LOCATING CHAMBERS IN AN EGYPTIAN PYRAMID USING COSMIC RAY MUONS*

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Just west of Cairo, Egypt, stand the three large pyramids of Giza that are shown in Fig. 1. Archeologists believe that these pyramids were built as monumenta to kings and as protection for the burial chambers of these kings who reigned in what is known as the Old Kingdom.[1,2] The ancient Egyptians believed that at least some people had a chance for life after death, but that for a satisfactory life after death it was important that the body of the deceased not be damaged. Therefore methods of mummification were developed to preserve bodies, and large structures were built to protect the burial chambers. Inside the burial chambers many artifacts were placed to be at the disposal of the person in his afterlife. If an undisturbed chamber were to be discovered in one of the Giza pyramids, we could learn a great deal about the people of that remarkable civilization that built these huge monuments some 4500 years ago.

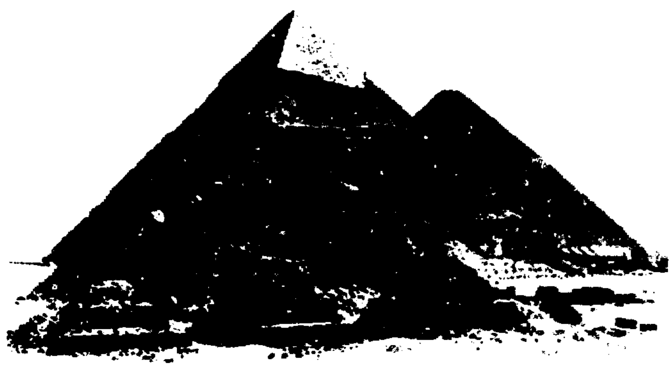


Fig. 1. The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. (Courtesy of the National Geographic Society.)

All of the chambers that have been found in or under the pyramids of the Old Kingdom had been robbed in ancient times and were found all but empty when they were rediscovered by Arab or European investigators. Only one unrobbed burial chamber of the old Kingdom has been discovered. This well-concealed tomb, which was not found until 1925, was near to, but not under the Great Pyramid at Giza. In it were found alabaster and gold vessels, a gold manicure instrument, and many personal objects and pieces of furniture that are believed to have belonged to the queen who was the mother of Cheops, the builder of the Great Pyramid. That such a tomb could escape detection so long shows how ingeneously the ancient Egyptions could conceal their tombs and encourages one to wonder whether a more richly furnished tomb of a king is still concealed inside a pryamid.

The Great Pryamid (Cheop's pyramid) has been an object of wonder from ancient times, as well it should be. This structure, which is built with sides that are true north-south and east-west to an accuracy of a couple of minutes of arc, contains, as Napolean remarked when he saw it, enough rock to build a wall 10 feet high and one foot wide around all of France. With a height of 450 feet it remained the tallest structure built by man for more than 4000 years. Inside the Great Pyramid there is considerable structure. In Fig. 2(a) one can see that in addition to a subterranian chamber there are three sizable cavities inside the pyramid, the so-called king's and queen's chambers and the grand gallery that leads up to the king's chamber.

The Second Pyramid, shown in Fig. 2(b), was built by King Chephren. Though it is very nearly the same height as the Great Pyramid, there are no known chambers inside the pyramid, and only one chamber undernearth it, the Belzoni chamber, named after the Italian explorer who rediscovered it in 1818.

This absence of rooms inside Chephren's pyramid seemed very strange to Professor Luis Alvarez. It seemed inconceivable to him that Chephren, who had watched while his father built the Great Pyramid, with all of its intricate internal structure, would then build a pyramid of nearly the same size with no internal structure at all. It seemed to him much more plausible that Chephren was more clever than Cheops in hiding the chambers in his pyramid and that they have escaped discovery. Luis also realized that one could use the experimental methods of high energy physics to find out in a nondestructive way whether or not such chambers exist.

Thus in 1965 Luis Alvarez proposed puting particle detectors inside the Belzoni chamber under Chephren's pyramid, detectors that could measure the direction of the penetrating cosmic ray muons that go through the pyramid, thereby effectively making an x-ray of the pyramid.[3] Unlike the other components of the cosmic radiation, muons almost never interact in the rock of the pyramid, but, like all charged particles, lose energy as they pass through matter. As a consequence, almost all of the charged particles that get through the pyramid are muons that started with an energy greater than 40 GeV. Since the number of muons that will be stopped in the rock of the pyramid is greater for a greater thickness of rock, the number of muons that get through in any direction can be used to measure the relative thickness of the rock in that direction.

The experiment was funded in 1966, primarily by the U. S. Atomic Energy Commission, with significant support coming from the National Geographic Society, the Smithsonian Institution, the IBM corporation, the Hewlet Packard corporation, and Mr. William Golden. The experiment was

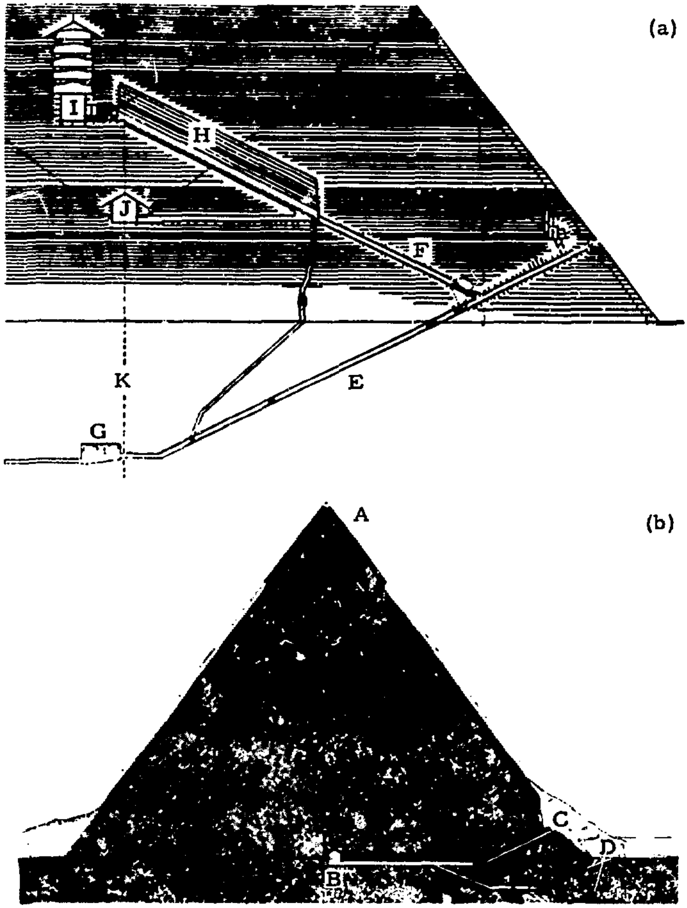


Fig. 2. Cross sections of (a) the Great Pyramid of Cheops and (b) the Pyramid of Chephren, showing the known chambers: (A) Smooth limestone cap, (B) the Belzoni Chamber, (C) Belzoni's entrance, (D) Howard-Vyse's entrance, (E) descending passageway, (F) ascending passageway, (G) underground chamber, (H) Grand Gallery, (I) King's Chamber, (J) Queen's Chamber, (K) center line of the pyramid.

a collaborative effort (The Joint U. A. R. —U. S. A. Pyramid Project) that involved many people from the Ein Shams University in Cairo and the Lawrence Berkeley Laboratory of the University of California, with the assistance of the U. A. R. Department of Antiquities. The equipment was designed and built in Berkeley and installed in the Belzoni chamber and was ready to work in early 1967. But it was not until a year later that actual operations started. Results from the data that were collected in 1968 and early 1969 were reported at the Washington APS meeting in April 1969 and published in Science in February 1970.[4]

Figure 3 shows a picture of the apparatus as it looked in the Belzoni chamber. The schematic diagram in Fig. 4 shows the relative positions of the three counter planes and the two magnetostrictive spark chamber planes. Whenever a charged particle was detected simultaneously in each of thcounters, which occurred about once each second, information from the spark chambers was recorded on a magnetic tape that was in a building outside the pyramid. From this information one could calculate the point where the particle hit each of the spark chambers. Preliminary processing that included this position calculation was done at Ein Shams University on an IBM 1130 computer that was donated by IBM. Subsequent analysis of the data has been done in Berkeley using CDC 6600 and CDC 7600 computers.

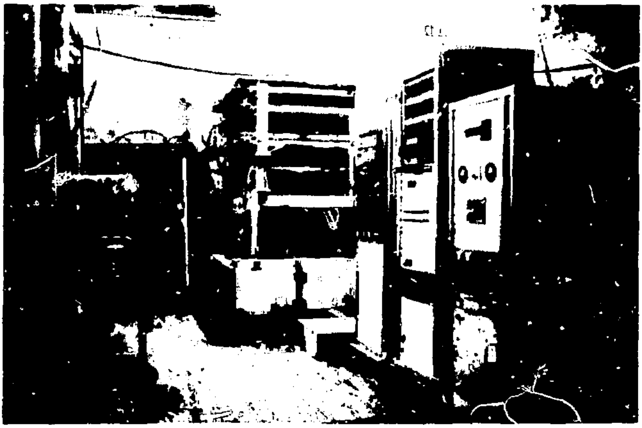


Fig. 3. The equipment in place in the Belzoni Chamber under the pyramid.

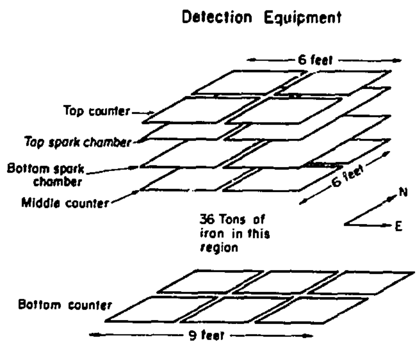


Fig. 4. A schematic diagram of the detection apparatus, showing the relative positions of the scintillation counters and the spark chambers.

The schematic model of the pyramid in Fig. 5 helps one to visualize how the analysis of the data is done. If we had a powerful x-ray generator in the Belzoni chamber that could produce x-rays that could penetrate the pyramid, and if we put a huge photographic plate on top of the pyramid, we would get an x-ray picture of the pyramid. Of course we cannot do this, but we can produce a picture of this type by calculating for every muon that we detected where it intersected such a plane and plotting a dot at that point. The pictures that I will show you are plots of this type, though in some cases techniques have been used to try to enhance the contrast or correct for effects that are instrumental.

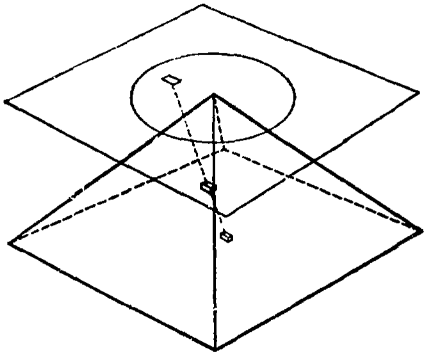


Fig. 5. Geometry of the Second Pyramid, showing the projection technique used to produce a simulated x-ray photograph. The plane on the top of the pyramid can be thought of as the "film plane."

One property of our detection apparatus is that it has maximum efficiency (maximum acceptance) for muons that go perpendicular to the spark chamber planes, and the acceptance becomes zero for a direction near 45° from that plane. Therefore if one looks at the raw data and observes the numbers of events in different directions, the main effect that one will observe is due to this property of the apparatus rather than any property of the pyramid. Figure 6(a) shows a display of the raw data with the contrast somewhat enhanced. In order to look for properties of the pyramid one needs to calculate and correct for the geometrical acceptance of the equipment. Figure 6(b) shows the result of such a correction. On it one can see clearly the light areas at the top and along the edges of the pyramid where the rock is thickest.

The next step of analysis is to correct for the known features of the pyramid to see if any unexpected features stand out. To do this one must use the known geometry of the pyramid, including the surface irregularities, which were measured from an aerial survey of the pyramid. We also must know the properties of the cosmic ray muon spectrum. This happens to be rather simple in our case. To a very good approximation the cosmic ray muons that can get through the pyramid are isotropic (at least out to 60° from the vertical) and obey a simple power law in energy. As a result, the number of muons observed is very nearly proportional to the reciprocal of the square of the thickness of rock that the muons pass through. Figure 6(c) shows the plot with the known features of the pyramid corrected for. As a comparison, Fig. 6(d) shows what the effect would have been if there had been a chamber in Chephren's pyramid about the size of the king's chamber in the Great Pyramid.

Though plots like these are illustrative of the analysis, the most sensitive way to use the data involves a numerical analysis that divides the plot up into many subdivisions and compares the observed population with the predicted population. Such an analysis shows that these data indicate no significant deviation from what is expected from the known pyramid, whereas if there were a king's chamber in Chephren's pyramid [like the one put into Fig. 6(d)] there would be a very significant effect (with a few adjacent bins having effects of five or six standard deviations in size).

The conclusion from this phase of the experiment was that in the region where the experiment had adequate sensitivity (within 35° from the vertical)

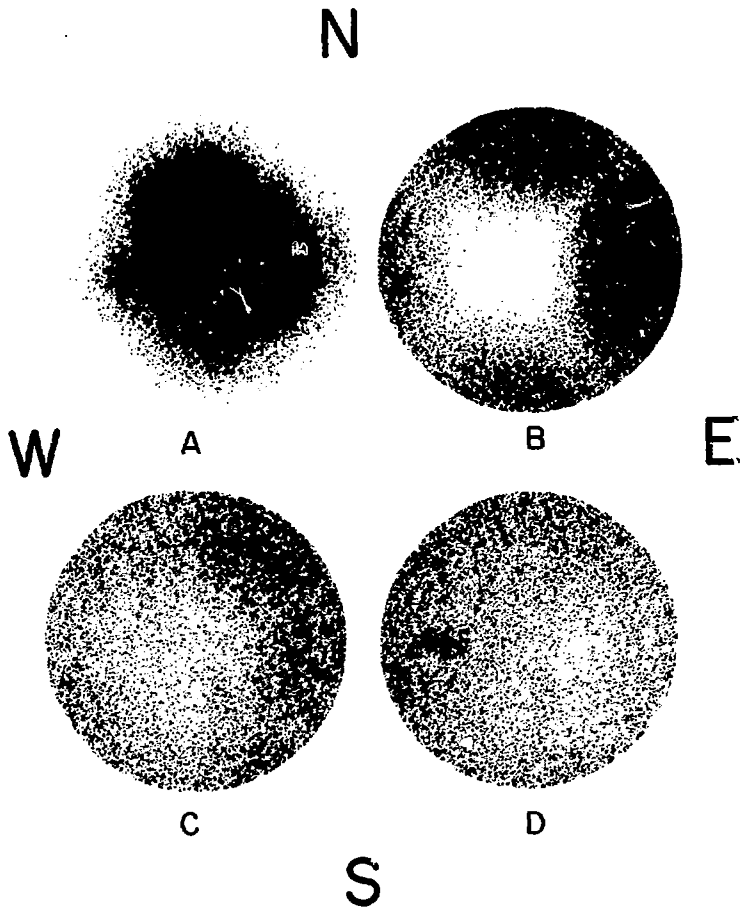


Fig. 6. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure as well as geometrical acceptance. (d) Same as (c) but with a simulated chamber.

there is no chamber as large as the king's chamber. This result did not rule out the existence of a sizable chamber, it only ruled out the existence of a sizable chamber in the region where we looked, a region that covered only about 19% of the volume of the pyramid. Therefore it was of interest to try to look in other directions to explore more of the pyramid.

Last year the National Science Foundation made some money available for the continuation of the project, and a new phase of the experiment is in progress. A University of California employee, Nick Chakakis, is now in Egypt collecting more data. In the present phase of the experiment the same equipment is being used but with a few modifications. Only the top two counter planes are being used, and the equipment is on a mount that allows it to be tilted and rotated in different directions.

Figure 7 shows the data from the first run in this present phase of the experiment. The apparatus was pointed toward the west face and tilted at 45°. This plot, like the one in Fig. 6(b), includes corrections for the acceptance of the apparatus, but, unlike Fig. 6, muons are shown as white dots rather than black dots. The dark area at the top of the picture is the top of the pyramid and the edges of the pyramid are seen as dark areas going out from the top. The top of the pyramid is visible here because the detection equipment in the Belzoni chamber is somewhat to the east of the center of the pyramid. A horizontal line near the bottom of Fig. 7 is at the position of the horizon. There is a large depletion of events near the horizon, because the cosmic ray muon flux falls off greatly near the horizon and also because our detector is a little below ground level. The events that are observed below the horizon line are not due to muons that come up from the ground, but rather are ones that come "backward" through the apparatus from the east.

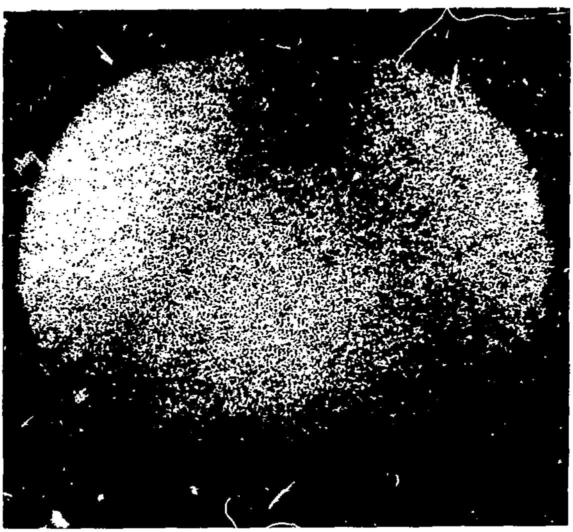
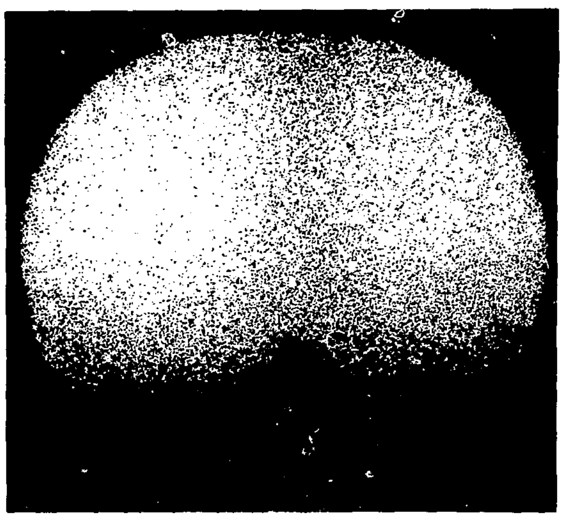


Fig. 7. A simulated x-ray photograph, corrected for the geometrical acceptance of the apparatus, for data collected when the detector was pointed toward the west at 45° from the vertical.

Figure 8 shows data from a run with the apparatus pointed toward the northeast with a tilt of 55° from the vertical. Figure 8(a) shows the raw data (all 380 000 events) with no corrections, whereas Fig. 8(b) is corrected for the apparatus acceptance. On these figures the horizon line is very clearly seen, and on top of the horizon, near the middle, is the "shadow" of the

Fig. 8. Simulated x-ray photographs for data collected when the detector was pointed toward the northeast at 55° from the vertical.

(a) Uncorrected data.



(b) Corrected for the geometrical acceptance of the apparatus.

Great Pyramid seen through about 500 feet of limestone, providing a beautiful demonstration of the method. We have as yet no evidence for the existence of any chambers inside Chephren's pyramid. We are continuing to look and intend to finish the experiment this year.

Footnote and References

*Work partially supported by the U. S. Atomic Energy Commission.

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