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Educational measurements of cosmic rays using small scintillation detectors

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Summary. — An experimental set-up, based on a small plastic scintillator tile with an embedded wavelength shifter fibre and APD sensors has been used to perform educational cosmic rays measurements. Readout electronics has made advantage of *Quarknet* card timing capabilities. The time-over-threshold technique has been exploited as a simple method to extract information about the signal amplitude, in order to estimate the energy deposit in the detector. Coincidence measurements have been performed both in two-fold and three-fold configurations, unveiling the possibility to reconstruct the shower axis using the triangulation method.

PACS 01.40.E – Science in school.
PACS 01.50.Pa – Laboratory experiments and apparatus.
PACS 29.40.-n – Radiation detectors.
PACS 96.50.S – Cosmic rays.

1. – Introduction

Cosmic rays physics experiments are particularly suitable as educational activities to introduce high school and undergraduate students to various aspects of modern physics and related experimental techniques. They do not require big and expensive facilities like particle accelerators and related concerns on radiation protection. Experiments involving cosmic rays physics can make use of very different experimental set-ups, from very simple one (like just one or a small array of Geiger counters in coincidence) to more complex arrays employing scintillator-based or gaseous detectors. An example of the latter configuration is the EEE Project which involves several Italian high schools and scientific institutions [1]. A more complete review of such experiments may be found in [2].

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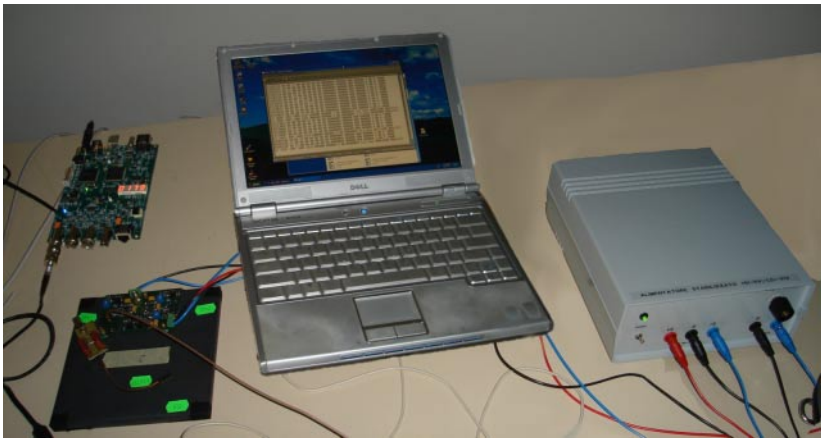


Fig. 1. – Experimental set-up: scintillation tile (bottom left corner), *Quarknet* card (top left corner), PC with *hyperterminal* connection, power supply.

An intermediate solution could be arranged using small scintillator-based detectors. In the past, scintillation light produced at the passage of the ionizing particles in the sensitive volume of such detectors was usually collected by photomultipliers. However these devices are not very practical and their use could be challenging in some situations because of their massive dimensions, fragile structure and considerable costs. In relatively recent years new devices, such as Avalanche Photo Diodes (APD) and Silicon Photomultipliers (SiPM), have been developed and have replaced standard photomultipliers in many applications.

A station made up of few single scintillator detectors as large as 10–20 cm placed at distances of the order of 5–15 m, if operated in coincidence, may be suitable to detect and reconstruct extensive atmospheric showers in an energy range of the order of 10^{14}–10^{16} eV. Different stations may constitute an array, with relative distances of hundreds meters or even few km. An example of a large extended array is the SEASA Project in Stockolm [3]. Different physics items may be exploited: the detection of extensive air showers and their arrival distribution, the dependence of the detected flux on the weather conditions, the correlation between different telescope stations, and so on.

To reduce costs and achieve a relatively easier operation, in order to be used also with high school teams or in undergraduate laboratory courses, a small scintillation tile [4] was used. Most of the needed electronics was obtained using a *Quarknet* acquisition card, developed at Fermilab specifically for this kind of purposes [5].

2. – Experimental set-up

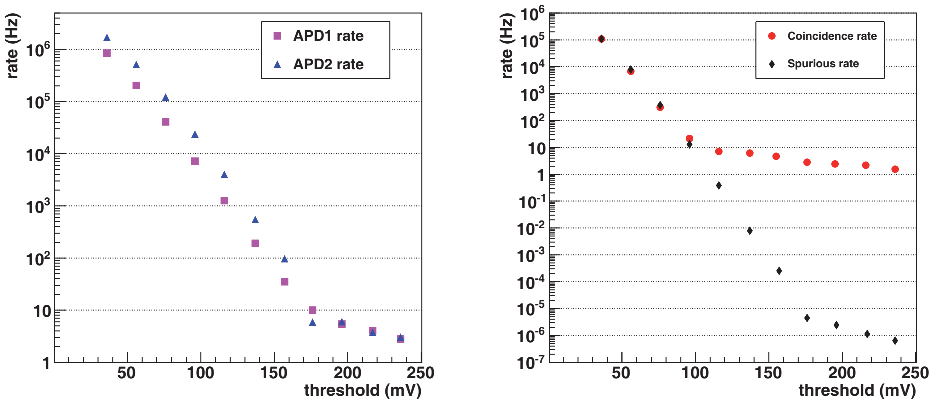
2·1. *Scintillation detector*. – The detection set-up is based on a small plastic scintillator tile (15 cm × 15 cm, thickness 1 cm). The readout electronics is mounted on a small board fixed on the tile itself (see fig. 1). Such detectors have been also employed to build high-granularity systems for triggering cosmic muons in the test of the ALICE TOF modules at CERN. A two-coils wavelength-shifter (WLS) optical fibre is embedded in a circular groove machined in the scintillator. Two avalanche photodiodes (Metal Resistor, MRS APDs) are glued at each end of the WLS fibre to collect the scintillation photons.

Such devices do not require high voltage power supplies, since they are planned to be operated at a low voltage. The readout electronics provides a digital ECL signal when either one or both APD sensors pass an adjustable threshold. However the ECL signal is not standard since its length is variable and, as it will be discussed in the following, it is related to the time-over-threshold of the original analog signals. A selectable jumper allows the choice of one of three possible operational modes (APD 1, APD 2, APD 1 & 2), with a common threshold, which can be adjusted between 30 mV and 250 mV. The analog signals from the single APDs can be extracted as well from the readout card. Each detector module needs a ±5 V for the electronic card mounted on the detector and a variable voltage, in the order of 30 V for the APD bias. Home-made power supplies have been employed to reduce costs. Several modules based on this set-up were recently tested for further measurements [6].

2˙2. *Electronics and data acquisition.* – For a station made by up to 4 individual detectors, a *Quarknet* card may be used (see fig. 1). This card, developed at Fermilab, is distributed to educational institutions to provide a useful tool for educational cosmic ray experiments. It may accept up to four analog/digital signals from photomultipliers or other detectors, and provides discriminator and trigger logic for the four channels. In addition, the relative time between the individual inputs is also available, which allows to perform time measurements of the rise and fall times (0.75 ns resolution) associated to each input signal. Other capabilities of the card are the absolute time stamping of the events, provided by a GPS receiver, with a resolution of 40 ns, an atmospheric pressure sensor, and five built-in scalers (with a 4-digits numerical display), to record the four individual inputs plus the trigger counts. The output stream from the card may be sent to a PC via USB and *hyperterminal* connection. The stream consists of ASCII lines which can be decoded off-line to extract all the relevant information for the collected events, including rise and fall time of the signals involved and UTC standard time stamp if available. Additional commands allow temperature and barometric pressure to be read, as well as other information on the GPS data (number of visible satellites, reliability of the signal). Trigger logic is implemented using a programmable logic device chip, which allows any trigger logic, from singles to 4-fold coincidences. Discriminator output pulses are sent to TDCs, to measure the time associated to leading and trailing edges of each pulse relative to the internal clock (25 MHz). Specific additional information on the *Quarknet* card may be retrieved from the *Quarknet* Collaboration [5].

3. – Preliminary tests and signal analysis

3˙1. *Threshold tuning.* – Preliminary tests of a possible detection set-up were first carried out on each individual tile, by measuring its count rate in single mode (APD 1 or APD 2) and in coincidence mode (APD 1 & 2). Figure 2 reports the results for one of the tested detectors. From these results, it is apparent that the single rate is very high at low threshold. As the threshold approaches 170 mV, the rate nearly equals that expected for the true cosmic muons traversing the detector (in the order of 10 Hz). The experimental count rate of the coincidence signal (APD 1 & 2) was compared to that expected for random coincidences. The width of the coincidence window was estimated from the data measured at very low threshold, where the spurious rate overwhelms the rate due to the passage of cosmic particles. When operated in coincidence mode, the threshold may be lowered to about 120–130 mV, still maintaining the spurious rate at a negligible level, in the order of 0.01 Hz or even less.



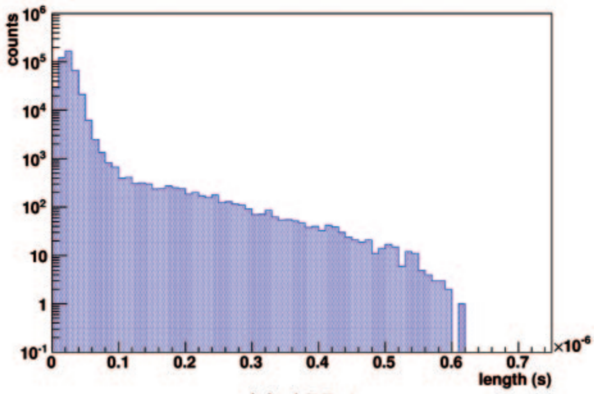
(a) *Single APD rates* (b) *Coincidence rate*

Fig. 2. – (a) Rate of the single APDs as a function of the applied threshold. (b) Rate of the coincidence signal as a function of the threshold compared with the spurious rate.

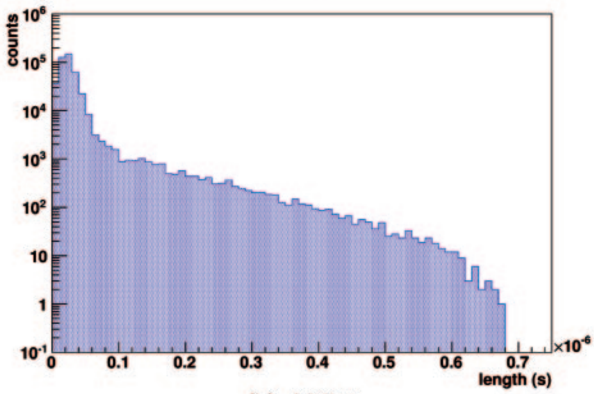
3·2. *Detector light collection.* – The signal amplitude delivered by each of the two photosensors reflects somehow the energy deposited by the passage of cosmic particles in the sensitive volume of the scintillator tile, convoluted by the effect of the light collection process in the WLS fibre and the efficiency of the photosensor. A good approximation of the magnitude of the signal amplitude may be obtained by the time-over-threshold technique, which is included in the capabilities of the *Quarknet* card. Figure 3 shows typical distributions of the signal amplitudes of the two photosensors, by their time-over-threshold. Also shown is the distribution of the coincidence signal amplitude provided by the readout front-end card.

Another interesting feature is the correlation between the signal amplitudes of each photosensors and their sum. In each event the scintillation photons emitted at the passage of the particle are conveyed at the two ends of the WLS fibre and eventually collected by the two photosensors. For a fixed total number of photons produced in the scintillation plate, the amount of light collected by each photosensor should show a dependence on the position hit by the particle. For example if the cosmic particle produces the scintillation light very close to one of the two ends of the WLS coils, it is very likely that one photosensor will collect most of the photons while only a small fraction of them will reach the other one. From this, it is apparent that for a fixed total amount of scintillation light the prediction is an anticorrelation between the signal amplitude of each photosensors. Figure 4a shows the correlation between the amplitudes A0, A1, measured in the two photosensors, for a given interval of the sum A0+A1, which is a very good approximation of the total scintillation light produced. A net anticorrelation is observed between the two amplitudes, whereas a point region would be expected for a symmetric sharing in the number of collected photons between the two photosensors.

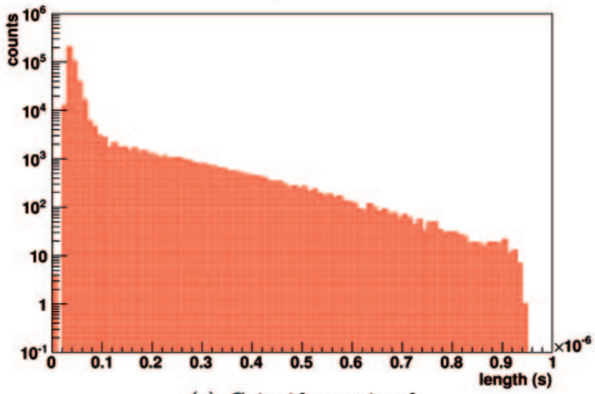
The coincidence signal provided by the readout front-end card is an ECL signal. Its width is proportional to the time during which the two signals are both over threshold. It follows that this width (obtained by the use of the time-over-threshold technique) is roughly equivalent to that given by the sum of the two analog amplitudes. A rough correlation between the two quantities is expected, which is shown in fig. 4b.



(a) *APD 1*

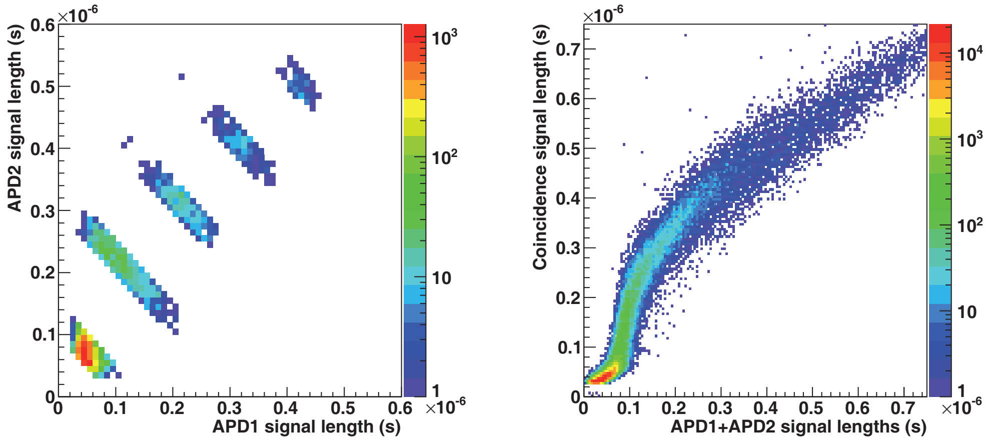


(b) *APD 2*



(c) *Coincidence signal*

Fig. 3. – Signal length distribution of the three channels (APD1 (a), APD2 (b), coincidence signal (c)).



(a) (b)

Fig. 4. – (a) APD1 signal length *vs.* APD2 signal length for different slices of the sum APD1+APD2 (100–150 ns, 300–350 ns, 500–550 ns, 700–750 ns, 900–950 ns). (b) Coincidence signal length *vs.* APD1+APD2 signal length.

4. – Coincidence measurements

4·1. *Time difference spectrum.* – Correlation between different cosmic particles hitting simultaneously two or more detectors can be measured using the time capabilities of the *Quarknet* card. Muons belonging to the same atmospheric shower are predicted to lie in a "pancake" thick few hundreds of nanoseconds. However most of them are actually very close each other (in the order of few ns) and the difference in the arrival times is mostly due to the inclination of the shower with respect to the plane in which the detectors lie. Setting up a proper time window for the *Quarknet* card it is possible to detect such coincidences with two or more detectors located at various distances. Figure 5 shows the time difference spectrum for two detectors placed close each other, 120 cm and 480 cm respectively. To build the time difference the rise front of the signals from each detector was considered. The centroid of the distribution is shifted a few ns from zero, simply due to the different cable length in the two channels. The RMS of the distribution increases from about 4–5 ns (when the detectors are very close or separated by about 1 m) to about 11 ns, for a relative distance of 5 m. Such values incorporate both the intrinsic time resolution of the detectors and the associated electronics, as well as the difference in the arrival time of the secondary cosmic particles to the two detectors, which is statistically greater at growing distances.

Table I reports the coincidence rate as a function of the distance measured in the three configurations mentioned above. The last value, measured at about 5 m distance, corresponds to about 70 coincidences/day, which is much larger than the expected random coincidence rate, smaller than 1/day in a time window of 50 ns. This gives the possibility to separate the individual detectors of even larger distances.

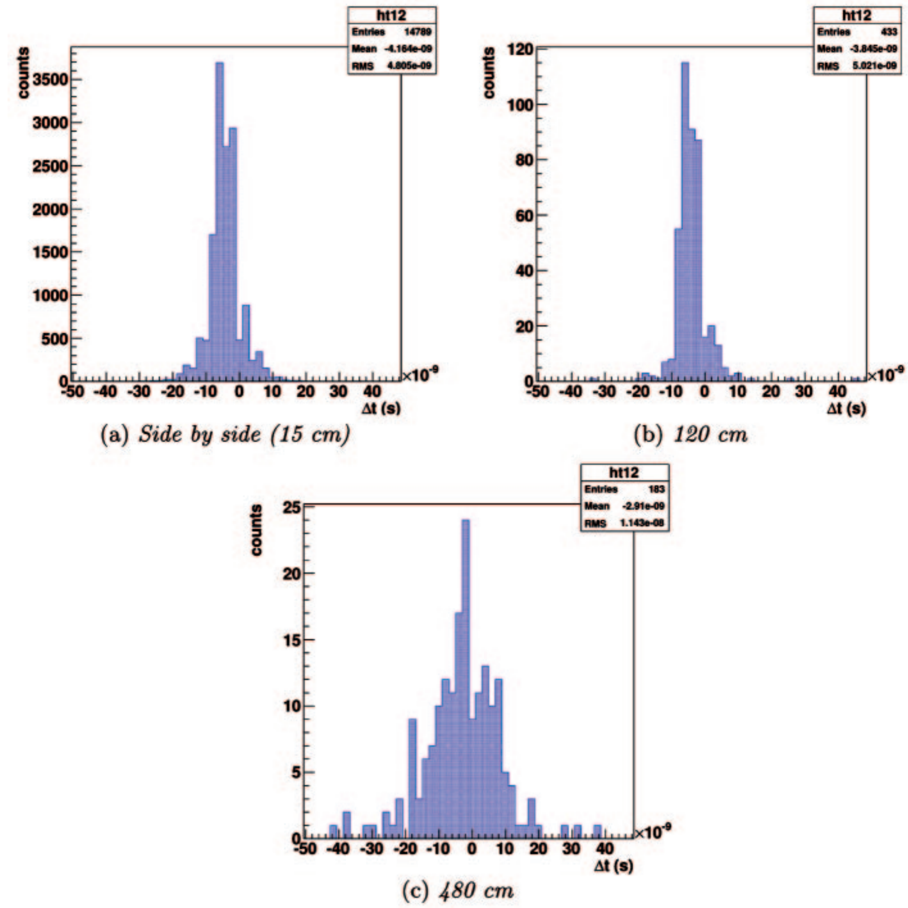


Fig. 5. – Time difference spectrum at various distances. (a) 15 cm; (b) 120 cm; (c) 480 cm.

4·2. *Triangulation*. – At least three detectors are needed to perform a simple triangulation measurement. As sketched in fig. 6 the difference between the arrival times of muons belonging to the same shower is related to its inclination with respect to the plane determined by three detectors in the space. Simple mathematical steps are needed to

TABLE I. – *Summary of coincidence measurements at different relative distances.*

Relative nominal distance (cm)	Coincidence rate (Hz)	Approximate no. of expected events/day
15	0.06 ± 0.0005	5200
120	0.005 ± 0.0002	430
480	0.0009 ± 0.00007	75

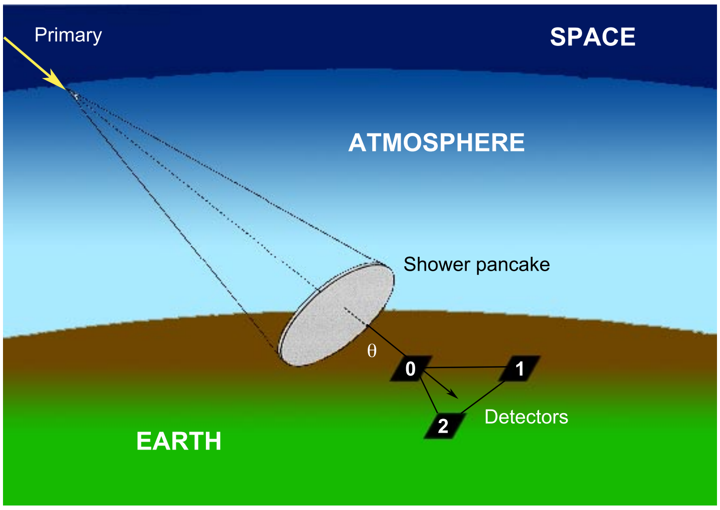


Fig. 6. – Primary cosmic ray produces a shower "pancake" which allows the three detectors to determine the incident angle.

make this relation explicit:

$$A = c\frac{d_2 - d_1\frac{y_2-y_0}{y_1-y_0}}{(x_2-x_0)-(x_1-x_0)\frac{y_2-y_0}{y_1-y_0}},$$

$$B = c\frac{d_2 - d_1\frac{x_2-x_0}{x_1-x_0}}{(y_2-y_0)-(y_1-y_0)\frac{x_2-x_0}{x_1-x_0}},$$

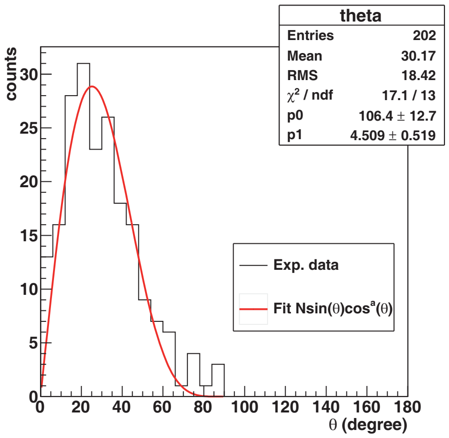
$$A = c\cos\theta\sin\phi,$$

$$B = c\cos\theta\cos\phi,$$

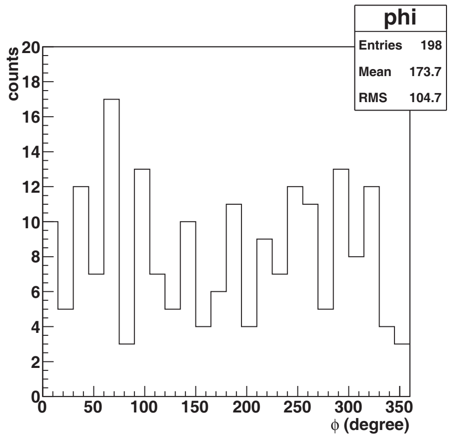
where $d_i = c(t_i - t_0)$, t_i is the arrival time of the muon at the i-th detector, (x_i, y_i) is the position of the i-th detector and (θ, ϕ) is the axis direction of the incident shower.

With four or more detectors redundant information is available, thus allowing more precise measurements. Different approaches can be used in this latter case, however leading to similar formulae.

Three detectors were employed to perform these measurements. They were placed at the corners of an equilateral triangle of 5 m side. All two-fold coincidence events were stored, while in the analysis procedure only three-fold coincidences could be used for triangulation calculations. Three-fold coincidence rate is relatively low, and about 10 days of measurements were required to gain about 200 events. Figure 7 shows the zenithal and azimuthal distributions of the shower direction. The zenithal distribution has a characteristic shape, whereas the azimuthal distribution is flat (actually, as it is well known, a slightly east-west asymmetry is expected, but much more statistics would be needed). The zenithal distribution is a convolution of a geometric effect (solid angle dependence on $\sin\theta$), which is dominant at low angles, and the real distribution of cosmic muons, which rapidly goes to zero at high angles. When measured as single particles, cosmic muons are expected to show a $\cos^2\theta$ distribution. However, since they



(a) θ *distribution*



(b) ϕ *distribution*

Fig. 7. – (a) Zenithal (θ) and (b) azimuthal (ϕ) distributions obtained with the triangulation method.

are measured in three-fold coincidence, their distribution is expected to be proportional to a higher power of $\cos\theta$. A fit with the function $N \sin\theta \cos^a \theta$ was performed, which is shown in fig. 7a. The parameter $a = 4.5$ gives the exponent of $\cos\theta$. The probability of two or more independent events occurring at the same time is equals to the product of the probabilities of the individual events. This simple statistical argument would lead to $a = 6$, provided that the three events being considered, *i.e.* three muons hitting simultaneously the three detectors, were independent. However because the muons are supposed to belong to the same shower, thus making them somehow correlated, the expected exponent is accordingly smaller.

5. – Conclusions

The possibility of making use of a relatively minimal set-up to perform educational experiments involving cosmic rays physics has been investigated. The different aspects involved can help to introduce students to experimental physics: general concepts on cosmic rays physics, operation of scintillation detector coupled with modern photo-sensors, simple data analysis, and so on. As a preliminary step some tests were carried out in order to get confidence with the capabilities of the experimental set-up and to arrange the best working conditions. Actually this phase may be considered in itself as an interesting opportunity to introduce students to some common tuning-up activities in the experiment preparation.

The response of the employed detectors to the passage of cosmic particles was analyzed to some extent. Further studies may include the attempt to extract energy loss information from the measured signal length spectrum. Energy loss is a complex phenomenon, based on stochastic processes. However these spectra may be compared with predictions made by Monte Carlo simulations and transport code like GEANT3.

Time coincidence measurements leading to quantitative results were carried out. For instance two-fold coincidences are interesting in the study of the so-called *decoherence curve* where the rate is plotted as a function of the relative distance. The reported measurement shows the possibility to extend this study up to a distance of about 10–15 m.

This function may be put in relation with theoretical predictions on the lateral distribution of an atmospheric shower of such energy (10^{14}–10^{16} eV). Another interesting feature is the shape of the time coincidence spectrum, which becomes more and more wide at growing distance. However a three-detector station is the minimum to obtain a more complete reconstruction of the shower, which includes the estimation of the axis direction, as it has been shown.

More complex stations may be employed, *e.g.*, telescopic configurations, in order to study particular aspects or to cut on some particular regions of angles and energies of the secondary particles. Underground, open air or high-altitude measurements may be planned to compare different rates and detector responses. Data may be compared with weather conditions provided by a sensor which can be installed in the *Quarknet* card. Finally different stations may be linked using the GPS facility included in the *Quarknet* card, thus widening the variety of aspects that can be analyzed.

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