Learning Particle Physics Using Timepix-Based Pixel Detectors at CERN S'Cool LAB

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S'Cool LAB[1] is an international out-of-school hands-on learning laboratory at CERN. At S'Cool LAB, high-school students work with high-tech equipment to independently perform modern physics experiments that are linked to the technology and physics of CERN. Among the S'Cool LAB equipment is the MX-10 particle camera, which uses the Timepix chip as part of its hybrid pixel detector. This chip was developed by the Medipix2 Collaboration[2], hosted at CERN, and the detector as a whole has now been re-purposed for students by JABLOTRON ALARMS a.s.[3]. One goal of S'Cool LAB is to integrate this pixel detector into hands-on workshops and to evaluate its educational potential while taking into account students' conceptions about radiation. Here, we introduce S'Cool LAB and the pixel detector, give an overview of possible experiments, and explain in more detail the current use of the detector in S'Cool LAB.

1 S'Cool LAB

S'Cool LAB is an international hands-on particle physics learning laboratory at CERN, Geneva, Switzerland. It aims to provide insight into the working methods, technology, and research of the world's largest particle physics laboratory and to make the physics and technology of CERN understandable for students through hands-on experimentation (Figure 1).

The main target group of this out-of-school learning place is high-school students (ages 16-19) who come from all around the world to visit CERN. In addition to guided tours through CERN's research facilities, selected student groups regularly take part in hands-on workshops in S'Cool LAB.

During these workshops, students work with high-tech equipment to perform modern physics experiments. All experiments are grouped into the categories particle acceleration, particle detection, and applications of particle physics. Currently, a workshop consisting of three experiments is offered: Students first build their own particle detector (a diffusion cloud chamber based on dry ice and Isopropanol) and observe tracks of cosmic particles and natural radiation. Afterwards, students study particle acceleration using an electron gun and learn about electrically charged particles in electric and magnetic fields – prerequisite knowledge to understand particle accelerators and colliders like the LHC (Large Hadron Collider) at CERN. Furthermore, students work with X-ray machines and the MX-10 pixel detectors to learn about the interactions of photons with matter and thereby gain insight into applications of particle physics in our every-day life such as medical imaging in hospitals, for example.

1 Homepage of CERN S'Cool LAB http://cern.ch/s-cool-lab
2 Homepage of Medipix Collaboration http://cern.ch/medipix
3 Homepage of JABLOTRON ALARMS http://www.jablotron.com

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Fig. 1. S'Cool LAB - a hands-on particle physics learning laboratory at CERN.

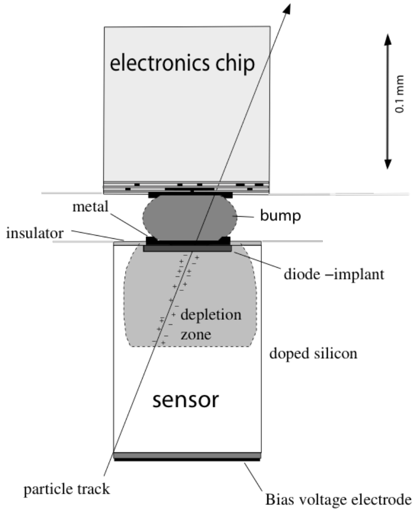

Fig. 2. Cross section through one pixel of a hybrid pixel detector with a particle track (reprint from Rossi, 2006).

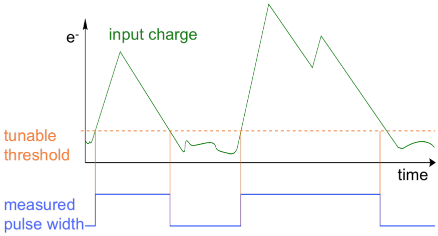

Fig. 3. Illustration of the energy measurement mode of Timepix. The time period in which the input charge stays above the threshold setting is proportional to the deposited energy.

S'Cool LAB not only serves as a learning opportunity for students, but also as a test bed for physics education research. Research on students' conceptions about modern physics is of particular interest. All activities in S'Cool LAB have been developed in an iterative design process taking into account students' interests and conceptions, physics curricula, and aspects of CERN physics and technology.

2 Hybrid Pixel Detectors

Among S'Cool LAB's equipment is a hybrid pixel detector that uses the Timepix chip. The Timepix chip was developed by the Medipix2 Collaboration, hosted at CERN, and the detector as a whole was re-purposed for high-school students by JABLOTRON ALARMS a.s. in the MX-10 particle camera.

Hybrid pixel detectors consist of two layers. One part is a pixelated, semi-conducting sensor material, where ionising radiation deposits certain amounts of energy depending on the path and momentum of the particles while traversing the material. This energy can be measured through ionisation processes in the semi-conducting material with an array of charge-sensitive amplifiers in a readout chip. The readout chip represents the second layer and is segmented into the same number of pixels. The two layers are connected one by one to the corresponding pixels of the sensor via solder bumps as shown in Figure 2.

2.1 The Timepix Electronics Chip Series

The original purpose of the detector chips developed in the Medipix Collaboration that started in 1999 was medical imaging, hence its name. This technology transfer effort from detectors for particle physics to medical applications resulted in a pixel detector readout chip series called Timepix (Llopart, 2007). In addition to counting photons in a defined measurement period (Medipix mode), the pixels can be alternatively configured to measure the deposited energy or the arrival time of an event. The sensitive area measures 1.4 x 1.4 cm2 and hosts 256 x 256 pixels, which results in a size of 55 x 55 μm^2 per pixel. Depending on the sensor and the bonding process, a certain minimal energy sensitivity of

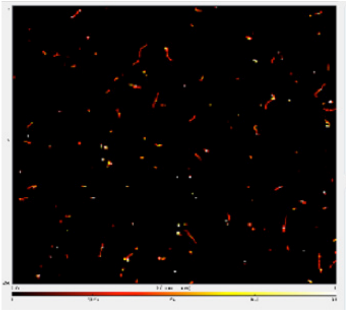

Fig. 4. Screenshot of a background measurement (35 min) with an MX-10 pixel detector and Pixelman software. The colour map represents the amount of energy.

a hybrid pixel detector assembly is achieved per pixel. The energy calibration of the MX-10 particle cameras used in S'Cool LAB results in a lower threshold setting of 5 keV, providing a very sensitive measurement tool for a wide range of experiments.

2.2 Detection Principle

The energy deposited by ionising radiation frees electron-hole pairs in the depletion zone of one or multiple pixels in the sensor material (made of silicon in the case of the MX-10). Electrons or holes are collected through an externally applied electrical field, converted into voltage pulses and digitized by Timepix. Depending on the sensor type, either electrons or holes are converted. In energy mode, the duration of a voltage pulse above the threshold level is measured per pixel as shown in Figure 3 and transmitted from the MX-10 via USB to a computer. After calibrating every pixel with the known energy spectra of radioactive sources, the deposited energy can be calculated based on the measured pulse width. The typical energy range for Timepix pixels spans from the threshold setting up to several MeV.

3 Learning With MX-10 Pixel Detectors in S'Cool LAB Workshops

Pixel detectors can be used as a versatile tool not only in particle physics research or medical imaging but also in physics education. If the detectors are refurbished in a compact way and accompanied with a simple analysis software, students can use them to perform a wide range of measurements with background radiation or radioactive sources, as demonstrated previously by Whyntie et al. (2015).

3.1 Examples of Possible Experiments Tested With the MX-10 Detector

3.1.1 Background Radiation

Students can study tracks of particles originating from space or from naturally occurring radioactive isotopes in real-time. Different types of particles are distinguished by the specific signature recorded with the detector (Bouchami et al., 2011). A screenshot of a background measurement (35 minutes) using the Pixelman software4 is shown in Figure 4. A pattern recognition algorithm associates straight tracks with muon candidates (Figure 5), curly tracks with beta candidates (Figure 6), heavy blobs with alpha candidates (Figure 7), and dot-like shapes with gamma candidates (Figure 8).

In addition to pattern recognition, the software can be used to display the energy information of single tracks or to produce histograms of the energy distribution of the different types of particles.

4 Homepage of Pixelman software http://www.aladdin.utef.cvut.cz/ofat/Pixelman

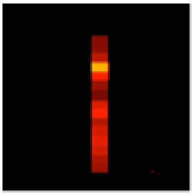

Fig. 5. Snapshot of “straight track” shape (muon candidate).

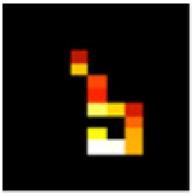

Fig. 6. Snapshot of “curly track” shape (beta candidate).

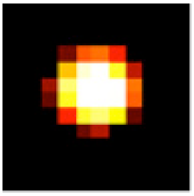

Fig. 7. Snapshot of “heavy blob” shape (alpha candidate).

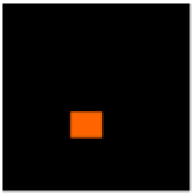

Fig. 8. Snapshot of “dot” shape (gamma candidate).

3.1.2 Properties of Ionising Radiation

Students can use the detector to verify the inverse square law (Figure 9), study the attenuation of ionising radiation in matter, determine emission energy spectra of radioactive sources, and examine slightly radioactive every-day objects like thoriated tungsten rods (Figure 10).

3.1.3 X-Ray Imaging

Combining the MX-10 detector with an X-Ray source, students can use the detector as an on-line X-ray camera. Objects like insects or memory cards can be X-rayed and the variable absorption of photons in the material results in a radiograph (Figure 11). In addition to imaging, energy spectra of the X-Ray source can be measured at different acceleration voltages (Figure 12).

3.2 Students’ Conceptions About Radiation

“For museum professionals, knowledge of the audience’s conceptions of the issue to be presented in an exhibition should always be considered in the exhibition development process, and it should be noted that the audience’s conceptions may prevent the intended interpretation of information presented at a museum.” (Henriksen & Jorde, 2001)

Awareness of students’ conceptions is essential not only for museums (Henriksen & Jorde, 2001) but also for out-of-school learning places, including S’Cool LAB. Indeed, knowing students’ conceptions about the underlying physics concepts is needed to successfully design learning activities with hands-on experiments and to foster understanding. Measuring particle properties using pixel detectors naturally builds on students’ conceptions about radioactivity and radiation. Previous studies investigated students’ understanding of ionising radiation and associated concepts like radioactivity, irradiation or contamination (Figure 13).

In addition to a general lack of distinction between these different concepts among students (Millar, Klaassen, & Eijkelhof, 1990), it has been shown that radiation is perceived as dangerous, especially if the source is artificial (Eijkelhof, Klaassen, Lijnse, & Scholte, 1990). An exception is the use of ionising radiation in hospitals: In this context students consider radiation safe (Millar, 1994). Several other students’ conceptions about different aspects

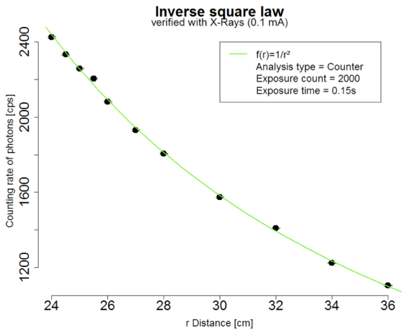

Fig. 9. Inverse square law.

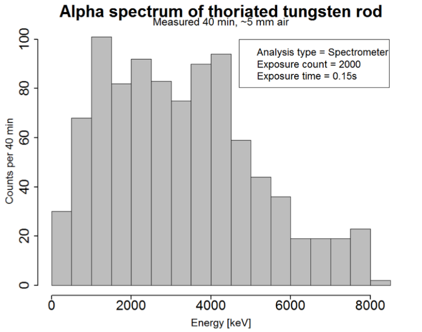

Fig. 10. Alpha spectrum of thoriated tungsten rod.

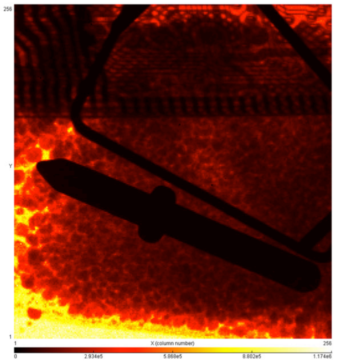

Fig. 11. Radiograph (solder pin, staples, salt grains, and memory card).

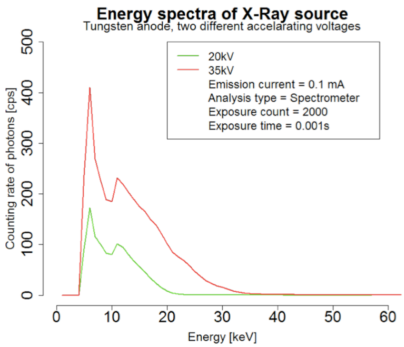

Fig. 12. Energy spectra of an X-Ray source (tungsten anode).

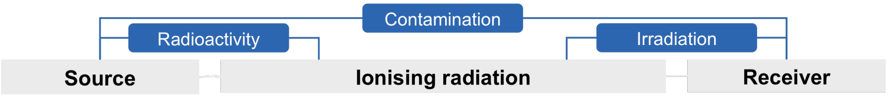

Fig. 13. Concepts associated with ionising radiation (Millar, Klaassen, & Eijkelhof, 1990).

of radiation have been studied so far; of interest for S'Cool LAB are especially conceptions that can be explicitly addressed during a workshop, e. g.:

- *"After irradiation with X-rays, objects become radioactive themselves."* (Eijkelhof, Klaassen, Lijnse, & Scholte, 1990)
- *"The transparency of material is the same for X-rays as for visible light."* (Clément & Fisseux, 1999)
- *"Ionising radiation is deflected by a screen like visible light."* (Riesch & Westphal, 1975)

Many of the misconceptions reported by previous studies have one thing in common: Students "*do not have a secure understanding of the particulate model of matter*" and therefore show "*sever difficulties with the atomic and sub-atomic level explanation of radioactive phenomena*" (Klaassen, Eijkelhof, & Lijnse, 1990). This suggests that learning about the properties of different particles and their interactions with matter could possibly reduce known misconceptions among students. Workshops in S'Cool LAB try to assess students' misconceptions and to confront students with unexpected observations through the use of Prediction-Observation-Explanation tasks.

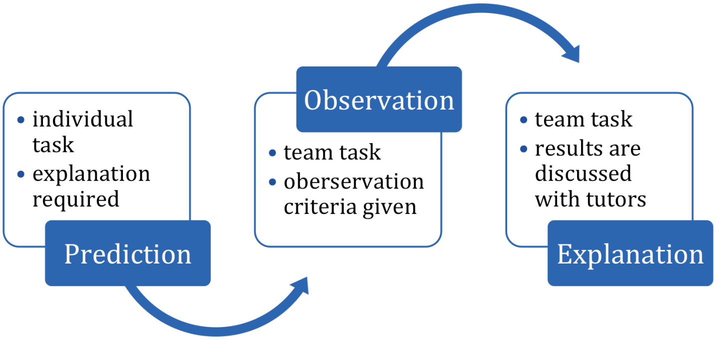

Fig. 14. Prediction-Observation-Explanation cycle in S'Cool LAB.

3.3 Prediction-Observation-Explanation (POE) Tasks and Students' Conceptions

3.3.1 Prediction-Observation-Explanation (POE) Tasks in S'Cool LAB

Prediction-Observation-Explanation (POE) Tasks (White & Gunstone, 1992) are an integral component of learning activities in S'Cool LAB to

- assess students' conceptions about the phenomena they are studying, and
- to promote conceptual learning during experimentation.

The schematic flowchart of the use of POE tasks in S'Cool LAB is shown in Figure 14.

First, students are asked to predict the outcome of an experiment and explain their reasoning. To cognitively activate all students and prevent social loafing, this step is designed as an individual task. The experiments are constructed in such a way that students will predict the outcome incorrectly – if they hold certain misconceptions – and be surprised by the outcome. By asking the students to explain their reasoning, students' conceptions can be assessed in this step (Liew & Treagust, 1998). In a second step, students perform the experiment in a team and observe the outcome carefully, based on given observation criteria. Depending on the students' initial prediction, the outcome might bring their misconceptions to their attention and unravel inconsistencies in their reasoning. Finally, students discuss differences between prediction and observation within the team and with the help of tutors, to explain the experiment and to promote a better understanding of the underlying concepts.

3.3.2 Example of a POE Task in S'Cool LAB – Irradiation vs. Contamination

To probe whether students fail to distinguish between the concepts of irradiation and contamination as suggested by Eijkelhof, Klaassen, Lijnse, & Scholte (1990) a corresponding POE task is used in S'Cool LAB workshops: students irradiate salt and measure whether it becomes radioactive using pixel detectors by comparing three consecutive measurements (see Figure 15). Before they start the experiment, students predict the outcome based on their previous knowledge.

After analysing student worksheets of 86 students who participated in S'Cool LAB workshops between September and December 2015, 63% of the students' predictions show misconceptions about X-radiation (Table 1). Students apply matter-like properties instead of process properties to radiation and consider radiation as something that *"salt takes up"* or *"is absorbed"*, which would result in additional particles originating from salt after irradiation. This reasoning was documented in findings by Eijkelhof, Klaassen, Lijnse, & Scholte (1990). Some students think that *"X-rays can make salt unstable"* and salt would therefore become radioactive. Only 21% of the students predict correctly that there would be approximately the same number of particles in measurements A and C. 16% of the students neglect background radiation completely and predict no particles in both measurements.

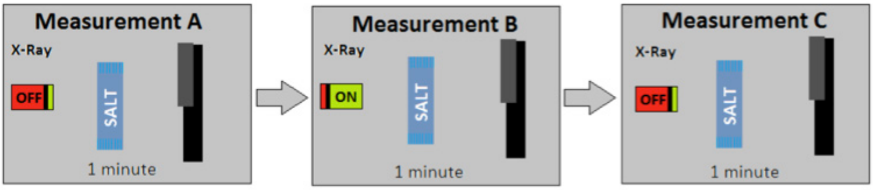

Fig. 15. Measurement schedule for POE task "Irradiation vs. Contamination" in S'Cool LAB. Students are asked to compare the number of particles measured by a pixel detector in A and in C.

The detector will measure…	Prediction (N=86)	Example for students' explanations of their prediction	Observation (N=81)
... more particles in C than in A	43%	*"Salt takes up radiation." "X-rays can make salt unstable." "Radiation from B is still present."*	28%
... approx. the same number of particles in C and A	21%	*"Salt does not radiate, stores no X-radiation."*	36%
... fewer particles in C than in A	20%	*"Salt blocks." "Salt absorbs the X-rays."*	22%
... no particles in C or A	16%		14%

Tab. 3. Students' predictions including example explanations and their observations.

After performing the experiment, only 36% of the students observe the outcome correctly and do not report a difference between measurements A and C. They seem to adapt their theories, resulting in explanations like *"Photons are consumed in the same way as for normal light: If the light is off, there are no photons"* or *"Radiation doesn't stay within the chamber after it is switched off"*. 14% of the students report no particles, neither in A nor in C. This might be explained by software problems or by a very low number of particles from background radiation during the measurement.

In summary, students' predictions and explanations show poor knowledge and a lack of distinction between the concepts of irradiation and contamination, consistent with previous findings. Rather detailed instructions in student worksheets and guidance by tutors does not guarantee that students observe and interpret experiments correctly. Instead, students' observations and also their reasoning seem to be influenced by stable misconceptions. Findings from Miller, Lasry, Chu, & Mazur (2013) support this assumption: They found that even for demonstration experiments in university lectures, only 85% of students report the observation of an experiment correctly. Their findings also underline the importance of correct observations for conceptual learning and suggest that students make more correct observations when working with POE tasks.

In the future, student worksheets and the experiments in S'Cool LAB will be further developed to increase the number of correct observations, e.g. by longer measurement times and therefore clearer results. In addition, learning in S'Cool LAB workshops will be measured quantitatively using a concept test.

4 Conclusion

Pixel detectors are versatile research tools, not only in particle physics but also in physics education. Students can study single particles' properties in a very accurate way but also use them as on-line particle cameras. The POE task described in chapter 3.3.2 shows one example of how pixel detectors are currently used in S'Cool LAB workshops. Although this task might not exploit the full potential of the detector, it shows the potential of POE tasks assessing students' understanding and reasoning when working with the detector. The POE task also shows that support from tutors is essential for students when performing and interpreting an experiment when the physics background is new to the students.

We believe that the visual and real-time measurement of particles through pixel detectors has the potential to improve students' understanding of the particulate nature of radiation and can thereby help to reduce misconceptions among students. Results from the observation and explanation steps already suggest that students can learn about radiation in this environment. Currently, a concept test based on findings from the POE tasks is under development and will be used before and after workshops to measure conceptual learning in S'Cool LAB.

References

Bouchami, J., Gutiérrez, A., Holy, T., Houdayer, A., Jakůbek, J., Lebel, C. , Leroy, C., Macana, J., Martin, J.-P., Pospíšil, S., Prak, S., Sabella, P., Teyssier, C. (2011). Measurement of pattern recognition efficiency of tracks generated by ionizing radiation in a Medipix2 device. *Nucl. Instr. and Meth. A 633*, 187–189.

Clément, P., & Fisseux, C. (1999). Opacity of Radiography, Perplexity of Teachers and Pupils in Primary School. *Research in science education in Europe*, 15-21.

Eijkelhof, H., Klaassen, C., Lijnse, P., & Scholte, R. (1990). Perceived Incidence and Importance of Lay-Ideas on Ionizing Radiation: Results of a Delphi-Study Among Radiation-Experts. *Science Education 74*(2), 183–195.

Henriksen, E., & Jorde, D. (2001). High school students' understanding of radiation and the environment: Can museums play a role? *Science Education 85*, 189–206.

Klaassen, C., Eijkelhof, H., & Lijnse, P. (1990). Considering an alternative approach to teaching radioactivity. In P. Lijnse, P. Licht, W. de Vos, & A. Waarlo, *Relating macroscopic phenomena to microscopic particles: A central problem in secondary science education* (pp. 304-315). Utrecht: Cd Press.

Liew, C.-W., & Treagust, D. F. (1998). The Effectiveness of Predict-Observe-Explain Tasks in Diagnosing Students' Understanding of Science and in Identifying Their Levels of Achievement. *Annual Meeting of the American Educational Research Association*, (p. 22). San Diego.

Llopart, X. (2007). Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements. *Nucl. Instr. and Meth. A 581*, 485–494.

Millar, R. (1994). School students' understanding of key ideas about radioactivity and ionizing radiation. *Public Understand Sci 3*, 53-70.

Millar, R., Klaassen, C., & Eijkelhof, H. (1990). Teaching about radioactivity and ionising radiation: an alternative approach. *Physics Education 25*, 338-342.

Miller, K., Lasry, N., Chu, K., & Mazur, E. (2013). Role of physics lecture demonstrations in conceptual learning. *Physical review special topics – Physics education research 9*.

Riesch, W., & Westphal, W. (1975). Modellhafte Schülervorstellungen zur Ausbreitung radioaktiver Strahlung. *Der Physikunterricht 9*(4), 75-85.

Rossi, L. (2006). *Pixel Detectors*. Springer Verlag.

White, R. T., & Gunstone, R. F. (1992). *Probing Understanding*. Great Britain: Falmer Press.

Whyntie, T., Bithray, H., Cook, J., Coupe, A., Eddy, D., Fickling, R. L., McKenna, J., Parker, B., Paul, A., Shearer, N. (2015). CERN@school: demonstrating physics with the Timepix detector. *Contemporary Physics*. 451-467