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Searching for possible hidden chambers in the Pyramid of the Sun

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Abstract: The Pyramid of the Sun, at Teotihuacan, Mexico, is being searched for possible hidden chambers, using a muon tracking technique inspired in the experiment carried out by Luis Alvarez over 30 years ago at the Chephren Pyramid, in Giza. A fortunate similarity between this monument and the Pyramid of the Sun is a tunnel, running below the base and ending close to the symmetry axis, which permits the use muon attenuation measurements. A brief account of the project, including planning, detector design, construction and simulations, as well as the current status of the project is presented.

Introduction

There is growing interest in measuring atmospheric muons for a variety of applications, ranging from the search for empty cavities in historical monuments [1,2], to monitoring volcanic activity [3], and homeland security [4]. Here we report on the status of an Alvarez-type muon attenuation experiment [1] aimed at solving important archaeological questions in the Mexican Pyramid of the Sun at Teotihuacan. In spite of its fame, little is known about it, one of the largest pyramids in America, or even about the people who built it 20 centuries ago. Early excavations showed no identifiable internal structures of the kind recently uncovered in the nearby Pyramid of the Moon, which are also a relatively common feature in other prehispanic monuments in Mesoamerica. Then, what was the purpose of building such a large structure? was it just a ceremonial monument? or could it be a mausoleum housing the remains of an important person? A revealing discovery made in the early 1970's (shortly after the Alvarez experiment) was the existence of a tunnel running 8 meters under the Pyramid of the Sun, ending beneath its symmetry axis. Besides the archeological implications of such a remarkable finding, it represented the unique advantage of providing a site to install an atmospheric-muon detector to search for possible ($> 1m^3$) cavities in the body of the pyramid. From now on we shall refer to this tunnel (in particular to its end point) as the "observation tunnel".

Here we would like to illustrate the progress being made in this project, emphasizing on aspects of the experiment which may be of interest to experimental cosmic-ray scientists, namely some limitations of the Alvarez method, and an improved readout method for Multi Wire-Chamber Proportional Chambers (MWPC) used in low count-rate muon tracking. Although the basic ideas behind our experiment are not far from those of Luis Alvarez and his team [1], there are important differences between the monuments at Teotihuacan and at Giza, in particular their external shape, their size, and their building materials. Thus new estimates and simulation work [2] have been undertaken to determine the detector design changes required to carry out the experiment at Teotihuacan. First we concentrate the relevant experimental parameters, such as sensitivity, resolution and efficiency, on the basis of what is known about the local muon spectrum, the pyramid's external geometry and internal structure, keeping in mind the Egyptian experiment. We deal with aspects difficult to take into account in a physical simulation, such as the uncertainties introduced by an irregular geometri-

cal shape and the somewhat heterogeneous nature of its matter composition. Then we estimate the spatial resolution of the experiment using GEANT4 [5] simulations in which multiple scattering and other interactions processes are included, as well as the pyramid's physical characteristics, such as its location (latitude and height) its external topogical shape and hypothetical mean internal composition, based on local observations.
Concerning hardware, here we describe the basics of the method, as well as some improvements which have been proposed to improve the resolution while keeping the setup as simple and robust as any field measurement requires.

About the Alvarez method

The Alvarez *et al.* [1] method consists of two important aspects: simulation and experiment. The first part requires the best possible knowledge of the pyramid's external dimensions, its detailed geometrical shape, and a guess of its internal materials (elemental composition and density distribution), all of this assuming that the pyramid is solid (cavity-free). Then, the simulated muon distribution reproduced by a hypothetical detector, having the same structure as the real one, is subtracted from the experimental observations to search for possible differences. Significant deviations in a given direction indicate an appreciable matter density difference in the corresponding subtended volume.
Compared to the Egyptian pyramids, the Mexican one is more difficult to simulate as it lacks a simple geometrical shape. In the early 1920's Noguera, and Gamio excavated a 2*m* high, 1*m* wide tunnel running in a near straight line across the 200*m* pyramid base, and 8*m* above the observation tunnel. This is very valuable, as it supports the hypothesis that the ancient Teotihuacan architects used similar construction materials throughout the entire pyramid, as found in this tunnel. It also represents a well located cavity to be used for calibration purposes. Another important problem is the internal mass density (ρ), as the Mexican monument seems to be more heterogeneous than in the Egyptian case, and its mean value is appreciably smaller than the density of rock. Hence, if the hidden chamber has rocky walls, this could compensate the effect of a gas-filled cavity on ΔM, the difference of matter with or without cavity along the muon path on which the method is based [1]. To quantify this, we defined [2] the detected cavity size L_d as,

$$L_d = L_r - L_w\,(\rho_w - \rho_p)/\rho_p \qquad (1)$$

where L_r represents the real cavity size, L_w is the total wall thickness, ρ_w and ρ_p are the wall and pyramid mean densities.
Then, total wall-cavity compensation for a rocky wall (ρ_w = 2.65 g/cm^3) results when $L_r/L_w = (\rho_w - \rho_p)/\rho_p = 0.4$.
The amount of matter M traversed by a muon along its trajectory of length L inside the pyramid, may be estimated through the underground muon count N. The "sensitivity" ξ of this method may be defined as the ratio,

$$\xi = \Delta N / (N)^{1/2} \qquad (2)$$

where ΔN is the expected signal value and N is the muon count. For the differential intensity we use:

$$F(E, \theta) = \kappa E^n \cos^m(\theta) \qquad (3)$$

where E is the muon energy in GeV, θ is the polar angle referred to the vertical direction, n and m are slowly varying functions the muon energy [2]. The proportionality constant κ in Eq. (3) is mostly a function of the location altitude and affects the observation time T. Using approximations given in [6], which are based on experimental compilations by Hebbeker and Timmermans [7] the differential vertical (θ = 0°) energy spectrum (E< 100 GeV) can be described within a 10% accuracy using a n = 2.687 value. With this approximation, the statistics necessary to obtain a given sensitivity may be estimated using:

$$N \approx \{\xi\, L/[(n-1)X]\}^2 \qquad (5)$$

In the worst case, *i.e.*, when the maximum muon pathlength is $L \approx$ 80 m, the statistics necessary to detect a X = 1 m cave with a sensitivity ξ = 5 would be $\approx 5 \times 10^4$ counts.
Since the Egyptian pyramid is twice as tall as the Mexican one, our experiment is expected to be □ 5 times more sensitive for the same cavity size X.

Another important aspect of the experiment is space resolution, which depends on the detector ability to reconstruct particle tracks. The resolution is quantified as the uncertainty associated to the reconstructed "entry point" of muons on the external boundary of the pyramid. Multiple scattering and detector reconstruction limitations transform this point into a finite size radial (i.e., perpendicular to the trajectory) distribution known as the "point spread function". Roughly speaking, this function resembles a Gaussian having a standard deviation σ_R which can be taken as an estimate of the resolution. Our GEANT4 simulation [2] determined that a $\sigma_R \approx 0.02$ L is to be expected for cavities located in the mid region of the pyramid volume.

The external part of the Pyramid of the Sun has a relatively thin (< 0.5 m) rock layer, most of which was placed there a century ago for weather protection, and an external topology which is more complicated than the Egyptian case.

As an example, we shall simulate an empty volume located in the same location as an existing internal structure in the Pyramid of the Sun located near the top, known as the Smith tunnel. The dimensions of this hypothetical tunnel are 60 $\times$ 2 $\times$ 3 m^3. The resulting dependence of the sensitivity parameter ξ on the horizontal projection angles θ_z and θ_x is presented in Fig. 1 top and Fig. 1 bottom, respectively. Here, the hypothetical Smith tunnel is clearly seen in the top figure ($\theta_z \approx 15^{\circ}$), while in the bottom figure corresponds to the broad structure at $\theta_x \approx -25^{\circ}$.

Experimental aspects

The experimental setup consists on two 1m x 1m scintillator planes, for muon identification and backgrounds rejection, and six MWPC´s for muon tracking. The multi wire detector design is based on practical considerations, such as the simplicity, low cost and reliability, these field applications are often required to have. Concerning readout, low counting rate applications often rely on simple delay line (DL) chains, which reduce the digitizing channels to two, instead of the direct reading alternative, having as many readout channels as wires. Given the rough environmental conditions inherent to some practical applications (remote locations, humid tunnels, etc.), simplified electronics is not only a reduced cost option, but also represents less maintenance. Yet, the position dependence affecting pulse shaping along large DL chains limit the use of standard Constant Fraction Discrimination (CFD) connected on the two preamplified MWPC ends.

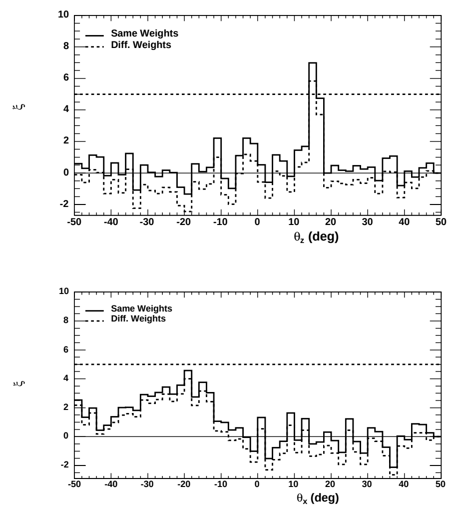

Figure 1: Dependence of the parameter ξ in on the projection angles θ_z (top) and θ_x (bottom). The solid and dashed lines are the result of using different energy spectra [6].

The recent availability of sufficiently fast waveform digitizers (WFD) allowed us to propose [6] the use an alternative readout, in which detailed pulse analysis is carried out offline, allowing room for considerable position resolution optimization. This was experimentally demonstrated [8] using a 1m x 1m, 200-wire, DL-MWPC read through a standard CFD configuration, which is compared here to data acquired using the WFD. The latter mode permitted an off line emulation of a digital CFD-like procedure in which the time constant is allowed to vary with wire position, resulting in a considerable improvement in the position resolution.

The chamber, schematically represented in Fig. 2, has anodes consisting on 200-wire planes. Each wire is 1m long, 25 μm thick, gold-plated tungsten, and are separated 5 mm from one another, also forming a sensitive area of 1m x 1m.

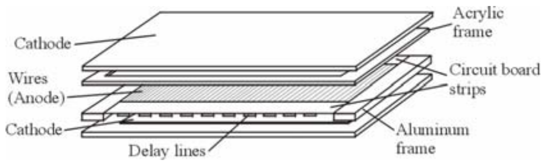

Figure 2: Schematic view of our MWPC's.

To illustrate the space-resolution improvement resulting from our proposed WFD readout [8], in Fig. 3 we compare the best time difference spectra obtained in both, the digital CFD emulation described in this section, and the standard (analog) CFD method.
An overall 50% improvement on FWHM values was obtained, with a reduced position dependence, what demonstrated the advantages of our proposed digital method.

Current status

Over four years have lapsed since this experiment was granted the necessary permissions and funding. As samples of the progress being made, here we discussed briefly two aspects of the project which may be of interest to ICRC participants. Yet, a project like this involves many other technical (and practical) issues, such as installing an electrified, low-humidity laboratory, as well as telemetric communications in the observation tunnel. While this manuscript is being written, we expect to complete the integration and laboratory tests of the full muon tracker within the next months. Then the detector should be transported to the observation tunnel to initiate the data taking, expected to last a minimum of one year.

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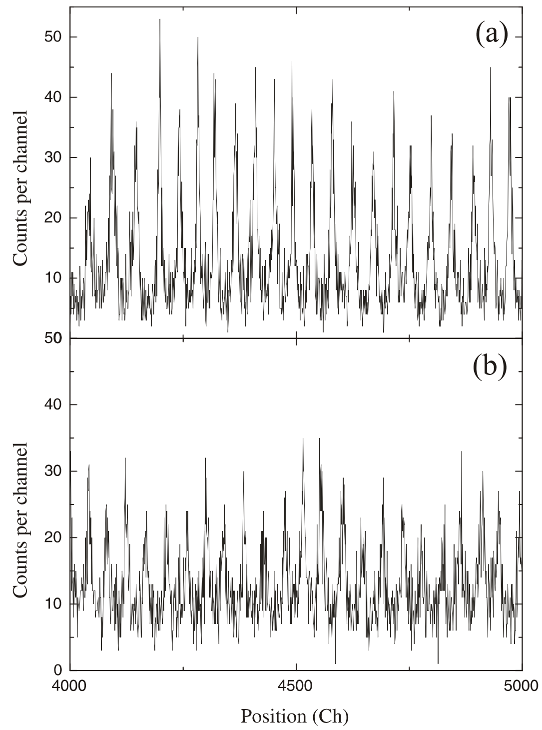

Figure 3: Magnified region of the experimental MWPC muon position spectra, obtained using (a) the digital process, and (b) the standard process.

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