Muon Radiography in the Egyptian Pyramids

K. Morishima
Nagoya University
Khufu’s Pyramid

4500 years before

Height: 147m
Width: 230m
Pyramids at Giza

Khufu
Height: 147m

Khafre
Height: 144m

Menkaure
Height: 65m
Scan Pyramids
International Scientific Project

Organization: Egyptian Ministry of Antiquities, Cairo University and HIP institute
Participating countries: Egypt, France, Canada and Japan

Non-destructive Imaging Technologies

- **Muon Radiography**: Nagoya University, KEK, CEA
- Infrared imaging: Laval University
- Laser 3D reconstruction: Iconem

Targets
- Khufu’s Pyramid
- Khafre’s Pyramid
- Bent Pyramid
- Red Pyramid
Target Pyramids

Egypt
Imaging of Pyramid

Side view

Cosmic-ray muons

Muon detector

Angular distribution

Edges of pyramid
Imaging of Pyramid

Cosmic-ray muons

Angular distribution

Edges of pyramid

Side view

Muon detector

Hidden Chamber
Imaging of Pyramid

Cosmic-ray muons

Muon detector

Hidden Chamber

Unexpected muon excess

Angular distribution

Edges of pyramid
Nuclear emulsion
Nuclear Emulsion Film

Three dimensional Tracking Detector for charged particles

Technical advantages

- Sub-micrometric spatial Resolution in three dimension, detection in 4pi steradian
- No electric power, light weight, thin, Water proof -> No limitation to installation place
- Mass production -> Large area detector, multi target, multi position in parallel
Nuclear emulsion

Shielding package

After photographic development

0.075m²

25cm

30cm
Nuclear Emulsion Scanning System based on Optical microscope
Nuclear Emulsion Scanning System based on Optical microscope

Large FOV (5x5mm²) Lens
-> Scanning Speed : 1m²/day

Three Dimensional Track Reconstruction
Scanning System “Hyper Track Selector”
Measurement system of cosmic-ray muons

Nuclear Emulsion

Scanning System

Digital data of three dimensional track
Khufu’s Pyramid

Main entrance

Al mamoun’s Corridor

Grand Gallery

Queen’s Chamber

King’s Chamber

North

South
Tourist root

- The King’s Chamber
- Grand Gallery
- Queen’s Chamber

Diagram:
- South
- King’s Chamber
- Grand Gallery
- Queen’s Chamber
- North
- Main entrance
- Al mamoun’s Corridor
Measurement from Queen’s Chamber
Measurement from Queen’s Chamber
Measurement from Queen’s Chamber
Nuclear Emulsions
Nuclear Emulsion Detector
Measurement from Queen’s Chamber

Axis of Grand Gallery

East

West

King’s Chamber

Grand Gallery

Queen’s Chamber
Measurement from Queen’s Chamber

**Position 1**
Analysis sample: 4.4M tracks
Period: 98 days
Area: 0.45 m²

**Position 2**
Analysis sample: 6.2M tracks
Period: 140 days
Area: 0.45 m²
Observation from the Queen Chamber

Cosmic-ray Image

East

Structures (Simulation)

Grand Gallery

King’s Chamber

West

West

East

King’s Chamber

Queen’s Chamber

Grand Gallery
Observation from the Queen Chamber

Cosmic-ray Image
Muon Flux \((\text{Red}: \text{Many} \leftrightarrow \text{Blue}: \text{Few})\)

Expected (Simulation)

East

West

Grand Gallery

King's Chamber

Queen's Chamber

East

West

Axis of Grand Gallery

Grand Gallery

King's Chamber

Queen's Chamber

Red: Many, Blue: Few
Observation from the Queen Chamber

Cosmic-ray Image

Muon Flux (Red: Many $\leftrightarrow$ Blue: Few)

Expected (Simulation)

East

West

King’s Chamber

Grand Gallery

Queen’s Chamber

Grand Gallery

King’s Chamber

West

Expected (Simulation)
Observation from the Queen Chamber

Cosmic-ray Image

Muon Flux (Red: Many ←→ Blue: Few)

Expected (Simulation)

East

West

King’s Chamber

Grand Gallery

Queen’s Chamber

East

West

Grand Gallery

King’s Chamber
Observation from the Queen Chamber

Cosmic-ray Image
Muon Flux (Red: Many ↔ Blue: Few)

East
Result (Data)

West
Result (Data)
Observation from the Queen Chamber

Cosmic-ray Image

Muon Flux (Red: Many $\leftrightarrow$ Blue: Few)

East

Result (Data)

Excess Region $\rightarrow$ Grand Gallery

West

Grand Gallery $\rightarrow$ Excess Region

King’s Chamber $\rightarrow$ Grand Gallery

King’s Chamber

Queen’s Chamber

Grand Gallery

East

West
Observation from the Queen Chamber

Cosmic-ray Image

Muon Flux (Red: Many $\leftrightarrow$ Blue: Few)

East

Result (Data)

Excess Region

Grand Gallery

King's Chamber

West

Result (Data)

Excess Region

Grand Gallery

King's Chamber
Observation from the Queen Chamber

Histogram
Result (Data)

Excess Region

Grand Gallery

0.40 \leq \tan \theta_y < 0.70

Cosmic-ray Image
Muon Flux (Red: Many $\leftrightarrow$ Blue: Few)

East
Result (Data)

Excess Region

Grand Gallery

King’s Chamber

West
Result (Data)

Grand Gallery

Excess Region

King’s Chamber

Histogram
Result (Data)
Observation from the Queen Chamber

Cosmic-ray Image
Muon Flux (Red: Many $\leftrightarrow$ Blue: Few)

![Histogram](image1)

Result (Data)

Excess Region

$0.40 \leq \tan \theta_y \leq 0.70$

Grand Gallery

![Cosmic-ray Image](image2)

East Result (Data)

Excess Region

Grand Gallery

King’s Chamber

West Result (Data)

Excess Region

Grand Gallery

King’s Chamber
Observation from the Queen Chamber

Cosmic-ray Image
Muon Flux (Red: Many ↔ Blue: Few)

East Result (Data)
Excess Region
Grand Gallery

West Result (Data)
Excess Region
Grand Gallery

King’s Chamber
Queen’s Chamber

King’s Chamber
Grand Gallery

East
West
Observation from the Queen Chamber

King's Chamber
Grand Gallery
Excess Region

Cosmic-ray Image
Muon Flux (Red: Many ↔ Blue: Few)

East
Result (Data)
Excess Region
Grand Gallery

West
Result (Data)
Excess Region
Grand Gallery

East
West

Queen's Chamber
King's Chamber
Grand Gallery
Discovered big void inside Pyramid!

- Cross section is similar to the Grand Gallery
- Length: more than 30m
- Location: 40m away from the Queen Chamber

Future prospect of Khufu’s Pyramid

Revealing precise three dimensional structure
Future prospect of Khufu’s Pyramid

Revealing precise three dimensional structure
Future prospect of Khufu’s Pyramid

Grand Gallery

ScanPyramids Big Void

ScanPyramids North Face Corridor
Future prospect of Khufu’s Pyramid

Revealing precise three dimensional structure
Measurement of density of Pyramid

New technology for archaeological heritage all over the world
Cosmic-ray Imaging

- Volcano
- Fault
- Nuclear Power Plant
- Blast Furnace
- Dum
- Tunnel
- Pyramid
- City
- Tomb
- Underground cavity
- Industrial plants
- Research, disaster prevention
- Geological survey
- Infrastructure Inspection
- Cultural Assets
- Archaeology