Paper

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'Detektory Dla Szkół': a pilot detector-lending project for Polish schools

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Abstract

This article presents the Polish project entitled 'Detektory dla Szkół' ('Detectors for Schools', throughout the paper referred to as 'the programme'). It was developed at the Education and Training Division of the National Centre for Nuclear Research (Narodowe Centrum Badań Jądrowych, NCBJ) in Poland. The programme allows the schools to borrow from NCBJ two types of radiation detectors: Geiger–Müller counter and CosmicWatch detector(s). Student participation in the measurements is expected.

Keywords: nuclear physics teaching, detector lending, secondary education, natural radiation

1. Introduction and motivation

For a long time we have been aware that there is a certain serious problem in Polish schools—a concentration on theory. And while it is the Polish case that we know best this problem does not seem to be limited to Poland only—when talking to our colleagues from other, usually neighbouring, countries we got the impression that they share this problem, at least in the physics education. Students very rarely prepare, perform, analyse, or present experiments. It is also very rare for teachers to perform experiments in front of the class. The main reason for this is the lack of time and scarcity of the experimental equipment at schools. This is a general problem, but it also applies to the teaching of atomic and nuclear physics in particular.

Generally speaking, most teachers use ready-made suggestions contained in the textbook selected for implementation and the workbook adapted to it. Physics lessons are strongly theoretical, they are dominated by the verbal method (mostly lecture-like) and the solving of mathematicised problems. Experiments, observations and measurements are carried out too rarely, especially by students alone or in small groups. This is very unfavourable from the point of view of completing the process of science education, as the research methods like observations, deductions, controlled (laboratory) experiments, modelling and verifying model predictions, form the foundations on which sciences are built. Problem-solving tasks, working with source materials, and making measurements should be one of the main forms of student activity in the process of teaching physics. In addition to building knowledge and practical skills, experimenting may also help to improve other areas like learning from colleagues, cooperating, exchanging messages, as well as planning one's own learning. It is therefore necessary to find a way to recognize that the participation in the process of learning and discovery should be treated as a separate value. Also: when talking about nuclear physics one should remember, that experiments and demonstrations can support the students' understanding of safe use of radiation and its use in medicine, industry and science, as well as nuclear technology in general. Experiments can enhance the knowledge about the omnipresence of natural radiation mostly coming from naturally existing radioactive sources.

The research method based on the hands-on experimenting may be the answer to many problems, but the schools worldwide, generally, do not have advanced equipment for teaching experimental nuclear and radiation physics. Depending on the type of school, number of students in class and available equipment, the arrangements necessary for students to perform an experiment can pose considerable difficulties. Many teachers still think that experimental nuclear physics includes expensive radiation detectors and an ionising radiation source that requires special care.

Instrumentation is one of the biggest difficulties to overcome when trying to involve students in hands-on activities. In the Polish case there seems to be two main reasons for this state: lack of space in the school building for permanent storage of the equipment, and lack of finance to pay for it. The 'Detektory dla Szkół' programme was designed to tackle all obstacles discussed above. The detectors are provided free of charge, they are lent for a limited period only, and the use of natural (even grocery-store procured) radioactive sources is strongly advised.

It should be noted, that according to the Polish law (Regulation of the Minister of Education introducing core curriculum [1]) a physics teacher introducing concepts related to nuclear physics is not obliged to perform experiments. The issues that physics teachers are obliged to raise ('theoretically') during classes are the following:

- the way the atomic nucleus is built,
- the properties of nuclear radiation (including a description of the basic differences and similarities between the nature and properties of α, β and γ radiation),
- radioactive decay including definitions of stable and unstable nuclei and the half-life,
- nuclear reactions, including charge and nucleon number conservation, as well as the energy conservation including binding energy, mass defect and nuclear energy (mass-energy equivalence),
- fusion and chain reaction in heavy nuclei, as well as fission of light nuclei, discussed as 'sources' of released energy,
- advantages and disadvantages of nuclear power including radiation safety.

This list (at least in part) has been a guide in designing the proposed example experiments and demonstrations that can be done with the help of borrowed detectors (see section 4 of the paper).

The paper is structured as follows. After this Introduction the basic rules and the history of the programme are discussed. In section 3 the experimental set-ups are presented. In section 4 the example experiments that utilise the detectors are presented. Conclusions and outlook are given in section 5.

2. The concept of the programme

A number of times the following question has been asked: 'how can a simple, inexpensive radiation detector, that could be used in showing basic features of radiation and demonstrate natural radioactivity be obtained?'. With that in mind, a didactic Geiger–Müller counter (GM) was designed and NCBJ staff built a couple of pieces as a proof-of-concept (its description can be found in subsection 3.1)

Somewhat later the Cosmic Watch (CW) detectors [2, 3] were designed. Their history and evolution is described on the project web page [4]. The design of CW was done in a collaboration between MIT and NCBJ. As our division already had some GM counters we started to entertain the

Figure 1. The usual kit of lent detectors. On the left-hand side of the photo Didactic Geiger–Müller counter (together with two connecting USB cables) is shown. On the right-hand side two CosmicWatch detectors (together with connecting jack-jack and power-supplying micro-USB cables, and USB charger) are presented.

idea of a detector pool for physics teachers. Some cosmic watch detectors were purchased to supplement the GM counter pool.

The basic idea of the programme is quite simple: ‘your project—our detectors’. The teachers from all over Poland are encouraged to prepare educational projects in the field of ionising radiation physics that includes students measuring ionising radiation with the help of borrowed equipment. It is possible, but not encouraged, for the project to be mostly based on the example experiments (described in section 4). Sent project description should include the purpose, type of measurements performed, duration (up to three weeks) and the number of students involved. For our part, we offer the detector kit (usually one GM counter and 2 Cosmic Watch units, see figure 1), training in the use of the detectors and (if required) any other assistance. This training and assistance is implemented remotely via the teleconferencing platform.

If a proposal is accepted, an agreement between the school principal and NCBJ must be signed. The kits are lent free of charge, but the school must accept financial responsibility in the case of any damage.

The students are expected to write a concluding report which is evaluated by NCBJ’s researchers. Students are encouraged to record and analyse their own data, however the possibility of the detectors being used solely for the classroom demonstrations is not excluded.

Further details may be found on the programme webpage ([5], in Polish only).

It should be noted that the programme is not the only project of its type. One may mention, for instance, CERN@School [6] and CREDO [7, 8] projects.

3. Experimental set construction

Both types of detectors can work as stand-alone units, or can be connected to a PC running a special software.

3.1. Didactic Geiger–Müller counter

The principle of Geiger-Müller tube operation was invented in the 1920s by Hans Geiger and Walther Müller [9] and soon became widely popular. Nowadays GM counters are one of the standard devices for measuring ionizing radiation in the nuclear industry and ensuring radiation safety [10].

Didactic GM counter is a device based on GM tube STS 6 (old device made in the former USSR). This tube is sensitive to x-ray, high energy beta, muon and (with reduced sensitivity) gamma radiation, while (due to the metal walls) blind to standard-energy alpha radiation.

The tube is connected to a high voltage (approximately 420 V) power supply board. This board also acts as a filter which separates pulses from HV and sends them to the Arduino Uno board [11]. Arduino processor is programmed to count the pulses, show the basic data (time of measurement, number of pulses, current pulse rate) on the built-in LCD screen (2x16 characters), make sounds through a buzzer, and send the data to the computer via the USB-B port. It also provides stable low voltage power to the HV board. The Arduino board itself can be powered from an internal lithium-ion rechargeable battery or externally via USB-B connection. The battery can be recharged without taking it out from the device through a micro-USB connection (that can be fed from a powerbank or cell phone charger). All the internal parts are housed in a plastic casing ($22 \times 22 \times 4.2$ cm^3) with an acrylic window, that allows the device to be visually inspected by the students. The design is based on similar device build earlier for NCBJ by Warsaw University of Technology students.

It is necessary to note that the devices used for radiation safety require calibration and our didactic GM counter lacks it, thus it cannot be used to determine the radiation hazard. On the other hand it is sensitive to even small amounts of radiation, making it useful for educational purposes, where only weak natural radiation sources are measured. Making students familiar with natural radioactivity is the first goal of our project. Having known fixed geometry, our didactic GM counter can be used for investigating some basic radiation phenomena (i.e. radiation absorption in matter, the intensity dependence on the distance). The transparent acrylic window also makes it interesting for technically inclined students who can become more familiar with the principle of measuring ionising radiation itself.

The didactic GM counter is provided ready to use. The simplest way of taking the measurement is by turning it on with a single switch and reading the basic data from the screen. For more complex data taking it is necessary to connect the counter to the computer (via USB printer cable) and run an application (also provided), which gives the possibility of showing real-time data measurements on a computer screen for a large group of students, as well as giving the opportunity for simple analysis or exporting the data for further processing.

3.2. CosmicWatch scintillation detectors

CW muon counters were developed as a result of international cooperation between NCBJ and Massachusetts Institute of Technology [2, 3]. Although the word ‘muon’ in the name of the device strongly suggests it measures muons, it is also sensitive to high energy beta rays and (with much reduced sensitivity) gamma radiation. Due to the 1 mm aluminium cover it is blind to the alpha particles. The active part is a $5 \times 5 \times 1$ cm^3 plastic scintillator of the type typically used for charged particle registration.

Scintillators (both plastic and inorganic crystal) with photomultiplier tubes are used widely in the nuclear industry, radiation safety and scientific research [10]. Unfortunately high precision photomultipliers require quite expensive, power- and space-consuming HV supplies and data-processing electronics. The CW muon detector uses a silicon photomultiplier (SiPM), which does not need such high voltages as photomultiplier tubes (29.5 V compared to about 1000 V in a tube), is much more compact, robust and (last but not least) much cheaper (see for instance [12]). If a charged particle (either coming directly or ‘produced’ by an incoming neutral particle or quantum) hits the scintillator, the light is emitted. The light is absorbed by the SiPM and an electric signal of amplitude corresponding to the amount of absorbed light is produced. This signal is amplified and prolonged, so it can be measured by the Arduino Nano micro controller. The micro controller reads the pulse amplitudes, counts the pulses, calculates some additional information (counter dead time, rate etc), and displays the information on the built-in OLED display (64 by 128 pixels cooresponding to four lines of ~20 characters each). The data (signal timestamp and amplitude) can also be transferred to the computer via mini USB port and/or saved on the microSD card (if present). The detector is powered through the mentioned mini USB port—either by the connected PC, by powerbank, or USB charger (in the later cases without data transfer possibility).

Having such a complex design, the CW muon counter is surprisingly small (about $10 \times 7 \times 4.5$ cm^3) and lightweight (about 200 g), and this feature makes it perfect for school and outdoor measurements.

Being sensitive to background radiation CW counters can be used to measure natural radioactivity as well as investigate some basic radiation phenomena, similarly to our didactic GM counter. Since the height of the pulse is a measure of the energy the particle loses in the scintillator, more advanced data processing is also possible (i.e. spectrum analysis). Some of it can be done using application on the CW project website [4] and a Python script (also available as a Windows executable) provided with the counters.

A very important feature of the CW detectors (and the main reason for their development as cosmic muon detectors) is the built-in capability for coincidence measurement. If two units are connected (by the standard audio 3.5 mm male-male cable) and booted within a second, one of the detectors becomes 'master' (displays all the counts) and the other one becomes 'slave' (displays only counts that happened within 20 μs time window after a count in the 'master'). Cosmic muons have a velocity close to the speed of light (approximately 30 cm/ns or 300 m/μs) so they easily fall within the time window. On the other hand: a) only relatively heavy and high energy charged particles can pass through two casings without being stopped or deflected, which pretty much filters out all the other types of natural radiation, and b) the rate of natural radiation is rather small compared to the inverse of the time window, so the probability of 'false coincidences' caused by two separate particles or quanta is negligible. It all means that one can be quite certain that the 'slave' counts only pulses triggered by the muons. This feature makes a pair of CW counters a powerful tool to investigate phenomena like solar activity, cosmic ray showers, muon intensity dependence on height above mean sea level or shielding (i.e. concrete in buildings, rocks in mines), muon angular distribution, and many more.

4. Examples of use

This section describes a set of measurements that can be made using the GM and CW muon detectors. The list is considered useful for those intending to use the detectors for educational purposes and students who are planning to make their own measurements.

4.1. Demonstration experiments

Ideally the first point of contact with the detector for both students and teachers is the series of demonstration experiments that can be performed with the programme kits. Use of easily available sources (uranium-containing granite or other minerals, soil, potassium compounds, thorium-doped welding rods, old watches with radium paint etc) and either of our detectors, allows teachers to prepare and demonstrate phenomena linked directly to the science curriculum without the need for special investments, radiation protection measures etc

Simple demonstrations and experiments listed below can be performed as a part of regular lesson, while more advanced experiments, which use a sophisticated mathematical apparatus or require more than few minutes of time, should be done as extracurricular activity.

The currently proposed demonstrations are listed below.

- Demonstration of natural background radiation. During the experiment users will investigate radiation originating from natural radioactive elements in the ground or concrete walls, certain types of rock and foodstuffs. Teacher may show differences between the background radiation outside and inside a building as well as in a well- and badly-ventilated room.
- Inverse square law. This demonstration requires a point-like source—for instance the gamma and beta radiation originating from the thorium-doped welding rods. The relationship between distance and intensity of measured radiation is investigated. One counts the number of incidents per second at different detector-source distances. Students find that the intensity (the number of counts per second) decreases with the square of the distance.
- Attenuation and absorption of radiation by materials. In this demonstration radiation from the welding rods may be used to demonstrate gamma radiation range in aluminium or acrylic glass. It can be shown that the number of particles registered by the detector obeys the expected exponential decrease as the thickness is increased.

Once familiar with operating the detector, students (and, if applicable, teachers) are encouraged to organise into research groups to record their own data, then analyse them and share the results. The measurements that can be performed with the kits can last between a few hours to more than a week. This method is an educational technique relying on the students' individual work and may be performed in schools as an extracurricular activity. Ideas for long-term measurements have been described in subsections 4.2 and 4.3.

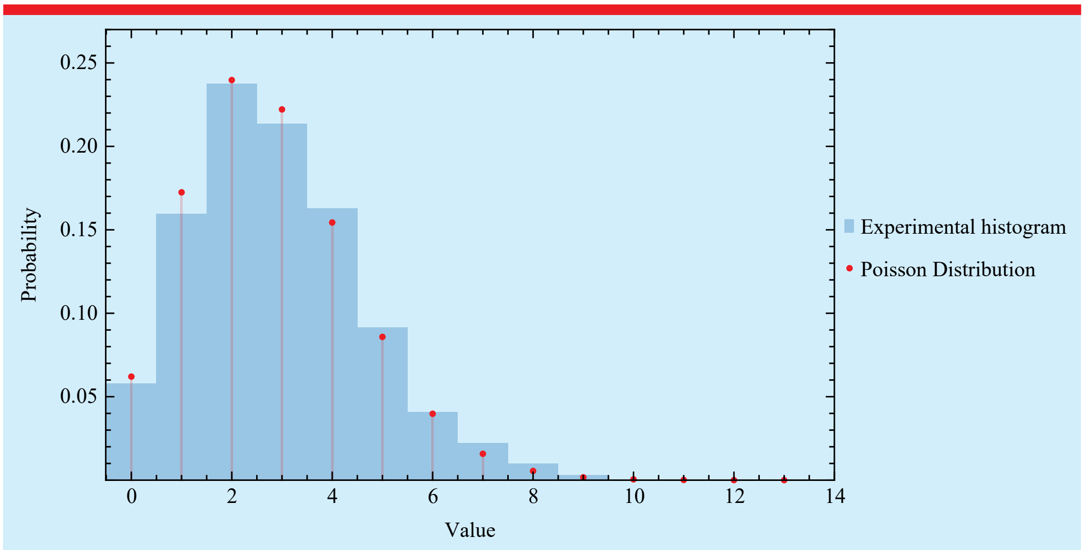

Figure 2. Histogram of the count numbers in the example measurement described in the text.

4.2. Statistical analysis of the measurement of background radiation

Radioactive decay and consequently the emission of radiation (either corpuscular or gamma) is a randomly occurring process. Therefore any measurement of the radiation emitted is subject to statistical fluctuations. To observe this phenomenon we propose the following measurement to study the statistics of random events. The detector better suited for this measurement is the GM counter. Besides showing the omnipresence of natural radiation (see for instance [13]) this measurement allows students to acquire a basic knowledge of the methods of the mathematical statistics. In particular it allows the simplest techniques of statistical analysis, and use a spreadsheet for analysing, graphing, and comparing results to be learnt.

In the experiment one measures the 'same' countrates (or counts per certain time) many times. It may be the measurement of background radiation (like in the example shown), or of a radioactive source. This experiment allows to verify that radiation measurements (rates) can be described using the Poisson distribution. It also allows to study the Gaussian distribution as a special case of the Poisson distribution (see for instance [14, 15]).

The example measurement of background radiation was performed at ground level in Otwock–Świerk. The count numbers registered in three-second intervals were recorded on the PC for about 5 hours, with the total number of counts being 17 409. The count numbers were histogrammed and normalised. Figure 2 shows the distribution of the data (how often a certain count number was registered) obtained during the test in NCBJ. The histogram represents empirical measurements and the red points represent the distribution fitted to these measured values.

The data collected by the GM detector can be downloaded to a computer and analysed. The teacher can divide the data into sets (like combining one-second-long measurements into 'longer' ones) in order to give different tasks to any group of students in a computer lab. Students may make a comparison between obtained experimental data and theoretical results, and have a chance to practice generating and fitting histograms. In case of longer measurements the distribution becomes Gaussian-like, which allows for the discussion of the normal distribution. The data may be analysed in order to understand

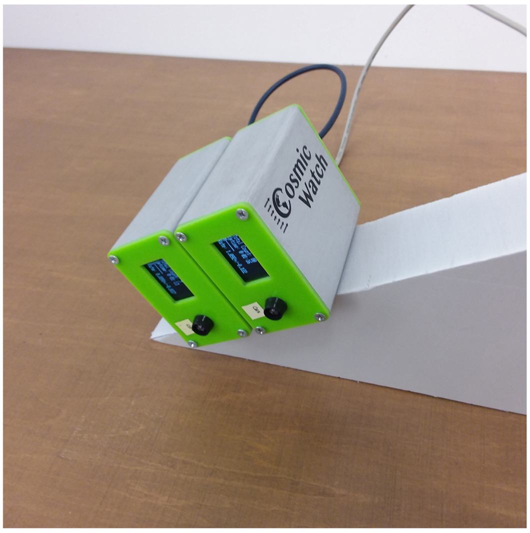

Figure 3. Example of the setup for measuring cosmic ray rates as a function of the zenith angle. One can see a pair of CW detectors working in the coincidence mode (dark cable being the coupling cable, grey one being the powering one) located on the frame. This particular frame allows to register muons travelling at inclination angle of about 30°.

the importance of statistical analysis in modern physics.

4.3. Measurement of the cosmic-ray muon angular distribution

The experiment discussed in this section is adapted from the one proposed at MIT by Axani, Frankiewicz and Conrad in 2018 [2, 3]. It allows the students to study the cosmic ray muons. It is also a rare occasion to perform particle physics hands-on experiment. It also allows the students to learn how to formulate one's own hypotheses on the nature of a phenomenon, and to verify them experimentally.

Cosmic muons are particles originating from the decay of heavier particles, pions and kaons, produced in the upper atmosphere by incident cosmic rays (mostly protons emitted by the Sun). To investigate the rate of muons as a function of the zenith angle, one can use two CW detectors operating in coincidence mode (described in subsection 3.2). The detector configuration is shown in figure 3. The frame allows for the setup to be inclined at the defined zenith angle. The

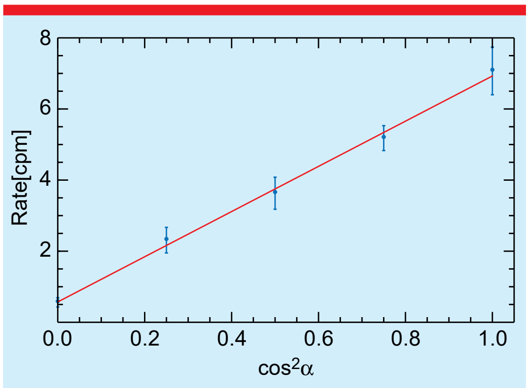

Figure 4. Zenith angle distribution of atmospheric muons.

data shown in figure 4 were collected in Otwock-Świerk at ground level.

Figure 4 presents the rate of registered muons as a function of the zenith angle. Each data point represents approximately an hour of data collection. The decrease of the measured numbers with an increasing angle is clearly visible. According to the literature (for instance [16]) the cosmic muon intensity follows a cosine squared dependence on the zenith angle. This dependence fitted to the data is shown on figure 4 with the red line.

5. Outlook and conclusions

At present, the main tasks for programme leaders are dissemination of the knowledge about the programme throughout Poland, and improving its adaptation to the condition of Polish teachers and students. In the first step to achieve the first goals, the information about the programme was sent to units of pedagogical supervision in Poland (‘Kuratoria’) as they also provide information for teachers about many educational programmes and competitions. In addition, all teachers and students visiting NCBJ are informed about the programme and encouraged to borrow detectors.

It is planned to evaluate the programme by means of a survey addressed to the teachers who participated in it. The survey will not only aim to get the programme assessed by the teachers, but also help to determine how many students have practically used detectors, and what kind of measurements were taken. For the Education and Training Division of NCBJ, a particularly valuable part of the survey will be comments on how to improve the process of lending detectors, and how to make their use easier.

The design, construction, and idea for teaching programme of a low-cost detector set have been described. The Detector Lending Programme provides multiple sets of two types of detectors for schools with which they can do research projects. Thanks to the borrowed detectors, the classes gain a completely different course, as the vast majority of students may actively participate in the classes. A shift from teacher-centred traditional approach towards a pupil-centred active learning approach attracts most pupils, improves their learning and learning outcomes. Suggested methodologies and actions should cause a future increase of the number of technically oriented students, the general scientific interest in science, and the public engagement in the understanding of physic processes.

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