Using a simple scintillator kit to experience gamma ray detection

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Abstract. A simple scintillator kit developed by Ian Bearden [1] was used to prepare a learning experience on gamma ray detection for secondary students. The goal is to offer an opportunity to collect gamma spectra, analyse data and understand how coincidence measurements are useful in space physics and in many other applications.

1. Introduction

Updating the upper secondary school’s curriculum can also means offering to students the opportunity to understand how actual research in physics is working, starting from the basic concepts of classical and modern physics. Data acquisition techniques and measurement principles in various fields in experimental activities today have many characteristics in common, they are based on analysis of energy spectra and in any case on indirect measurements whose validity, potentials and limits must be kept under control.

Subnuclear physics and astrophysics are experimentally investigated by studying the particles produced in micro or cosmic events. In order to be detected, these particles must interact with the matter that constitutes the active part of a detector, generally producing in it charge carriers set free by ionization, or photons emitted by luminescence stimulated by the incoming radiation. In the second case, photons emitted by the active material (scintillator) are collected and counted by a photomultiplier (PM), a device whose operation is based on the photoelectric effect (PM tube - PMT) or the creation of electron-hole pairs in a doped semiconductor (silicon PM - SiPM). Detectors based on a scintillator seen by a PM are very important nowadays in many fields of applications in which gamma rays must be acquired and analysed, as in the case of the Positron Emission Tomography (PET).

2. The educational context

Understanding the processes involved and the detection principles of a modern detector is not only an interesting topic of applied physics. It allows to put in context the methodology of the experimental research and it constitutes, from the educational point of view, an opportunity for orientation and formation in the field of experimental physics.

In this perspective, in the last years many projects of simple and affordable experimental setups have been developed, to be used in didactic measurements of ionizing radiation, for example from cosmic rays or small radioactive sources. In particular, two recent projects provide very low cost sensors, both based on scintillators coupled to a SiPM: one is the CosmicWatch [2], the second has been developed by J. Bearden [1]. The availability of these types of sensors allows two types of use: a "black box" mode, where the focus is on the data measured, and a mode where the underlying physics of detection is the
main focus. The latter allows the design of educational activities in which the main concepts and principles involved in experimental activities in this field are highlighted.

Taking the opportunity of a collaboration, as educational spinoff, with the project "HERMES" [3], an experiment aimed to study astrophysical topics as Gamma Ray Burst and EM counterparts of gravitational waves, we decided to design a teaching/learning (T/L) intervention module as pilot proposal for secondary school’s students on gamma detectors and space physics.

3. The structure of the educational path
The overall structure of the T/L intervention module can be summarized as follows.

3.1. Introduction to the device.
Students become familiar with the experimental apparatus and they explore the main features of the voltage signal produced by the sensor, represented as a waveform displayed on an oscilloscope, in terms of amplitude, duration and frequency of the events. They learn how to use the trigger level and they qualitative investigate the amplitude distribution of the events.

3.2. Sensor operation.
Knowing that the signals are produced by gamma rays, the student are asked to make some hypothesis on the type of processes involved in the generation of the electrical signal in the sensor (photoelectric effect, ionization,…), using their previous knowledge in a creative way.

Students are lectured (or read a reference) about the operation of the SiPM sensor, and the role of the scintillator and the processes taking place within the scintillator. After that, they are asked to rework the concepts acquired and to sketch them.

3.3. Explaining and analyzing the spectrum.
After students understand the basic processes to convert gamma photons to visual photons, to electrons, to current and to voltage, all transformations going on in the scintillator and the SiPM, a sequence of active engagement tasks is used for the students to be able to explain the shape of the acquired spectrum and analyse it.

This sequence involves discussions on the expected spectrum of a beta decay, a single gamma decay, multiple contemporary (within the resolution of the sensor) gamma events and simultaneous beta and gamma events. At the end, students predict the shape of a spectrum, which derives by a combination of all considered events.

3.4. Acquisition of the spectrum of internal events.
The sensor we used to develop the path [1] has a small $\gamma$ ray source ($^{176}$Lu) embedded. Students are asked to acquire a rough spectrum in energy of the emitted $\gamma$s, by setting the trigger level to different values and plotting the differences of counts for the different settings. An automatic acquisition of the spectrum is therefore suggested and data obtained are compared to literature.

Optionally, a discussion on statistical errors can be introduced to analyse the differences between the obtained spectra.

3.5. Measuring a large external event.
Students are asked to imagine how to design a detection device that has to detect a cosmic ray event, which releases a large number of gamma photons at approximately the same time and to distinguish it from other sources of signals.

Tasks: - Suggest an experimental setup using the sensors and a measurement strategy to achieve this goal. - Discuss the strategy with other groups and the instructor.

1) The scintillator used for the sensor is a LYSO crystal (Cerium-doped Lutetium Yttrium Orthosilicate), in which the a small fraction of the Lu component is the radioactive isotope.
The proposed activity aims to make students aware of the need for measurements with more detectors acquired in coincidence in order to characterize the presence of more time-coinciding photons, which is the signature of the shower in the cosmic ray event.

The expected result is the design of a measure with two spatially close sensors, acquired in coincidence. Two different experimental setups are then proposed to perform a counting measurement: an external coincidence system, generating a logical signal, or the trigger discrimination of the multiplicative combination of the signals.

4. The setting and data collection
The course has been preliminarily tested in a class of high-school students in Treviso (Group 1, N=17, grade 13), in an extracurricular activity called Experimental modules for high-school students in Udine (Group 2, N=21, grade 13), summer school for motivated high-school students (Group 3, N=32, grade 12), in Udine, and in a summer school for motivated high-school students (Group 4, N=17, grades 10 – 13) in Ljubljana.

Only parts of the course described in section 3 were tested in these preliminary pilots. The introductory “black box” part (section 3.1.) has not been tested in any group. The theoretical explanation of the sensor’s basic operation (section 3.2.) has been tested in all groups, but to a varying degree. A very detailed explanation was given to groups 1, 2 and 3, while a very abbreviated one was given to group 4. The explanation and analysis of the spectrum (section 3.3.) was given most focus in all the groups. The acquisition of the spectrum of internal events (section 3.4.) was done in groups 1, 2, and 3 by the teacher and the spectra were analysed by the students. The part on coincidence events (section 3.5) was only briefly touched upon by the teacher. We report here on the activities related to the understanding of the spectrum (section 3.3). This part lasted for about 60 minutes. We collected data on clicker responses and graphing tasks, which will be explained in the description of the course.

5. The educational path on the explanation and analysis of the spectrum
A LYSO crystal has internal nuclear decays of Lutetium into excited Hafnium (beta) and form exited Hafnium into de-excited Hafnium (gamma).

\[ ^{176}\text{Lu} \rightarrow ^{176}\text{Hf}^{*} + \beta + \bar{\nu} \]  
\[ ^{176}\text{Hf}^{*} \rightarrow ^{176}\text{Hf} + n\gamma \]

The energies of both decays are deposited in the crystal and detected as one event. Due to this, the spectrum of the gamma events is modified by the spectrum of the beta events. The spectrum is in figure 1, and the beta lines are barely recognisable. The goal of the educational path presented here is to explain to students the formation of such a spectrum through a series of activities.

Figure 1. The spectrum of the internal decays of LYSO. The red arrows indicate the most visible gamma lines, which are modified by the large tail of the beta decay spectrum.
5.1. *What is a spectrum and how do we get it*

The creation of a spectrum is not trivial to students (figure 2). Even the students in the summer school, who had activities related to spectroscopy at the same school, had trouble identifying the process. We developed an activity whereby the students are given a series of pulses, such as those in figure 2b, with different heights, a coordinate system for a spectrum and are asked to create a spectrum from the series of pulses. The data has not yet been analysed, but our observations show that this not at all a trivial task.

![Figure 2](image)

**Figure 2.** A schematic representation of the sequence of events when creating a spectrum. a) A particle hits the crystal and creates an avalanche of visible photons. b) The avalanche is registered as a pulse on an oscilloscope. Here various pulses are visible, each of a different amplitude. c) Therefore it is plotted a histogram of the number of events as a function of their amplitude (mV).

5.2. *The energy of the beta and the prediction of the neutrino*

This first of a series of tasks on the beta decay has historical and epistemological importance, although it is not directly relevant to the sequence.

The students are required to think about energy conservation and to apply it to the beta decay\[4\], for which the list of the rest energies of all the observable particles (the Hf nucleus and the beta particle) is given and the only unknown is the kinetic energy of the beta particle. In a clicker activity, the students are then asked to choose which spectrum of the kinetic energy of the beta particle should be expected.

Among the options A, B, C and D in figure 3, C is the overall most chosen answer, with D next. In Groups 3 and 4, the correct answer A was the most chosen. This further shows that spectra are a difficult topic for students.

![Figure 3](image)

**Figure 3.** a) An energy diagram of a beta decay in the absence of a neutrino. b) The choices that the students are presented with for the spectrum of the kinetic energy of the beta particle.
The discussion then proceeds through the introduction of the real measured beta spectrum and its implications. Two competing hypotheses are presented: i) the energy conservation does not hold in the world of particles, ii) there is another, yet undetected particle. The detection of a neutrino is then discussed.

5.3. The emission of gamma photons
The gamma decay is treated in a similar way to the beta decay. Energy diagrams are used to discuss the energies of the gamma photons. Various energy levels are presented between the excited and the de-excited Hafnium. A clicker activity is used, where the students are asked to predict the energies of the emitted photons from the known energy levels.

The students’ answers were best in Group 3 (around 90% correct answers), followed by Group 1 (65%) while in Group 2 the results were evenly distributed. In Group 4 there were only 20% of correct answers. This could be due to the fact that the group was very heterogeneous in regard to the school year (from K-10 to K-13).

5.4. The absorption and spectrum of the gamma photons
The students are told that the emission of the various gamma photons is so fast that they all get registered as a single event. A clicker activity is then performed where the students are given a spectrum comprised of photons of two different energies detected as separate events (figure 4). They are asked to predict the spectrum, if both photons are always detected as a single event. The choices are given in figure 4.

The correct answer is B. It is also the only one consistent with the conservation of energy. The most chosen answer in Group 1 was A. In Group 2, A and B were chosen equally often, while in Groups 3 and 4 B was most chosen.

5.5. Simultaneous detection of a beta and a gamma
With the activities so far we have built an understanding of how energies are summed inside a sensor. The next activity asks students to predict the spectrum of a beta and a gamma detected simultaneously (figure 5).

This activity has only been performed with Groups 1 and 3. The results are somewhat surprising. Group 1 chose A, indicating a reasoning that should have made them choose C in the previous activity (section 5.4.). Group 3 chose B, which would indicate a reasoning that should have made them also choose C in the previous activity. These results indicate inconsistencies in the reasoning process which will be investigated in the future.

Figure 4. A clicker activity on the summation of energies in a sensor. Students are asked what spectrum would be the result of a measurement, if the original two photons were detected as a single event.
5.6. Escaping photons
The activities then proceed by addressing the possibility that some photons might escape if the crystal is small. Such escaped photons would not release their energy within the crystal and this energy would not be detected by the sensor. Therefore, in the case of three emitted gamma photons, the possible detected energies could be the sum of all three, all the sums of any two of the photons, or even the energy of each of the photon if the other two both escape. There is room here for another activity for the students to predict the resulting spectrum. Further discussion leads to the fact that the amplitudes of each of these peaks in the spectrum depends on the relative probability for that event to happen. For example, the peaks of the single photons are expected to be low, because the probability of two photons escaping the crystal is low. But, it gets higher when the size of the crystal gets smaller.

5.7. Predicting the final spectrum
The cumulative activity for this part of the course is predicting the shape of the expected spectrum, knowing that the beta is always absorbed, while some of the gamma might escape the crystal (figure 6). The students succeed to various degrees. The data has not been analysed yet, but our observations indicate that most students successfully predict the shape of the spectrum (figure 7).

5.8. Analyzing the final spectrum
The final activity in the sequence about explaining and analysing the spectrum is to analyse the actual measured spectrum. The spectrum has been accumulating over the course of the session and can be viewed. Student are now asked to identify the different gamma photons from the actual spectrum. This data has only been preliminary analysed. It suggests that students graphically identify the gamma lines, pointing at them with arrows or lines (more than 90% in each group). Most groups did not attempt to identify the photon energies. Only in Group 3 about 75% of the students attempted to identify the photon energies, of which only 50% (37% of all students in Group 3) correctly identified them. Only
in Group 1 many students (83%) attempted to identify the relative number of each event (its relative probability). Only 28% of all students in Group 1 did so successfully.

![Figure 7. a) The actual spectrum of LYSO’s internal decays can be constructed from three gamma spectra each combined with a beta spectrum. b) The final spectrum is the sum of these separate spectra. In this case the sum is “vertical” (summing the number, not the energy), because each combined gamma-beta spectrum represents an independent event.](image)

5.9. Cleaning up the spectrum
The next activities are part of the sequence on coincidence detection (section 3.5). The first of these activities asks students to suggest ways to detect only the gamma without the beta using two detectors crystals. The activity has been performed only once but under heavy time pressure, so its results are not representative. The ideas is that students should propose to detect the escaped gamma. The next step is to use a detector with a different crystal without internal decays (a plastic, perhaps) to detect the gamma.

However, this activity is specifically intended to proceed, even if LYSO crystals are the only available. In this case we introduce coincidence measurements. If two detectors detect the particle at the same time, it might be that one detected the beta decay and whichever photons were absorbed in the crystal, while the other detected the escaped gamma photon. These events are rare, so a long time for the accumulation of the spectrum is needed. Nonetheless, a time of about 30 min is sufficient to show the main features of the spectrum. The experiment can thus be started at the beginning of the session, and by the end the data will be collected.

The students are then asked to compare and contrast the internal spectrum with the spectrum of coincidences.

5.10. Dependence on distance
Once the coincidence measurement is set up, it is used to discuss the relationship between the number of coincidences and the distance between sensors. The students are supposed to consider the decrease in the solid angle that the second sensor covers as it is moved away from the first. The measurements reveal that some coincidences persist even at very large distances. These are random coincidences when two independent events, one in each sensor, randomly happen at the same time (more precisely, within the time window of the coincidence).

5.11. Dependence on the angle
One of the possible explanation for the coincidences is that they are the consequence of an external event to both sensors, such as a cosmic ray or a similar particle coming from a nearby laboratory. This activity relates to the task that students have in proposing a way to measure an external event involving large numbers of gamma photons. To test this hypothesis, a measurement of the dependence of the number of coincidences on the angle between the two sensors can be performed. If the particles come from a localised distant source, then a preferred angle should be observed, the angle from which the particles come. If no such angle is observed, then either the source is evenly distributed, or the events are not external.
The measurements that we managed to perform so far indicate no angular dependence. But the LYSO detectors might not be able to detect cosmic rays, or they are so few that other coincidences completely obscure them.

6. Conclusions
We presented a learning sequence designed to introduce students to experimental subatomic physics and astrophysics. The entire sequence is designed to cover multiple topics at different levels, using detectors as black boxes to study the nature of the detected particles or focusing on the very mechanisms within the detector to explain its output. The tested part of the sequence falls into the second category and focuses on explaining the complex spectrum measured by a LYSO detector. The topic is very rich and offers the possibility to address many fundamental concepts of physics and of physical representations, such as energy diagrams and spectra. It also offers insights into the world of elementary particles and their detection. The topic is also important, because it combines some practical challenges of experimental physics with some fundamental theoretical background, which is a combination crucial for experimental physicists. Our experimentations in class identified numerous topics where students’ understanding cannot be assumed, but instead needs to be specifically addressed. We will continue to develop the course and add activities to help students understand the concepts that resulted difficult and the technology that might shape future scientific discoveries.

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7. References
[1] Ian G. Bearden: Low Cost Detectors for Teaching Nuclear and Particle Physics, presented in San Sebastian GIRED-MPTL Conference (2018).
[2] S.N. Axani,, J.M. Conrad, and C. Kirbyz; The Desktop Muon Detector: A simple, physics-motivated machine- and electronics-shop project for university students, American Journal of Physics 85, 948 (2017)
[3] F. Fuschino et al.: HERMES: An ultra-wide band X and gamma-ray transient monitor on board a nano-satellite constellation, in press, arXiv:1812.02432v2 [astro-ph.IM] (2018)
[4] E. Etkina, G. Planinsic, A. Van Heuvelen: College Physics: Explore and Apply, 2nd ed., Pearson, ISBN-13: 9780134605500, New York, NY, USA (2019)