simulation system, comparisons between Monte Carlo simulations using Geant4 and the observation results confirmed the presence of SP-NFC by all nuclear emulsion detectors (Fig. 12).

The analysis of the observation results from the Descending Corridor estimated the approximate position and length of SP-NFC based on the extent of the muon excess regions obtained from all detectors. Subsequently, assuming that SP-NFC has a rectangular shape, parameters defining its three-dimensional position and shape within the 3D model were varied to find the conditions that best matched the simulation and observation data. Considering the statistics of the observed muons and the precision of the 3D model, an extremely high accuracy of less than 10 cm was achieved for cosmic ray imaging. Furthermore, The observation results from the detectors installed in the al-Ma'mun Corridor, which image SP-NFC from the side, confirmed that SP-NFC has a horizontal structure based on the distribution of the muon excess direction (Fig. 13).

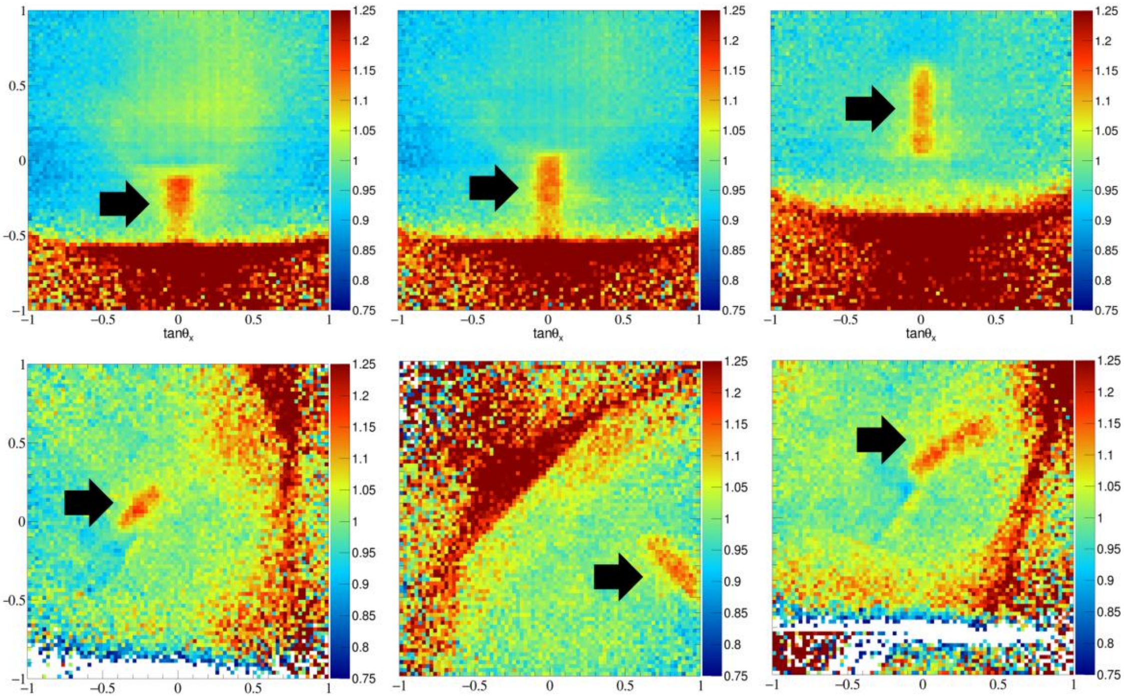

Figure 12: The distribution obtained by normalizing the observation results and simulation results of muon flux and then dividing the observation results by the simulation results. The top row shows the results from the three detectors installed in the Descending Corridor, and the bottom row shows the results from the three detectors installed in the al-Ma'mun Corridor. The red arrows indicate the muon excess regions corresponding to SP-NFC [7].

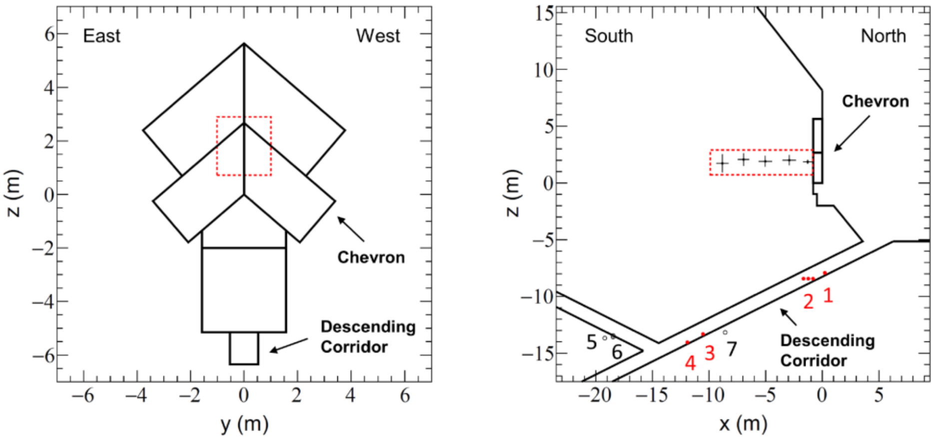

Figure 13: Left: Projection of SP-NFC analysis results onto the structure of the pyramid as seen from the north [7]. Right: Projection of SP-NFC analysis results onto the north-south cross-section of the pyramid [7].

These results revealed several surprising findings. First, SP-NFC is located behind the Chevron. As previously mentioned, the Chevron is a gabled structure also seen in the Queen's Chamber and the Relieving Chambers. Gabled structures are thought to protect the space below them, so there were no archaeological interpretations suggesting the existence of a void behind the Chevron. Second, SP-NFC is located just 80 cm behind the surface of the Chevron. This 80 cm distance exactly matches the thickness of the Chevron slab. In other words, a void sealed off for 4500 years lies just behind a single limestone slab. Additionally, it was found that the floor of this void is only a few tens of centimeters above the depression beneath the Chevron's gabled structure. Following the observations with nuclear emulsion plates, CEA conducted observations using gas detectors at three locations in and around the Descending Corridor. The results were consistent with those obtained by Nagoya University.

Based on these findings, the Technical University of Munich and Cairo University conducted geophysical surveys, including ground-penetrating radar and ultrasonic testing, to confirm the existence of SP-NFC at the location estimated by cosmic ray muon imaging [8] and the results were in complete agreement with the results from cosmic ray imaging. (Fig. 14).

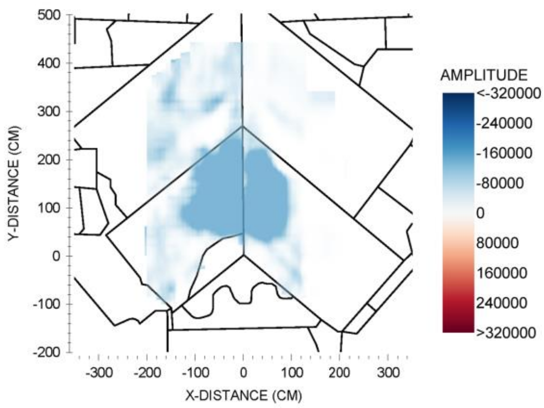

Figure 14: Result of ground-penetrating radar confirmation of the SP-NFC behind the Chevron [8].

3.5 Direct Confirmation of SP-NFC with a Fiberscope

In February 2023, we successfully used a fiberscope to capture images from beneath the floor of SP-NFC through a narrow gap between the Chevron slab and the stone structure behind it (Fig. 15). This imaging was conducted in the presence of several archaeologists, including former Minister of Antiquities Dr. Zahi Hawass and Dr. Mark Lehner from Harvard University. The fiberscope image revealed that the ceiling of SP-NFC has a gabled structure, with the structure above the Chevron continuing directly into the south side of the pyramid to form the ceiling. Furthermore, unlike the interior structures of the pyramid, the floor and walls of SP-NFC are not smoothed into flat surfaces, retaining an unfinished state from 4500 years ago. The reason why such a space was left unfinished remains unknown at this time.

A few days later, an international press conference was held in front of Khufu's Pyramid, led by the Egyptian Ministry of Antiquities. This series of achievements marked the first time in the world that the existence, position, and shape of a void discovered through cosmic ray imaging were confirmed with such precision.

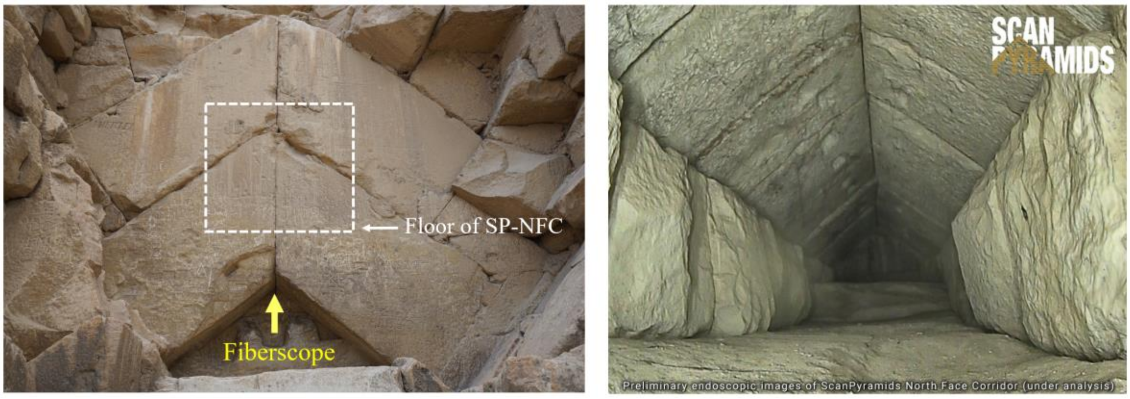

Figure 15: Left: Projection of the estimated location of SP-NFC from cosmic ray imaging analysis onto a photo of the Chevron. The fiberscope was inserted upwards from the position indicated by the yellow arrow. Right: Footage of the interior of SP-NFC captured by the fiberscope.

3.6 Other Observations in Khufu's Pyramid

In 2019, in addition to observations from the Descending Corridor and the al-Ma'mun Corridor, we also conducted observations from the Grand Gallery, the Relieving Chambers, and the Subterranean Chamber (Fig. 16).

The Grand Gallery is located directly below SP-BV, while the Relieving Chambers are situated below and to the south of SP-BV. By observing SP-BV from these multiple locations, we aim to estimate its three-dimensional position and shape. Tourists pass through the central pathway of the Grand Gallery, but we fixed wooden boxes on the stone steps approximately 50 cm wide on either side of the pathway and installed nuclear emulsion plates inside these boxes for observation.

From the Relieving Chambers, we attempted to estimate the tilt of SP-BV by observing it from an oblique angle below. However, the gamma rays originating from the granite that constitutes the Relieving Chambers caused an accumulation of electron tracks due to Compton scattering within the nuclear emulsion plates, increasing noise and making analysis difficult.

The Subterranean Chamber, being the lowest part of the pyramid's internal structure, allows us to visualize the areas around and below the Queen's Chamber that cannot be explored from the Queen's Chamber itself. However, compared to the Queen's Chamber, the transmission rate of cosmic rays is significantly lower, necessitating larger area and longer duration observations. Thus, we installed detectors with 30 nuclear emulsion plates each, covering an area of 2.25 m², at two locations and conducted observations for about six months. We are currently analyzing the data. The total detector area of 4.5 m² is the largest scale for cosmic ray imaging with nuclear emulsion plates.

Figure 16: Detectors installed in Khufu's Pyramid. Left: Grand Gallery, Upper Right: Relieving Chambers, Lower Right: Subterranean Chamber.

3.7 Observations of Khafre's Pyramid

ScanPyramids was interrupted by the Covid-19 pandemic starting in early 2020 but resumed in October 2022, initiating the exploration of Khafre's Pyramid. As previously mentioned, Khafre's Pyramid has already been observed by Alvarez and colleagues. We installed nuclear emulsion plates at the same location in Belzoni Chamber where Alvarez's team had installed their spark chamber (Fig. 17). This allows us to directly verify Alvarez's results, and by installing nuclear emulsion plates tilted at a 45-degree angle in addition to the usual horizontal installation, we can achieve comprehensive exploration of the pyramid from Belzoni’s Chamber. Additionally, we installed nuclear emulsion plates in the Descending Corridor and the subsidiary chamber near the north face of the pyramid, planning to explore the entire range possible with cosmic ray imaging, including areas not observed by Alvarez.

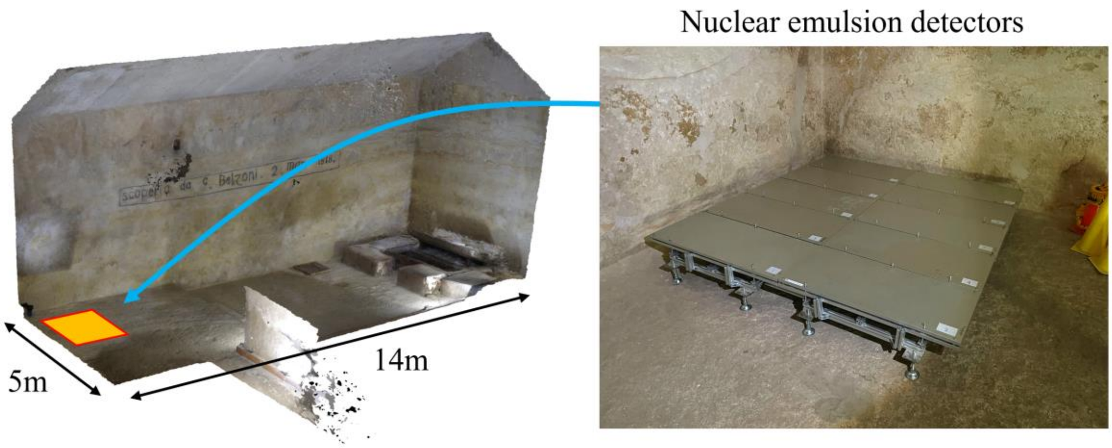

Figure 17: A 3D model of the Belzoni Chamber and the installed nuclear emulsion detectors. The positions of the detectors are indicated with arrows.

4. Conclusion

In this paper, we described the investigation of archaeological sites using cosmic ray imaging with nuclear emulsion plates, focusing on the progress of the ScanPyramids project that began in 2015. By leveraging the features of nuclear emulsion plates, such as their lightweight, compact size, high portability and requiring no power supply, detectors were installed at multiple locations inside Khufu's Pyramid, leading to the discovery of two unknown voids. The SP-NFC, discovered in 2016, was fortuitously located just 80 cm from the pyramid's surface, allowing for its direct confirmation with a fiberscope in 2023. This achievement marks the first instance of verifying a void discovered through cosmic ray imaging, and it is a highly valuable archaeological find. Additionally, it holds significant importance as an interdisciplinary research project utilizing cosmic rays. The next challenge is the direct confirmation of the SP-BV discovered in 2017, which requires precise estimation of the void's position and shape through the analysis of nuclear emulsion plates installed in the Grand Gallery. Furthermore, analyzing observation data from the Subterranean Chamber will extend the range of exploration.

Following the observations of Khafre's Pyramid that began in 2022, we also plan to explore Menkaure's Pyramid, continuing the cosmic ray imaging of the three great pyramids of Giza. Cosmic ray muon imaging not only visualizes internal structures and discovers unknown voids but also calculates integrated density, allowing for the estimation of the pyramids' total weight based on average density derived from their three-dimensional shapes. Differences in the total weight of the three pyramids can provide unique new data reflecting the internal structure, such as the density of the limestone used and the fill ratio of the stones, offering insights into the mysteries of pyramid construction.

The application of cosmic ray imaging to archaeological sites is not limited to Egyptian archaeology but is applicable to archaeological ruins worldwide. It has already been utilized in the investigation of the temple pyramid at the Copan ruins in Honduras of the ancient Mayan civilization, and the underground ruins in Naples, Italy [9], and even ancient tombs in Japan, and it is expected to become a new method for archaeological site surveys in the future.

Acnowledgment

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References

[1] E. P. George, Commonwealth Engineer, 455 (1955)

[2] L. W. Alvarez et al., Search for hidden chambers in the pyramids. Science 167, 832–839 (1970)

[3] Kunihiro Morishima, Nobuko Kitagawa, Akira Nishio, Development of Nuclear Emulsions for Muography, Muography: Exploring Earth's Subsurface with Elementary Particle, Chapter 21, (2022)

[4] M. Yoshimoto, et al, Hyper-track selector nuclear emulsion readout system aimed at scanning an area of one thousand square meters. Prog. Theor. Exp. Phys. 10, 103H01 (2017)

[5] K. Morishima et al., Observation of cosmic rays with nuclear emulsions inside Egyptian pyramids, Proceedings of the 35th ICRC, 295 (2017)

[6] K. Morishima, et al, Discovery of a big void in khufu’s pyramid by observation of cosmic-ray muons, Nature 552, 386–390 (2017)

[7] S. Procureur, K. Morishima et al, Precise characterization of a corridor-shaped structure in Khufu’s Pyramid by observation of cosmic-ray muons. Nature Communications, 14, 1144, (2023)

[8] M, Elkarmoty. et al. NDT and E Int., 139, 102809 (2023)

[9] T. Valeri, K. Morishima et al., Hidden chamber discovery in the underground Hellenistic necropolis of Neapolis by muography, Scientific Reports, 13, 5438 (2023)