Meaningful student involvement. Students as “researchers”: a physics laboratory experience from space to microworld

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Abstract. Teaching physics and technology is a challenging, rewarding and exciting arena where teachers share the fascinating concepts of physics and technology evolution in a room full of young and inquisitive minds. Every day teaching experience confirms that Science learning motivation is correlated to real world applications. According to the last PISA-OECD survey, the performance of Italian students in STEM is below the OECD average. In the last years the Italian Ministry of Education, University and Research (MIUR) has been active in promoting a wide plan to improve STEM learning. These actions strongly supported the connections and collaborations between high schools, universities and research centers. In this framework, the Frascati National Laboratories (LNF) play a very important role in science dissemination through a rich program of physics education activities addressed to Italian teachers and students from all the world. The main idea is that meaningful involvement of students can take the form of engaging students as researchers. In this article the LNF activities for schools are presented with a focus on a case study of a work-related learning program attended by seventeen students of the high school “Liceo Siciliani” from Catanzaro (Italy) in February/March 2017. The students had the possibility to participate in two different experiences related to particle physics and nanotechnology. The project concerning particle physics will have a follow up, since the school “Liceo Siciliani” proposed an experiment on cosmic rays that will take place in the Calabria region, based on the experimental setup the students studied and used at LNF.

1. Introduction
The last PISA-OECD survey [1] shows that the performance of Italian students in STEM is below the OECD average. In recent years many actions [2] have been promoted by the Italian Ministry of Education, University and Research to support STEM teaching and in particular to underline the connection between science and technology in its applications in life. The Ministry encourages and supports collaborations between schools and university and schools and research centers, including work-related learning [3] projects.
We present a case study of out-of-school learning that involved a group of seventeen students (aged 17-18) of the second last year of the high school “Liceo Siciliani” from Catanzaro, in a project organized by the personnel of the physics research centre Frascati National Laboratories, LNF (Italy). The project took place at the LNF facility and was dedicated to two research fields, particle physics and nanotechnology. It consisted of conducting hands-on activities in which students worked together with researchers. In the particle physics experiment, students learnt about elementary particles and how to study them using a particle detector. The acquired knowledge on how to use and characterize a detector and how to analyse data will be useful to them, since the school they attend proposed a follow-up experiment in the Calabria region where the experimental setup will be the same they used at LNF. The nanotechnology activity was dedicated to the preparation and test of graphene-based structures to study the application of physics in several fields like medicine and ecological monitoring.

The students had the possibility to study and participate in two experiments related to completely different physics areas, to understand the large variety of phenomena that can be investigated and the applications in ordinary life.

The first part of this article is dedicated to the presentation of the research activities carried out at LNF, after that the physics education and outreach initiatives organized by LNF will be described. Among the physics education programs, a focus will be devoted to the work-related learning project of interest for this article and the laboratory experiences will be presented.

2. Frascati National Laboratories (LNF)
Built in 1955, the Frascati National Laboratories (LNF) [4] were the first Italian research facility for the study of nuclear and particle physics with accelerators and they are nowadays the largest laboratories of the National Institute for Nuclear Physics (INFN) [5]. INFN is the Italian research agency dedicated to the study of the fundamental constituents of matter and the laws that govern them. It conducts theoretical and experimental research in the fields of particle, nuclear and astroparticle physics. The main missions are contributing to science progress, sharing with society the goals and results of scientific research, and transferring knowledge.

A distinguishing characteristic of the LNF is the experience in building particle accelerators. This activity started in 1957 with the 1.1 GeV electron synchrotron, the most powerful machine at the time, continued with AdA (1961), the first electron-positron collider ever built, and its successor ADONE (1969). This evolution culminated in 2000 with the construction of DAΦNE, the collider still in operation that holds the world record of low energy instantaneous luminosity. The facility hosts infrastructures for the design and construction of high-technology accelerators and detectors. Complementary activities to High-Energy physics research are carried out and they include:

- application of the synchrotron radiation emitted by the electrons of DAΦNE to the study of condensed matter;
- use of electron beams extracted from the DAΦNE injector for studying new detectors;
- medical and space applications;
- radiation dosimetry and environmental monitoring;
- management of computer networks and construction of advanced computing centers.

The LNF scientific community is also involved in international collaborations at CERN, in experiments in the United States, Germany, China and in other national laboratories.

2.1. The LNF Educational program
The LNF fosters science literacy via the Information and Scientific Documentation Office offering a large variety of activities addressed to students attending primary, secondary and high school up to teachers and lifelong learning. These activities are realized in collaboration with a team of volunteer staff and associated graduate students, postdocs, researchers, engineers and technicians. There are many events organized inside and outside the LNF to bridge science and society such as visits, exhibitions, public seminars at LNF or in local libraries or in schools. The high school student program will be described here. The program includes lectures on modern and contemporary physics and hands-on
activities in which students learn directly from the LNF researchers. The hands-on activities are
dedicated to quantum physics, particle physics, diagnostics and preservation of cultural heritage,
electronics, nanotechnology and superconductivity. The activities are organized in winter and summer
internships. The high school students are selected by their teachers. The goals of this program are
transferring knowledge and methodologies, making students experience the life of a researcher,
presenting the LNF research fields, promoting the teaching of physics, helping students in the choice of
higher education or career. Students usually work in small groups and share knowledge and experience
(groups are composed of students coming from different schools). They perform hands-on experiments
supervised by the researchers having the change to learn how to use modern technologies and analyse
data. Students investigate the application of physics to real situations and how to pose and solve a
problem.

3. Work-related learning program case study: cosmic ray detectors and nanotechnology
This section is devoted to the presentation of the laboratory experience “from the space to microworld”.
The whole project lasted five days (20 hours) between February and March 2017 including seminars on
modern physics, a visit to the LNF facility and interviews conducted by students of the director of LNF
and of the researchers. The group of seventeen students was divided into two subgroups working at two
different activities, one concerning particle physics and the other related to nanotechnology.

The intent was to make students act as researchers and to provide them with a broader understanding
of the variety of research activities carried out at LNF. Students performed the activities under the
supervision of Professor Francesco Scerbo. The mentors of this project are researchers of the LNF who
gave students basic and advanced knowledge of the physics area of interest and guided them during the
experimental phase. The students were selected by Professor Scerbo on the basis of their interest in
scientific disciplines and on their grades.

At the end of this project the students reported about these activities to their peers and teachers at
school; there was no assessment phase. Concerning the particle physics experiment, students should act
as mentors and guide for other students once the experimental setup will be installed near their school.

3.1. Realization and characterization of a muon telescope
In this activity, students, guided by LNF researchers, were introduced to particle physics and in
particular to the technology used in experiments to identify and tag particles: the particle detectors.
Students were involved in the assembling and in the study of the performance of a particle detector
dedicated to muons, called muon telescope [6]. The aim was to provide students with knowledge and
skills to characterize and to use this device to measure the cosmic ray muon flux and the muon mean
lifetime. The ultimate goal of this project is to realize a particle physics experiment in the territory of
the Calabria region employing the device students used during this activity. Students should be able to
deal with this experimental setup and analyse the data recorded.

The unit lasted three days (10 hours). It was structured in an introductory training part and an
experimental part with data acquisition. In the introductory training part, the sessions of theory and
practical demonstrations were organized to be sequential and equally spaced in order to make students
test and experiment what they had learnt immediately after the explanation. Students were divided into
small groups, each group had at their disposal a fully equipped experimental setup. Researchers
constantly asked questions and posed problems to students to enhance interaction, motivate students and
have a feedback to monitor them. They introduced the basic concepts of particle physics, i.e. definition
and list of elementary particles with a focus on the muon, its properties and its mean lifetime, then they
talked about the state of art in this research field underlining achievements and open questions; after
that, researchers presented the basis of the interaction of radiation with matter that characterize particle
detectors and their technology to teach students how to detect the passage of particles, how to identify
and investigate them. Researchers also presented some experimental setups used in current experiments
(like Atlas at CERN).
Having given a general overview, researchers presented in detail the working principle of the detector used by students: the scintillation detector. During the whole activity students were in the laboratory so they could directly observe and use the detector guided by the researchers. The apparatus they had consisted in a portable muon detector (designed and assembled at LNF) composed by a scintillation detector (area 9x9 cm²) coupled to a Silicon photomultiplier (SiPM) and the read-out electronics (amplifier, threshold, shaper to digitize the signal and a trigger-logic circuit). The output signal was monitored by students by means of an oscilloscope (see Fig.1). The digitalized signal was sent to a Raspberry Pi giving counts and frequency (recorded by students in the data analysis phase).

During the introduction researchers showed a plastic scintillator to make students see how it looks like (once the material is inside the detector is no longer visible). When particles impinge on the detector, they excite molecules in the scintillating material (scintillator), consequently the excited states decay emitting visible light. The scintillator is coupled to a SiPM, an amplifying device in which the light is transformed into electrical pulses that can be processed by the electronics providing the information about the passage of a particle.

![Figure 1](image1.png)

**Figure 1.** These pictures show the experimental setup used by students: the oscilloscope, the muon detector (black square) and the electronics (open box on the right).

Researchers introduced the basis of the working principle of a diode and the concepts of background and thermal noise. After these explanations students switched on the detector and observed the signal on the oscilloscope. When a signal is recorded (a photon that hits the pixel of SiPM), a drop in the voltage with respect to a reference value (the supply voltage of the SiPM) is observed (see Fig. 2). As first task students had to determine the amplification factor of the SiPM i.e. the number of electrons created by one photon (current pulse). They followed the instructions given by the researchers and analysing the signal on the oscilloscope, they isolated the signal of a single pixel of the SiPM (see Fig. 2). They approximated the observed shape to a triangle to calculate the area that corresponds to the delivered charge (the charge of the signal). In particular students took the voltage value read on the oscilloscope and divided it by the value of the line impedance (50 Ω), that researchers provided them, to get the current value using the Ohm’s law. After that, students calculated the delivered charge from \( Q = I T/2 \), where \( T \) is the time they read on the oscilloscope (100 ns). Dividing \( Q \) by the electron charge, they obtained the total number of electrons. Since the first electron is created by one photon, students can calculate the amplification factor of the SiPM.
Figure 2. This image displays what students analysed on the oscilloscope, the voltage applied at SiPM as a function of time.

In the second phase, students learnt about the response of a detector, how to characterize it and find the optimized gain and operating conditions of the device. In particular, they studied the performance of the detector varying the applied voltage and measuring the corresponding current with multitesters and they drew the characteristic curve of the detector (current as a function of voltage, see Fig. 3).

Figure 3. The characteristic curve (current as a function of voltage) of the SiPM is displayed. In the elbow region, students determined the breakdown voltage.

Students analysed this curve to find the optimal operating condition of the detector that, as diodes, it coincides with the breakdown voltage, the point near the elbow on the curve.

Researchers gave students the basic knowledge of Python to use the Raspberry Pi and the graphic panel to start the data acquisition. After having tuned the best operating condition, students conducted a measurement of the cosmic rays flux and of the muon mean lifetime. In the first phase, the researchers, using an historical approach, presented the students a chronicle of the main experiments (balloon flights, sea immersion, cloud chamber) and scientists Wulf, Pacini, Hess, Bothe-Kohlörster, Rossi, Auger who contributed to the investigation of the origin of radioactivity leading to the discovery of the cosmic rays and their properties. The evolution of the experimental setups and technique to study cosmic rays is also presented from the electrometer, to Geiger-Müller counter and the coincidence method (taking the coincidence between the signals coming from different detectors to discriminate the signal from background). Cosmic rays are high energy particles originating in the outer space that travel at nearly the speed of light. When these high energy particles reach our atmosphere, they collide with air molecules producing a shower of secondary particles traveling through the atmosphere; the majority of the secondary particles that arrive on the Earth’s surface are muons. Since it is unstable, the muon decays into one electron, one electron antineutrino, one muon neutrino in 2.2 $\mu$s (mean lifetime). Muon are used to introduce the relativistic concepts of time dilation and space contraction to explain why we can detect them on Earth. Muons are created at an altitude of approximately 15 km and according to their lifetime only, they would travel 660 m at speed of light before decaying, making it impossible to us to observe
them. Assuming that muons move with a speed close to the speed of light, time dilation and space contraction occur. In particular, according to Lorentz transformation, in the frame of Earth, \( \Delta t = \gamma \Delta t_0 \), the muons’ lifetime will be 55 \( \mu s \) meaning that, in the frame of Earth, they can pass through the atmosphere reaching the Earth’s surface. Relativity is a topic that is covered in the last year of high school, in this case students had the chance to study it in advance and investigate the application of this theory in research.

After the introduction dedicated to theory, students tested the coincidence method. In particular the experimental setups were coupled to have two telescopes. Each telescope is composed of two detectors. Students recorded the change in the number of counts as they took the coincidence of the signals and changed the relative position between the two detectors. The coincidence of the signals allowed the students to separate signals coming from cosmic rays and background. Students, guided by the researchers, started an acquisition in which the two detectors are superimposed and they recorded the coincidence of the output signals for 5 minutes to calculate (given the detector area) the cosmic ray flux, the number of particles per second per cm\(^2\) and they agreed with the expected value of 1 particle, per minute per cm\(^2\).

In the last part, students together with researchers created a muon decay profile in order to measure the mean lifetime using the muon telescope. The two detectors are positioned on a rotating support at a distance of 20 cm, a lead block is placed in between (see Fig. 4).

![Figure 4](image_url) The muon telescope placed on the rotating support is shown. The two detectors are placed at a distance of 20 cm and a lead block is inserted in between. Students rotated the system and measured the number of muons at different angles.

To estimate the muon mean lifetime, students used the scheme in Fig. 5, where \( h \) is the height of the atmosphere 10 km, \( O \) is the point occupied by the observer, \( \theta \) is the angle at which we want to observe muons (assuming an isotropic distribution). Using the telescope, students measured the number of muons at \( \theta=0^\circ \) and at \( \theta=45^\circ \) and they inserted these values in the decay rate law to measure the muon mean lifetime. In particular at \( \theta=0^\circ \) the number of muons is \( N(\theta=0^\circ) = N_0 e^{-h/\lambda} \), where \( N_0 \) is the initial number of muons, \( \lambda \) is the mean free path and \( \lambda = c/\gamma \), \( c \) being the speed of light, \( \gamma \) the Lorentz factor \( \gamma=10 \) (this value is given by researchers) and \( \tau \) the value the students had to calculate, the muon mean lifetime.

At a certain angle \( \theta \), \( N(\theta) = N_0 e^{-L/\lambda} \), using the trigonometry students got the fraction \( N(\theta)/N(\theta=0^\circ) \). They inserted the values they measured with the telescope and they solve the equation in function of \( \tau \), finding a value in good agreement with the expected one.
At the end of this laboratory, students were able to use a scintillation detector and find the optimal operating settings. They learnt how to set the coincidence experiment, assemble a muon telescope, and use the software to record data. Moreover they were able to use the collected data to calculate the muon flux and the muon mean lifetime. Students will have at their disposal an experimental setup like this one in their school to carry out a measurement of cosmic-ray muon flux at sea level and on top of mountains.

3.2. The nanotechnology lab: graphene-based activities

The nanotechnology laboratory was focused on the production and the characterization of nanostructured materials, graphene nanoplatelets, and on the study of possible applications in everyday situations to bring contribution to ecological monitoring [7,8]. The activity plan was equally divided in theory and experimental part and took two days (7 hours). In the theory part, researchers instructed students about the definition of nanotechnology and nanostructured materials and they presented the procedures to produce and characterize the nanostructured materials. nanotechnology refers to the ensemble of methods and techniques to manipulate the matter at the atomic and molecular scale aimed at creating materials and products with special chemico-physical properties. Researchers presented three methods and techniques to investigate the properties of nanomaterials: Scanning Electron Microscope, Raman spectroscopy and Infrared spectroscopy. Researchers also illustrated some applications like biosensors, drug delivery and environmental remediation. In the experimental part, students were actively involved in the preparation of some graphene samples and in the realization of quality control tests, based on the methods cited above, conducted to characterize them.

Under the supervision of researchers, students divided in small groups, took the intercalated graphite and fill with it a container (6 cm long and 1 cm high) that they placed inside a microwave oven for few seconds (see Figures 6a, 6b and 6c). The warmed material expanded occupying a volume 300 times larger than the initial one and they got the exfoliated graphite (see figure 6d). After that, students performed the sonication of the samples producing 10 µm flakes. In order to make them easily usable, students carried out a filtration to obtain graphene free standing layer that, after being pressed, have a circular shape and that are called nanoplatelets (3 cm diameter -100 µm thickness).

After being instructed about the working principles, students used the Scanning Electron Microscope to investigate the morphology and the dimensions of the samples they create. Moreover they performed a quality control test using the Raman spectroscopy to check the thickness of the samples, the presence of defects and to determine how many layers compose the samples. With these tests, students had an immediate feedback of the quality of the samples they prepared. Furthermore students employed these samples to investigate the possibility to use them to counteract the environmental pollution. Together with the researchers they simulated in a Petri dish a polluted area due to oil spill and they place the nanoplatelets they produced inside this area (see figure 6e).

Students could observe the hydrophobicity of these nanoplatelets and their capability of attracting hydrocarbons as soon as they are placed close to the oil drops. In the final part of this lab, students participated in a quality control test carried out through the Infrared spectroscopy method. Some properties of graphene can be enhanced adding some components (functionalization).
Due to its symmetrical structure, graphene is invisible to infrared radiation so infrared spectroscopy is used to determine the presence of other components and study the functionalization of graphene. Using this method, students determined the presence and the quantity of stabilizers and drugs in pre-assembled samples. These samples are used by LNF researchers to study drug delivery. Students had the chance to test this technique and they have been informed about the use of graphene in the medical area.

This laboratory is an important testing ground for students to see how different disciplines like quantum mechanics, chemistry, material science are combined together in a forefront technology that they have the opportunity to study and use.

3.3. The interviews
In the final part of the project, students interviewed different people working at the Frascati National Laboratories to know more about the research fields carried out at this facility and to draw a complete profile of a researcher. Students interviewed the director of LNF and they asked him about the present and the future research programs of the facility to know the perspectives concerning future experiments and the development of cutting edge technologies. Secondly students interviewed the researchers to know more about their education, professional experience, the research they conduct, job opportunities with a STEM degree in the view of exploiting this experience for career orientation.

4. Conclusions
This article is dedicated to an out-of-school learning activity attended by a group of students of the second last year of high school at the National Laboratory of Frascati.

In these laboratories, students had the opportunity to experience the work in a research centre and they took part in two different hands-on activities together with researchers. They acquired knowledge about Modern physics and the technologies used to investigate it. Students gained skills in the use of modern technologies, analysing and comparing data. They worked on a particle physics experiment to study cosmic rays and they learnt how to use a particle detector. This experience will have a follow up in the region they live in, where an experiment on cosmic rays has been proposed using the same experimental up and the students will teach their peers what they had learnt. In the nanotechnology laboratory, students prepared and tested graphene nanostructures to study the application of physics in medicine and ecological monitoring.
In both laboratories students had the chance to work with modern technologies and understand the connections between different STEM disciplines. Students reported that this project was fruitful to deepen their knowledge of physics, know more about the job of a scientist and was helpful for career orientation.

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