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Cosmic ray telescope

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1 Cosmic rays

The existence of cosmic rays was discovered by Victor Hess in 1912, performing experiments on the ionization of the air. The cosmic radiation is composed by energetic particles mainly originating outside the Solar System and even from distant galaxies. It could be divided into two component: “primary” and “secondary”.

Of primary cosmic rays, which originate outside of Earth’s atmosphere, about 99% are the nuclei of well-known atoms and about 1% are solitary electrons. Of the nuclei, about 90% are protons, 9% are alpha particles and 1% are the nuclei of heavier elements. A very small fraction are stable particles of antimatter, such as positrons or antiprotons.

When cosmic rays penetrate the Earth’s atmosphere they collide with atoms and molecules, mainly oxygen and nitrogen. The interaction produces a cascade of lighter particles, a so-called shower secondary radiation, including protons, x-rays, muons, alpha particles, pions, electrons, and neutrons (figure 1). In first approximation about of 30% of the secondary radiation is composed by electrons and photons, while the 70% by muons.

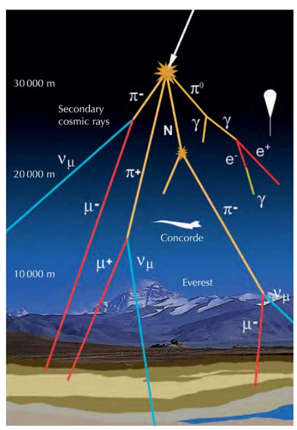


Figura 1: Esempio di cascata dei raggi cosmici.

1.1 Muons

The most considerable part of the cosmic radiation in the lower half of the atmosphere (altitude ≤ 5 km) is muons, produced by the decay of pions and kaons generated by the hadronic interaction of the primary cosmic rays with atmospheric nuclei. The energy spectrum, showed in figure 2, is almost flat below 1 GeV, decreases gradually proportionally to $\propto \mathrm{E}^{-2.7}$. The mean energy of muons at the ground at sea level is ≈ 4 GeV.

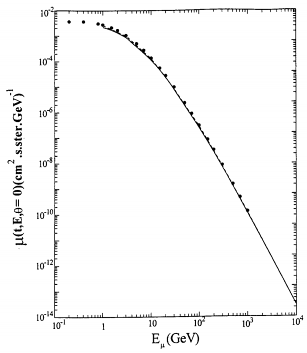


Figura 2: Vertical muon flux at sea level. (Allkofer et al., 1971)

2 Experiment

The idea is to realize a "Cosmic telescope" using a system composed by two detecting unit (SiPM S13360-6050CS Hamamatsu 6×6 mm^2 + Polyvinyltoluene scintillating plastic tile $4.7 \times 4.7 \times 1$ cm^3) assembled on a metal bar that can rotate on a pivot as showed in figure 3. In this way it is possible to measure not only the vertical flux on a surface, but also its zenith angle dependence.

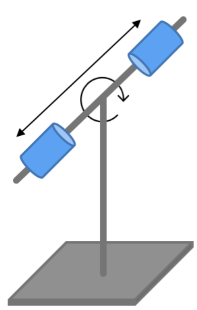
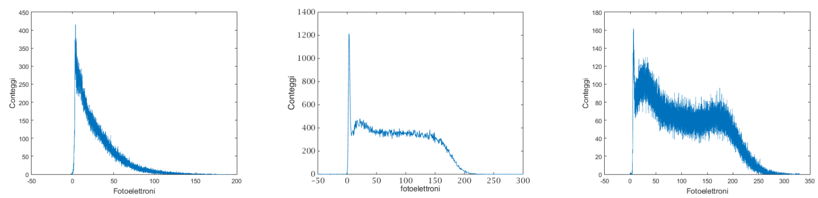


Figura 3: Drawing of the telescope.

Due to the high difference between the SiPM and scintillating material areas, an EJ-560 optical interface sheet thick 1 mm is interposed between them. Moreover, in order to increase the light detection efficiency, the two tile are painted with a reflective coating EJ-510. The improvement due to these expedients is reported in figure 4, where a ^{90}Sr spectrum is visible and the two contributions of Sr and Y are distinguish in figure 4(c).



(a) Without any expedient (b) EJ-560 optical interface sheet (c) EJ-560 optical interface sheet + eflective coating EJ-510

Figura 4: ^{90}Sr spectrum in photoelectrons.

3 Preliminary measurements

3.1 calibration mV-photoelectrons

The first step of the cosmic rays flux measurement is the identification of a methodology in order to determine a calibration between the level in mV of the signal and the photoelectrons generated. Imposing a threshold in mV (the only possible threshold with the Caen kit) it is possible to know the threshold in photoelectrons above which the signal is considered generated by a cosmic ray.

The calibration could be done considering a multiphoton spectrum and a dedicated coincidence system for the trigger of the signal generating the spectrum. The triggering system is a coincidence, schematized in figure 5, between the leading edge discriminator located on the Caen PSAU (Power Supply and Amplification Unit) that can trigger an event when the signal is above a threshold in mV, and the synchronization signal of a ultra-fast LED contained in the kit.

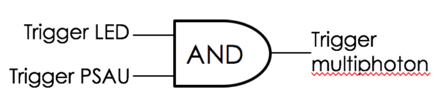


Figura 5: Schema of the coincidence system using for the trigger of the spectrum.

The output of the coincidence is used as trigger in order to realize a multiphoton peak spectrum. In this spectrum, if increasing the threshold of a ΔmV a peak in the spectrum, that corresponds to a certain number of photoelectrons, disappeared, than it is estimated $\Delta mV = 1$ photoelectrons, as showed in figure 6.

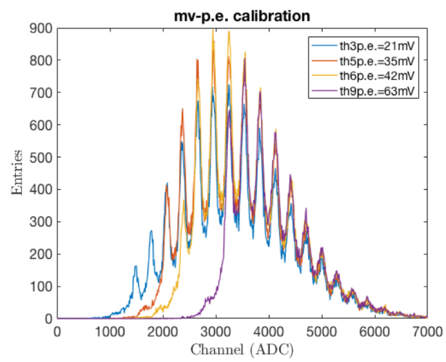


Figura 6: An example of mV-photoelectrons calibration. Increasing the threshold of Δ mV= 1 photoelectrons, a peak in the spectrum disappeared.

At the moment this type of measurement is not possible with the kit but only with an external coincidence module.

3.2 Muons vertical flux on a horizontal single detector

The first measurement consists in verifying the measured flux on single tile[1], knowing the expected rate. Indeed the vertical flux of high energy muons is[2]

$$I_v = 0.82 \cdot 10^{-2} \frac{1}{sr \cdot cm^2 \cdot s}.$$

The flux zenith angle dependence, as discussed in paragraph 5 for unit area is[3]

$$I(\theta) = I_v cos^2(\theta) \tag{1}$$

and so the total flux is calculated integrating the formula 1 over the full solid angle and it is equal to:

$$J\left(\frac{1}{s \cdot cm^2}\right) = \int_{\phi_{min}}^{\phi_{max}} \int_{\theta_{min}}^{\theta_{max}} 0.82 \cdot 10^{-2} \cdot cos^3(\theta) sin(\theta) d\theta d\phi \tag{2}$$

[1] Yet described in experiment guide SG6212 Caen Educational Catolog
[2] Olive et al., Particle Data Group, 2014
[3] Olive et al., Particle Data Group, 2014

The expected rate on a area of 4.7×4.7 cm^2 is equal to 0.45 Hz.

For the experimental the scintillating tiles are removed and the SiPM are powered to the operating voltage, a high threshold (~ 20 photoelectrons) was setted and the setup was shielded by natural background with some pieces of lead and copper in order to achieve a significant reduction of the random count rate (the background rate was less than mHz) and enhance the system sensitivity.

The measured rate of cosmic radiation in this condition is 0.51 ± 0.05 Hz.

4 Measurements with cosmic telescope

4.1 Random coincidence rate

The measurement of flux is provided counting pulses in coincidence generated in a fixed time interval by cosmic rays that pass through the two detectors.

As before, reducing the random coincidence rate, due to the dark count rate (ν_{DCR}) and natural background, below the order of mHz is essential. On an area of fews tens of cm^2 a flux (ν_{cosmic}) of the order of Hz is expected:

$$\nu_{cosmic} \sim Hz/\text{tens of cm}^2$$

The random coincidence ($\nu_{randCoinc}$) in a time coincidence interval of ΔT_{coinc} could be considered equal to:

$$\nu_{randCoinc} \sim 2\nu_{DCR}\frac{\Delta T_{coinc}}{t_{noise}}$$

Imposing a threshold such that the ν_{DCR} is ~ 4 Hz (~ 4 photoelectrons), which corresponds to a t_{noise} of 250 ms, in a time coincidence window $\Delta T_{coinc} = 50$ ns the expected rate of random coincidence is ~ 2.5 μHz.

Experimentally, in order to measure the random coincidence rate, the scintillating tiles are removed and the two SiPMs are powered to the operating voltage, connecting their power cable and MCX cable to the two channels of PSAU SP5600.

Fixed a threshold at ~ 4 photoelectrons, the rate of random generated pulses in $\Delta T_{coinc} = 50$, setted on the default software in the panel “Digital Output”, is < 5mHz

5 The zenith angle dependence of the cosmic ray flux

Assuming that the curvature of the Earth can be neglected and that the cosmic ray intensity (I) depends only on the amount of matter that the particle traveled through, the zenith angle dependence of the intensity can be expressed as in equation 3:

$$I(\theta, X_h) = I(0, X_h) exp\left(\frac{X_h}{\Lambda}(1 - sec(\theta))\right) \quad (3)$$

In the equation 3 X_h (g/cm^2) represents the the vertical depth while Λ is attenuation length of a particle passing through matter.

Generally, the zenith angle dependence can be expressed as

$$I(\theta, X_h, E) = I(\theta = 0) cos^{n(X_h, E)}\theta \quad (4)$$

where $n(X_h, E)$ depends on the cosmic rays energy and the atmospheric depth. From experimental data the overall angular distribution of muons has a dependence of n$\sim$ 2 [4].

In order to verify this trend it is necessary to fix the distance between the two detectors as needed. For example in figure 7 the distance is fixed at 7.5 cm and the rate of cosmic radiation is measured in coincidence between the two detectors for 12 different angles.

In order to perform this measurement the two scintillating tiles are inserted in the holders and the SiPMs are powered to the operating voltage, connecting their power and MCX cables to the two channels of PSAU SP5600. The coincidence window is switch on and setted in the panel “Digital Output” at 50 ns.

The interval time of counting measurements is fixed in order to reach a relative error of $\sim 10\%$.

Figure 7 shows the frequencies of cosmic rays measured at different angles θ. The frequencies does not drop at 0 Hz for large θ ($\theta > 75^\circ$) but reach a plateau value. The data are fitted with the theoric curve $a \cdot \cos^2(b \cdot \theta) + d$. The parameter d estimates the value of plateau for large angles and is equal to 0.0089 ± 0.0007 Hz.

[4] Grieder, *Comsic Rays at Earth: Researcher’s Reference Manual and Data Book, Elsevier, 2001*

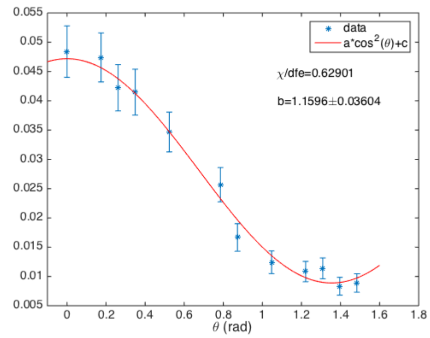
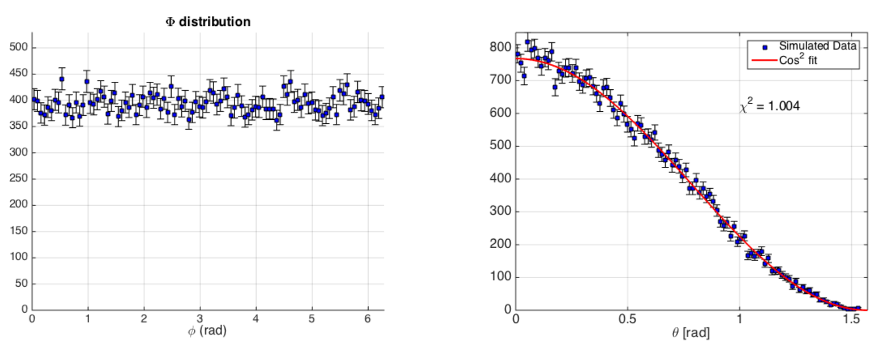


Figura 7: Cosmic rays flux as a function of zenith angle θ. The trend is described by a $\cos^2(\theta)$ function.

6 Simulation

A geometric simulation is implemented in order to estimate the expected flux and the measurement time to reach a desired relative error.

The first step consists in the simulation of the angular distribution of the incident rays. Cosmic rays impact on the tile uniformly in X and Y coordinates. The direction of rays is determined by two angles: the zenith angle (θ) and the polar angle (ϕ). The polar angle is simulated considering its distribution uniformly in the interval $[0, 2\pi]$, as imposed by the theory, while the zenith angle is simulated in an interval $[0, \pi/2]$ with a distribution $\propto \cos^2(\theta)$. The simulated distributions are showed in figure 8.



(a) Distribuzione dell'angolo polare. (b) Distribuzione dell'angolo azimutale.

Figura 8: Simulated angolar distribution of the incoming cosmic rays.

The second step is the determination of the impact point projection on the second detecting layer fixed at a distance z knowing that:

$$\begin{aligned} \Delta x = z \cdot sin(\phi)tan(\theta) \\ \Delta y = z \cdot cos(\phi)tan(\theta) \end{aligned} \tag{5}$$

If the ray impacts outside the second detecting layer, it is rejected. The fraction of rejected rays ε is the parameter that allows to estimate the measured flux (ν_f) by equation 6:

$$\nu_f = \varepsilon \cdot \nu_i \tag{6}$$

where ν_i is the initial expected flux on a single tile and is equal to 0.45 Hz (par. 3.2).

A graphic representation of this geometric simulation is reported in figure 9:

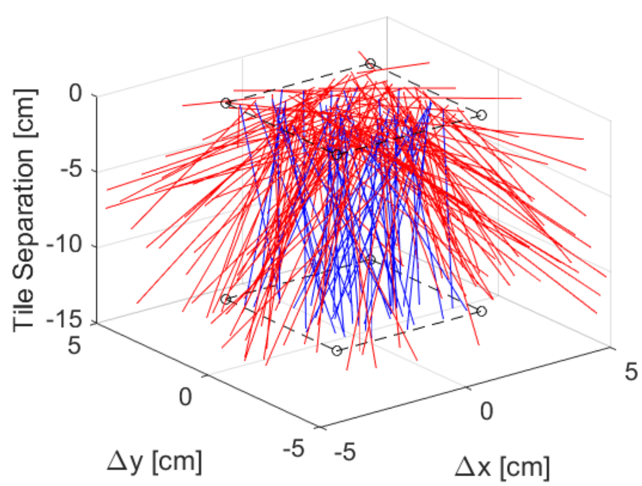


Figura 9: Simulation of cosmic telescope. The rays that impact outside the second scintillating are represented in red, while the blue ones are that impact inside.

The validity of the simulation is evaluated fixing the angle θ of the telescope at 0° and varying the distance between the detectors at [0, 0.7, 1.2, 2.3, 3, 4.1, 5.4, 6.9, 8.5, 10.5, 11.8] cm. The discrepancy between the measured rate and the simulated one could be described by a second-degree polynomial function $y = ax^2 + bx + c$ as showed in figure 10. The discrepancy increases as increasing the distance z between the detectors.

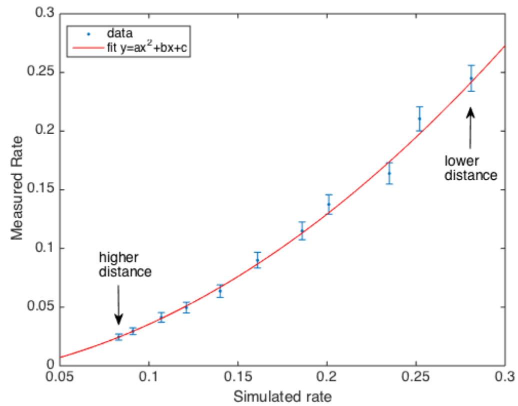


Figura 10: Trend of the measured rate as a function of the simulated one that allows to correct the predictions of the geometric simulation.

Obtaining an estimation of the expected flux (ν_f), it is possible to determine the measurement time (T) necessary in order to perform the measurement with a certain relative error (η) decided by the user, as described by the equation

$$T = \frac{1}{\eta^2 \cdot \nu_f} \tag{7}$$

7 Conclusions

A cosmic telescope in order to perform an experiment about the zenith dependence of the cosmic radiation flux is realized, pointing out also some critical issues about the current set up produced.

Some measurement are performed in order to verify the $\cos^2(\theta)$ trend of the cosmic flux measured by two detectors. The theoretical trend is confirmed within a confidence level of 1σ. A discrepancy is evident only at large angles ($> 75°$), where the flux reaches a plateau value and does not drop to 0.

In order to realize a sturdy educational experience for the students a geometric simulation of this model is implemented. In this way the user can change the distance between the two detectors, the angle of telescope inclination and the relative error of the measurement.