Fostering Curiosity and Learning: The Journey from Tool Development to Practical Education.

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Abstract. In recent years, universities and research institutions have launched outreach initiatives to make physics more accessible and engaging. Supporting this effort, CAEN has developed modular Educational Kits designed to teach statistics, particle detection, and nuclear imaging. These kits aim to inspire students and include tools for studying environmental radiation, such as cosmic rays and terrestrial radiation.
This paper focuses on two key kits: the Cosmic Hunter and the Educational Beta Kit, both designed for cosmic ray detection. Additionally, the Detection System Plus is mentioned, though it is still under development. We describe a series of student experiments that highlight how these tools are ideal even for high school and university physics labs. Through these hands-on experiments and data analysis, students can gain a deeper understanding of modern physics.

1. Introduction

In recent years, there has been a significant surge in outreach and educational programs developed by universities and research institutions. These initiatives aim to make physics and other scientific disciplines more accessible and engaging for a broader audience. The primary goals of these outreach efforts are to stimulate interest in science, promote a deeper understanding of fundamental physics principles, and inspire future generations of scientists. Engaging content and hands-on activities are crafted to capture the curiosity of diverse audiences, while complex concepts are simplified to enhance comprehension. Educational projects and role models further encourage young students to pursue careers in science.

The impact of these initiatives is evident. There has been a noticeable increase in participation rates in science fairs, workshops, and educational programs. Participants demonstrate improved understanding of scientific concepts, and there is a growing interest in STEM careers among young students (e.g., in China, 40% of graduates earned STEM degrees (2020), and in Germany, STEM enrolments exceeded 1M (2023-24)) [1,2].

CAEN S.p.A., a prominent industrial spin-off of the National Institute for Nuclear Physics (INFN), has also contributed significantly to these outreach efforts. Recognizing the importance of educational collaboration with the research community, CAEN has developed modular educational kits designed to offer a modern and flexible platform for teaching the fundamentals of statistics, particle detection, and nuclear imaging, using state-of-the-art technologies and methods.

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In addition to these kits, CAEN has introduced a global platform for Modern & Nuclear Physics education. This platform enables seamless sharing of experiments for students and scientists alike. It is studied to enhance communication and collaboration among members, and it offers comprehensive guides tailored specifically to each user's needs. This initiative is one of the CAEN's commitment to fostering a collaborative and engaging learning environment.

With a focus on young students, CAEN has developed engaging educational programs centered on environmental radiation, such as cosmic rays and terrestrial radiation, by creating specialized educational kits for these applications. Specifically related to cosmic ray studies, CAEN has introduced three different educational kits: the Educational Beta Kit, the Cosmic Hunter, and the Detection System Plus.

These educational kits are suitable for high school and university-level physics labs, offering practical experiments that integrate theoretical knowledge with hands-on experience. The Educational Beta Kit is primarily used at the university level, while the other two instruments are also suitable for much younger students. This approach ensures that learners of various ages can explore and understand complex scientific concepts through interactive and practical methods.

The Cosmic Hunter, an easy-to-use kit for cosmic ray detection, helps students understand the detection and analysis of cosmic rays through hands-on experiments. The Detection System Plus serves as a compact system for cosmic ray detection, providing a versatile platform for more advanced experiments.

By engaging with these tools, students can gain a deeper understanding of the scientific method and the principles of physics. CAEN's commitment to high-quality educational tools fosters a collaborative learning environment, enhancing scientific skills, critical thinking, creativity, and passion for discovery. This ensures that students are well-equipped for future studies and careers in the scientific field.

This paper introduces the elements of the CAEN kits and emphasizes their fundamental educational applications in the field of cosmic rays

2. Experimental Setup

2.1 Beta Educational Kit

The Educational Beta Kit, SP5600D, is the system solution that allows to perform beta and cosmic rays experiments. The set-up consists of modular plug and play devices USB controlled by a

Figure 1. CAEN Educational Beta kit.

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computer. A user-friendly software allows the user to easily operate the system and to perform a series of measurements.

The Beta kit [3], shown in Figure 1, consists of:

- A Power Supply & Amplification Unit (PSAU, SP5600). The PSAU supplies the bias for the sensors, features a variable amplification factor up to 50 dB and integrates a feedback circuit to stabilize the sensor gain against temperature variations. Moreover, the PSAU integrates a leading-edge discriminator per channel plus coincidence logic.
- A Desktop Waveform digitizer (DT5720A), with 2 input channels sampled at 250 MS/s by a 12bit ADC. The available firmware enables the possibility to perform charge integration and pulse shape discrimination.
- A Scintillating Tile (SP5608) composed by a support with an embedded plastic scintillating tile (48x48x10 mm^3), directly coupled to a SiPM (6x6 mm^2). The tile is the ideal tool for tests with beta emitting isotopes and cosmic rays. It is provided with paper and aluminium sheets and a source holder in order to perform beta attenuation measurements.

2.2 Cosmic Hunter

The Cosmic Hunter, SP5620CH [4], is a user-friendly system designed for cosmic-ray detection. It can function as an external trigger system for other experimental applications or serve as an educational tool. Its accessible design makes it ideal for students with limited technical expertise in electronic instrumentation. Consequently, the Cosmic Hunter is well-suited for both university-level physics labs and high school physics programs.

The main components of the Cosmic Hunter, shown in Figure 2, include:

- A coincidence module that functions as a counter, allowing users to provide bias voltage to the scintillating tiles and count the hits generated by muons on each tile.
- Two detection systems consisting of plastic scintillators directly coupled to SiPMs, along with frontend electronics.

The various elements of the kit can be assembled in customized configurations to meet specific applications and user needs.

Figure 2. CAEN Cosmic Hunter.

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2.3 Detection System Plus

The Detection System Plus, SP5622B [5], is a compact and user-friendly detector designed to measure the average rate of muons produced by primary cosmic rays. This system, featuring SiPM detectors and plastic scintillating tiles, is fully compatible with Cosmic Hunter. Its standalone nature and flexibility make it an excellent external trigger system for laboratory setups. This instrumentation, shown in Figure 3, allows students to gain hands-on experience in operating, handling, and optimizing detectors for microscopic particles that are invisible to the naked eye.

Figure 3. CAEN Detection System Plus.

As a result, the Detection System Plus is ideal for research, university-level physics labs, and high school physics programs.

Currently, the module is in its final production stage and will soon be utilized to create new learning experiences for students, further enhancing their understanding and engagement in the field of particle physics.

3. Educational Activities

Exploring and studying the cosmic rays, energetic and subatomic particles constantly bombard the Earth's atmosphere from all directions can be one of the most exciting experiences a student can have.

Cosmic radiation, discovered by Victor Hess in 1912, includes not only stable charged particles and consists of two components: "primary" and "secondary" cosmic rays. Primary cosmic rays are composed of heavy nucleus protons and helium, as well as electrons, neutrinos, photons, matter and antimatter (positron and antiprotons). Primaries are accelerated by astrophysical sources, while secondaries are produced by interacting with the atmosphere. The "secondary" cosmic rays are pions, kaons and electromagnetic showers. Muons and neutrinos are products of the decay chain of charged mesons, while electrons and photons originate in decays of neutral mesons.

All the proposed experiments have their own step by step guide that includes a detailed description to perform the data analysis of the physical process. The experiments address the essence of the phenomenon, complemented by basic and advanced statistical exercises.

In this paper section, a brief description of two applications on cosmic rays is reported.

3.1 Muons Detection, Flux Estimation, and Zenith Angle Dependence - Beta Educational Kit

One application of the CAEN Beta kit enables the detection of cosmic rays and the estimation of muon flux using a system composed of a plastic scintillating tile directly coupled with a SiPM. Muons, produced by the decay of pions and kaons generated from the hadronic interaction of primary cosmic rays with atmospheric nuclei, are the most common shower constituents at sea level. Cosmic muons are charged particles created high in the atmosphere (typically around 15 km) and have the highest penetration capability in matter. Their mass, absence of strong interactions, long lifetime ($\tau \sim 2.2\text{x}10^{-6}$ s), and time dilation allow them to traverse the atmosphere and reach the Earth's surface [6].

The signal cut-off threshold is adjustable and must be optimized to balance sensitivity and background noise. It should be set low enough to detect cosmic rays reliably while reducing random coincidences below the Hertz level (Figure 4). Once optimized, the muon vertical flux on the plastic scintillating tile can be accurately measured.

Students must consider various factors to estimate the flux: the zenith dependence of flux and the integration over the solid angle, the system geometry, and the literature values corresponding to sea level. Additionally, the detection efficiency of the system can be calculated by comparing the expected rate with the measured one.

The expected rate of muons passing through the scintillating tile is very low, necessitating fine-tuning of the system to significantly reduce the random count rate and enhance system sensitivity.

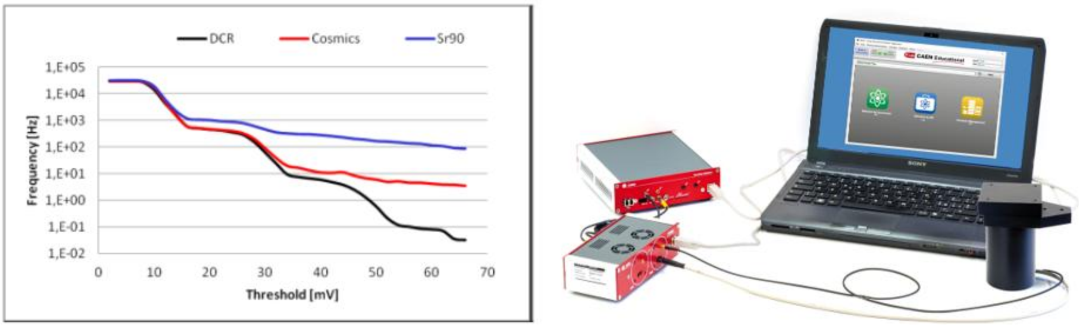

Figure 4. On the left, the signal frequency as a function of discriminator threshold. The red line represents the cosmic contribution, the black one the noise and the blue one the Sr-90 source contribution. On the right, the experimental setup.

Another interesting experience for the students is the study of the zenith dependence of the muon flux. Muons typically lose about 2 GeV to ionization before reaching the ground, with their

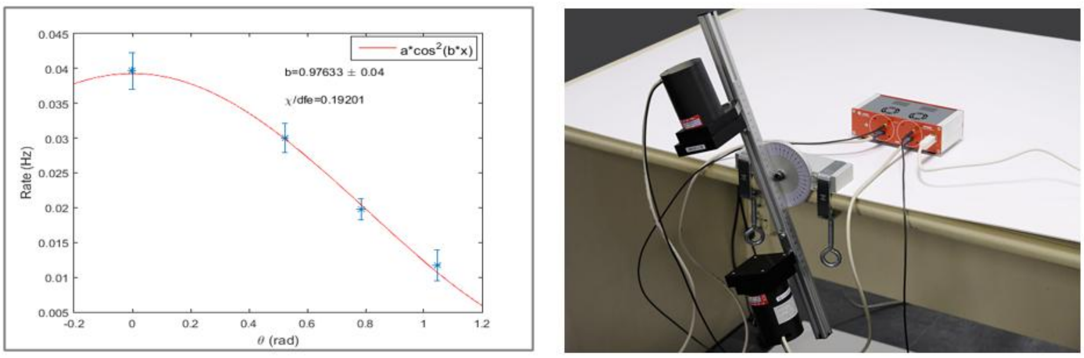

Figure 5. On the left, the Zenith angle dependence of the muons flux [Fit: y = a*cos^2 (b*x)]. On the right, the experimental setup.

average energy at ground level being around 4 GeV. When their decay (E_{μ} > 100 / cosθ GeV) and the curvature of the Earth (for θ > 70°) are negligible, the flux of cosmic muons can be expressed in terms of the zenith angle θ, with contributions from charged pions and kaons. For $E_{\mu} \sim 3$ GeV, the angular distribution of muons is proportional to $\cos^2\theta$ at sea level. The intensity of cosmic muons is primarily determined by the angular dependence of the zenith on their energy spectrum and energy [7].

By using an additional scintillating tile and a mechanical telescope [8], students can easily verify this dependence, as shown in the Figure 5.

3.2 Educational Experiences Using the Cosmic Hunter

The Cosmic Hunter is a highly versatile instrument widely used in outdoor educational activities focused on cosmic rays. Its flexibility stems from its lack of a predefined detection geometry, allowing it to be adapted to various experimental setups. Additionally, it operates without the need for an electrical power source also, using a simple power bank for mobile phones instead.
These practical applications not only enhance the learning experience for students but also foster a deeper understanding of cosmic ray interactions and their dependence on altitude.

This feature has made the Cosmic Hunter a popular choice for numerous outreach activities, where it has been employed as a demonstrator in public events to engage a broad audience with scientific discussions and demonstration. One particularly interesting application involves student-led experiments related to the measurement of cosmic ray flux as a function of altitude.

The measurement of the cosmic ray flux as a function of the altitude played a key role in the comprehension of the nature of both primary and secondary cosmic rays. The Earth’s atmosphere acts as a filter by absorbing most of the secondary particles produced by the interaction of the primary ones with the external layers of the atmosphere itself. Muons have the greatest penetrating capability and can reach the Earth's surface. For that reason, they constitute the hard component of the secondary cosmic radiation. The soft component consists mainly of gamma, positrons, and electrons that are easily absorbed by the Earth's atmosphere. Initially, the flux of the secondary cosmic rays as a function of the altitude endures a slight decrease due to the loss of the contribution of natural radioactivity from the terrestrial crust. However, evident increase in the flow of revealed particles is then observed.

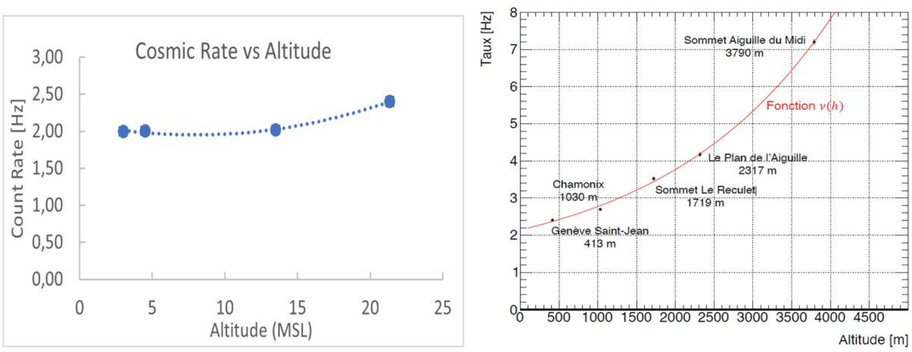

Figure 6. On the left, the cosmic rate measured at different building floors. On the right, the rate of cosmic muons as a function of altitude according to 5 different measurements [9].

The objective of this experiment is to analyse the behaviour of muon rates by conducting measurements at different altitude levels. When a charged particle crosses the black tile, its energy is converted into scintillation light. The photons produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator can be viewed via the coincidence module display, CAEN SP5621. The students can select the double scintillators coincidence mode via the related button on the front panel and set the integration time of the measurement. Because the acquisition of events occurs only in the presence of a coincidence, all events from a cosmic particle that crosses only one scintillating tile will automatically be discarded.

Before starting the acquisition, the students need to choose the system geometry and ensure that it remains constant at different altitude levels. These measurements can be taken on different floors of a building or at various elevations on a hill/mountain, as shown by the results in the Figure 6.

Figure 7. On the left, some high school students are engaged in high-altitude measurements with the Cosmic Hunter as part of the INFN OCRA project. On the right, two photos at different altitudes taken by a high school student for his final thesis.

In Figure 7, pictures of some high school students performing these types of outdoor measurements are shown.

The experiment described above is just one of the numerous educational applications that the Cosmic Hunter enables. Students can begin to understand the fundamentals of statistics underlying the detection process, study how the solid angle and the area of coincidence between

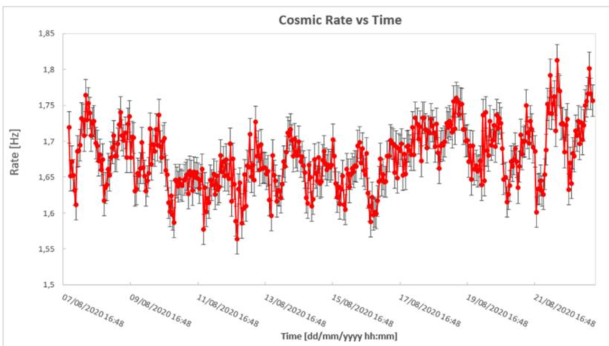

Figure 8. The typical cosmic rate night /day trend can be sometimes modified due to solar activity changes.

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two detectors can affect the measurement results, analyse the differences between vertical and horizontal cosmic flux, evaluate random coincidences, and study the efficiency of a single detector. Additional experiments include verifying the zenith dependence of muon flux, estimating the impact of environmental radiation on cosmic ray detection, studying the absorption of cosmic rays as they pass through solid matter, and analyzing how different materials affect their propagation.

Another intriguing experiment students can perform is the observation of cosmic flux variation due to solar activity. This experiment encourages students to engage in a detailed and critical analysis of acquired data, such as the differences between night and day (see Figure 8). The collected data can be compared with data from various websites designed to monitor solar activity in real-time [9]. By comparing these datasets, students can find correlations between the trends of cosmic rays detected by the system and solar activity, solar wind speed, the geomagnetic field, and other related phenomena.

4. Conclusions

By detailing the CAEN kits and their functions, we have shown how these kits can be effectively used for educational purposes. The versatility and user-friendly design of the CAEN kits make them ideal tools for both high school and university-level physics programs. Through hands-on experience, students can gain a deeper understanding of cosmic ray detection and the principles of particle physics.

Ultimately, these kits serve as valuable resources for fostering interest and knowledge in the study of cosmic rays.

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