Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

A 5E-based learning experience to introduce concepts relevant in Quantum Physics

To cite this article: Joseph Obbo *et al* 2024 *J. Phys.: Conf. Ser.* **2727** 012014

A 5E-based learning experience to introduce concepts relevant in Quantum Physics

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Abstract. We here present and discuss a 5E-based learning activity focused on introductory concepts of Quantum Physics experienced at the Bachelor of Electrical Engineering of a Kenyan University. The described constructivist environment aimed at supporting an effective understanding of concepts very relevant in Modern Physics, such as wave-particle dualism, discretization, de Broglie wavelength, Heisenberg Uncertainty principle, atomic models, particle in a box, etc., by triggering a chain of reasoned investigation, inquiry, problem solving, and collaboration with peers. As it is well known, the 5E-based learning cycle is a student-centred instructional approach which helps learners to broaden their views on the concepts and link together the ideas, by means of five phases of instruction: Engagement, Exploration, Explanation, Elaboration, and Evaluation. Our findings show the proposed workflows successfully engaged students into active learning, stimulating the activation of the inquiry process and, at the same time, supporting the clarifying of important experimental and technological aspects of modern physics. This learning path represents a feasible example of a combination of a traditional lecture-based teaching method with laboratory and computational activities.

1. Introduction and rationale of the research

Recent research on Physics Education require that university curricula should include "integrative laboratory experiences that promote inquiry, relevance, and hands-on activities" and suggest the learning experience replace the lecture as dominant mode and embrace active learning that includes laboratories, internships, and cooperative learning [1-4]. The need for research-oriented learning is on the rise globally as the way to teach students in the learning institutions as opposed to a problem-solving-based lecturing approach. Many scholars have come up with several learning schemes like 5E, 6E, and 7E learning cycles [5-8]. All these learning cycles focus on the active construction of meaningful knowledge and the stimulation of high levels of critical thinking skills. Experimental evidence shows that traditionally instructed first-year undergraduates in Engineering continue to experience difficulties on dualism wave-particles and, in general, in Modern Physics topics [9-17]. The origin of these difficulties may be related to epistemology – their view of scientific knowledge – or to concepts –

residual conceptual lacks – or both [18]. Indeed, an efficient strategy of instruction addressing both epistemological and conceptual issues is needed.

The example of the 5E-inquiry-based learning path here discussed was experienced in the two semesters of 2021 at Nairobi University (Kenya), during the lectures of Physics of the Bachelor of Science in Electrical and Electronic Engineering. The learning path was previously submitted to the national Commission for University Education in November 2019 for the approval. The 5E learning cycle is a student-centered instructional model where the students perform five phases of instruction: 1. Engagement (students activate and assess prior knowledge by connecting the "new to the known"); 2. Exploration (students explore a real-world problem); 3. Explanation (students explain their thinking); 4. Elaboration/ Extension (students elaborate on their reasoning, solidify and extend their understanding); Evaluation (students assess their own learning and their progress). The steps of the 5E approach are thoroughly described in [5,6,19]. The background of the proposed learning experience is the idea of letting the students to achieve blending and interconnecting separate pieces of knowledge. These are already acquired by students in different courses. Our goal is to help them to visualize and link the concepts lying beyond separate chunks of information or equations, by enforcing their collaboration and collective intelligence skills.

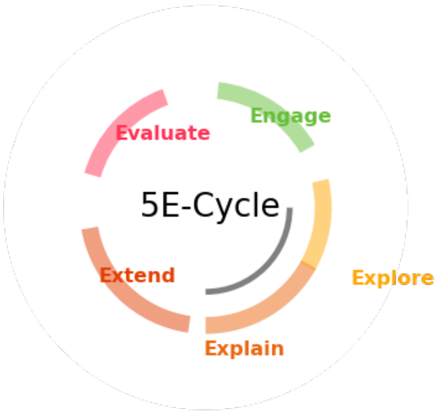

Figure 1: 5E-model of the learning progression used here

The workshop included several questions addressed to the students (a) during a series of open inquiries presented as quizzes (b) during an oral presentation of each group having performed the Franck Hertz experiment, (c) during the final exam on Rutherford experiment to question the nature of atoms. The open answer questionnaires represent a way to evaluate the learning progression via e-inquiries. The results presented here are based on (i) the qualitative analysis of the terms used by the cohort of students (word-clouds) to answer diagnostic quizzes; (ii) the quantitative analysis of the marks obtained at the final exam and at the entry test in the course of Physical Electronics in April 2022.

2. Materials and methodology

A sample of 78 freshmen at the Bachelor of Science in Electrical and Electronics Engineering at our University (51 males and 28 females) participated to these learning activities. The sample considered has the same background and shows complete independence from gender, cultural origin and community. Two groups of learners were enrolled sequentially, one group of 27 students during the first semester (July 2021-December 2021) and a second group of 52 students during the second semester (November 2021-March 2022). Student's scientist-like activities in each group were supported by two teachers having many years of expertise in the field of scientific research and on teaching physics at both high-school and university level courses. The preparation to the learning path was done through a traditional lecturing approach by using university general physics textbooks covering the introduction to the Modern Physics (Tipler and Gene – 2006, Marion and Hornyak – 1982, Giancoli – 2008) and all the didactical aspects of the experiments (i) with the LED and (ii) the photoelectric effect [16-18, 20]. The progression was found from the original research published on the illustration of quantum mechanics concepts [21] Other research-based methods to inquire on wave particle duality [22] have been considered as well.

The Group 1 answered to a quiz about the threshold voltage (Engagement phase) and had the opportunity to carry out two laboratory activities, (i) the LED experiment for the estimation of the Planck constant value (Exploration/Explanation phases) and (ii) the Franck-Hertz experiment (Elaboration/Extension phase), by using the set-up available at the engineering laboratory of the university. After that, the students were divided into smaller groups and then, encouraged to come up with the most relevant topics in Quantum Physics to be presented at the final examination (Evaluate phase).

Due to COVID restriction, unfortunately, Group 2 did not have the opportunity to complete the 5E-cycle-based learning path: they only see a demo in the lab of the University of the LED experiment for the estimation of the Planck constant value and did not experimentally verify the Franck-Hertz Effect. For these reason Group 1 will be our test group and we will consider Group 2 as control sample.
The final quiz (not compulsory) was answered only by 56 students, where both control and test group were mixed. The two quizzes were set in Google Forms and then shared with the students with the request to answer within three days. Results from these quizzes were not marked but they were used internally to ascertain the level of knowledge of concepts possessed by the students, both at the beginning of the course and after the end of the lectures. The final exam was corrected and marked out by using an external moderation procedure. Response data has been collected and can be submitted, upon request, subject to the anonymization of the student's name.

3. The activities of the 5E-cycle-based learning path

3.1. The entry quiz (Group 1 and Group 2)
During the Engagement phase, the test administered to the students was composed of eight questions asking high-school notions of Modern Physics. Students of both cohorts had previously engaged in science-like activities within their scholarship. Moreover, the Kenya Certificate of Secondary Education should allow them to get familiar with the concepts regarding photovoltaic effect before entering the university (Form 4 Physics).
The first five questions of the test were relevant for identifying the knowledge of concepts and historical conceptions, leading to the understanding of the quanta of energy. The knowledge of the energy associated with the work function in the photoelectric experiment has been verified by the questions six (Concept of "threshold voltage") and seven (Einstein equation for the work function). The last question was related to the experimental knowledge of the functioning of an electroscope.

Table 1. First three questions of the entry quiz administered to both cohorts of students at the beginning of the learning path about the investigation of the dual nature of matter.

Number	Question
1	How do you express colors from past lectures at high-school or during the chemistry labs?
2	Before Einstein, how was light considered?
3	What is the contribution from Einstein to light theory?

The results of the first three questions (reported in Tale I) are presented as a series of word clouds. The students were asked not to use the same words used in the question to redact their answers. For defining "color", the students associated the notion of wavelength and, secondarily, frequency. The pre-Einstein conception of light is quite appropriately associated with the Huygens waves. And the knowledge of Einstein's contribution to Planck's theory of quanta is accurate. Figure 2 gives a qualitative outcome that can be displayed easily as quick test feedback.

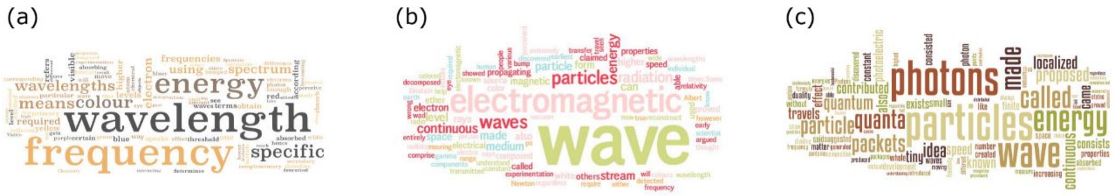

Figure 2: Word-cloud from the students answers to the first three questions

3.2. Laboratory sessions: LED and Franck Hertz Experiments (Group 1)

During the Engagement phase, the test administered to the students was composed of eight questions asking high-school notions of Modern Physics. Students of both cohorts had previously engaged in science-like activities within their scholarship. Moreover, the Kenya Certificate of Secondary Education should allow them to get familiar with the concepts regarding photovoltaic effect before entering the university (Form 4 Physics).

The exploration phase in the laboratory was preceded by the presentation of the hypothesis leading to a wave-particle model for the electron.

The group test was enrolled by following a learning progression including:

- Measurement of the Planck's constant using LEDs of different colors (see panel (a) of Fig. 3);
- Lab session on the Franck Hertz experiment (Fig.4);
- Group presentation to describe quantum nature of the electron, called “duality”.

In order to calculate the Planck’s constant, we followed the steps indicated in Ref.s [17, 23]. The discussion about the Bohr’s model and the Einstein explanation of the photoelectric effect led the students to the discovery of the mechanism of the working of a LED diode. During the learning workshop, special care was put into emphasizing the importance of separating literal expressions (formulas) from numerical applications. This was done using Jupyter Notebook services (CoCalc), and asking for a notebook reporting the results from the LED characterization experiment (panel (b) of Fig. 3). This way code and calculated values were written in Python 3 cells of the notebook, while the formulas were derived in the markdown cells. Students used the Notebooks as logbooks to note the followed procedure, the difficulties encountered throughout the activity and the changes they made during the inquiry process. Therefore, the explanation phase was centered on the Broglie wavelength/momentum description, the energy of the photon (Planck’s formula), the energy conservation (it was also recalled as superseding the usage momentum for the description of collisions), and the introduction of the Schrödinger equation.

As discussed in Ref. [3], the Franck Hertz experiment was introduced to students by starting from the problem of finding an experimental confirmation of the Bohr’s postulates asserting that atoms can absorb energy only in quantum portions. In this Elaboration phase the students were driven by the two instructors through a reasoned sequence of experimental steps, carried out within an elicited inquiry-based learning environment, towards the visualization and discussion of the experimental results [3].

During informal inquiries, while working in the Franck-Hertz experiment the students were asked to express their ideas in their lab reports, on matters such as:

“What is the specificity of collisions between objects in the quantum world?”;

“How can energy conservation help to access these problems?”

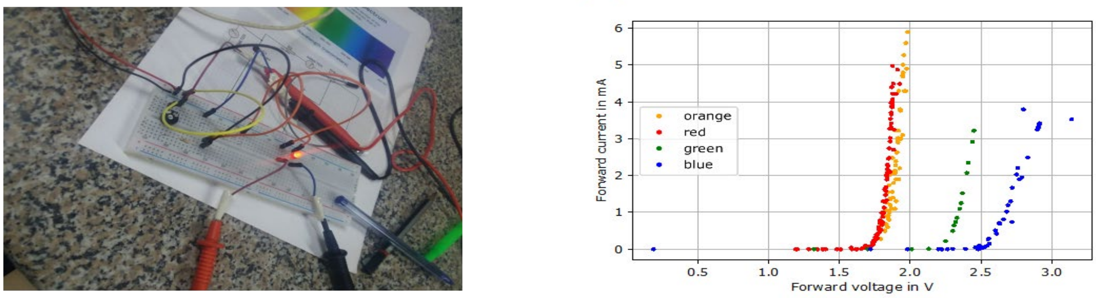

Figure 3: Pictures from the first lab activity on measuring Planck *c*onstant with various LEDs

Figure 4: Pictures from the Lab Sessions about the Franck-Hertz experiment

The hands-on with the Franck Hertz apparatus was carried out in small teams of five students; these teams were then given the possibility of communicating their results. This last activity was presented as a conference role-game session (gamification approach). Unfortunately, only the test group could benefit from it. Indeed, the Group 2 (control group) only attended a demonstration by the teacher of the experiment with LEDs of different frequencies in the laboratory and did not have the opportunity to carry out the Franck and Hertz experiment. This circumstance may explain their poor overall performance when asked to calculate the wavelength corresponding to the mercury energy gap.

3.3. Exit test – not compulsory (Group 1 and Group 2)

The final test (Evaluate phase), designed to investigate the acquired understanding of duality, consisted of height questions. The first three were focused on a detailed explanation of the de Broglie equation applied to photons. In the fourth question, the students were asked to recall the equation underlying the LED threshold voltage, but only 12 out of 56 were able to recall the conservation equation based on Planck's constant. The same students were asked to use this equation to write the wavelength associated with a transition of a given energy in eV. The majority of students gave a good response (34/56). The photoelectric effect was discussed though the paradox of a threshold wavelength. Almost half the students stick to a miss-conception assuming the photo-electric effect is triggered by the sole intensity of the radiation. When asked for an explanation of the work function, little less than half of the students can answer (27/56). Finally, the expected results from the seminal experiment involving "Zinc plate", "electroscope" and "UV lamp" were asked. Almost all students (54/56) are satisfied with explanations found on the internet that give simplistic electronic explanations, based on Drude-Lorentz models of the free electron. Only two were sensitive to the importance of energy levels. This can be ascribed to the fact that the majority of them had no contact with the Franck-Hertz experiment.
Of the 56 students, 16 good results came from the test group (59% of Group 1) and 18 came from the control group being more numerous (35% of Group 2).

3.4. Final exam (Group 1 and Group 2)

Even if each step of a 5E-based learning path should deserve an evaluation, both groups went to a final exam on the description of a Rutherford experiment, which was not seen during the lectures. The exam was based on a script-based questions in accordance to the syllabus approved by the University. In evaluating the answers, we considered to what extent the waves have been involved in understanding a collision phenomenon, i.e. also using the wave nature of electrons (as seen during the course). The competencies employed to describe an apparatus were recalled by a schematic task. Figures 5 and 6 show some examples of answers from the students. Figure 5 indicates that the description of the experimental setup is consistent with what has been seen in high school by the learners. The next step was to relate the new to the known, by asking students to propose a physical explanation for the backscattering of alpha particles. Panels of Fig.6 show two opposite explanations, involving either a classical-particle approach of collisions (left panel) or a wave diffraction description (we have not yet explained the Laue method for diffraction, at this stage). For this last learner, the overall understanding of the discipline was good, and the backscatter of an alpha particle was considered understood. It is important to notice that one student out of 27 of the Group 1 involved waves for the understanding of a collision, through an explanation of the undulatory nature of electrons as seen during the Franck-Hertz explanation. It is our opinion that these concepts are difficult to acquire in less than a year, and the remediation proposed is to delay over two different semesters, and to propose modeling activities in physical electronics that make extensive usage of the Schrödinger equation.

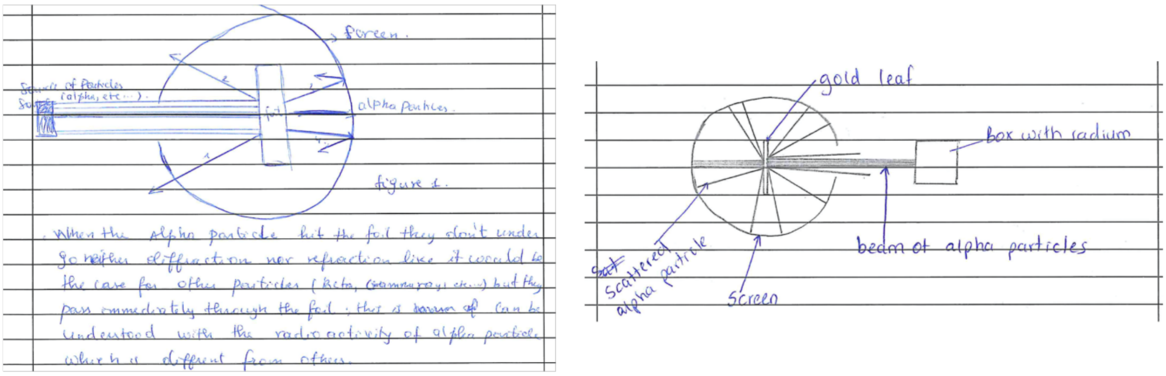

Figure 5: Examples of representation of the experimental apparatus of the Rutherford experiment

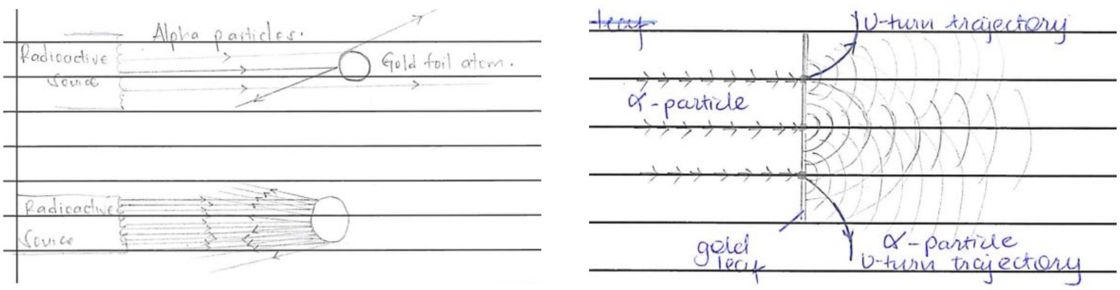

Figure 6: Examples of explanation of backward scattered particles in Rutherford experiment

3.5. Comparison between the Test and Control group outcomes

Panels (a) and (b) of Figure 7 show the distribution of marks at the final exam of the students belonging to Group 1 (Test) and Group 2 (Control), respectively. The maximum grade is 60. Because of the considerable difference in the number of participants to the two groups, the histograms show the percentages of students and not their number.

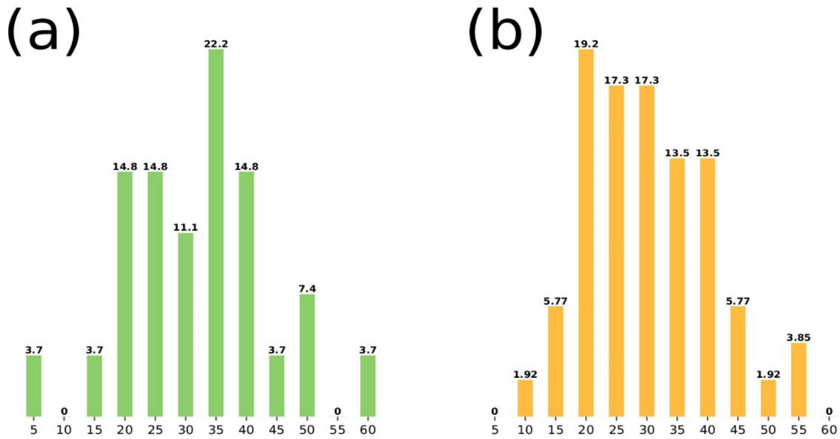

Figure 7: Distribution of final marks for students belonging to: (a) test group; (b) control group, respectively. The y-axis represents the percentage of students.

The average value of the final marks for the 27 students belonging to the Test group is 31, with standard deviation equal to 14. The average final grade for the 52 learners of the Control sample is 28, while the standard deviation is equal to 10. Moreover, the 52% of students of the Group 1 obtained a final mark greater than 30, while only 39% of students belonging to Group 2.

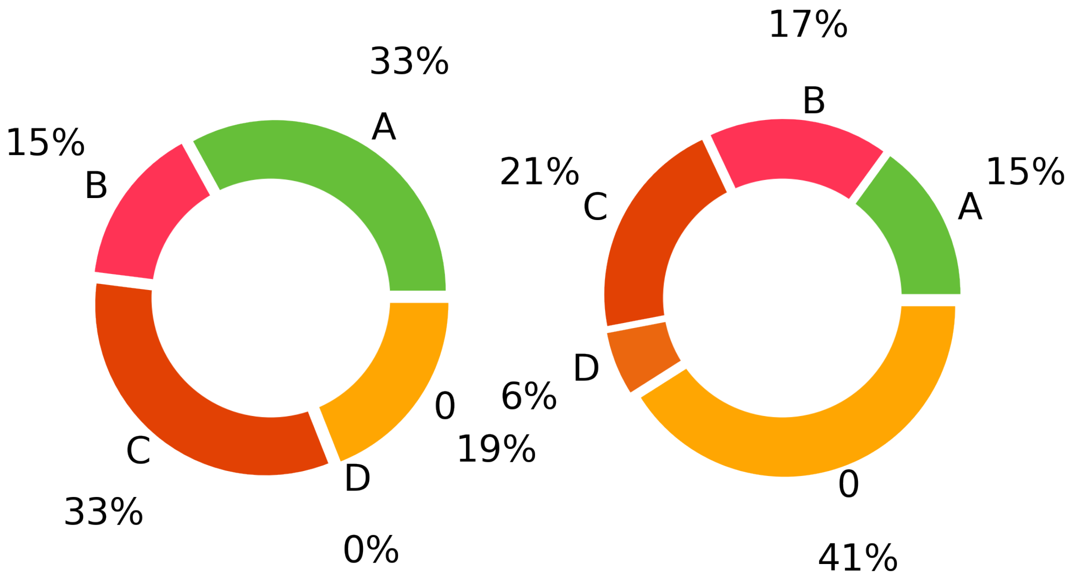

Figure 8: Distribution of marks obtained at the entry test of the Course of Physical Electronics from students belonging to the Test Group (left) and Control Group (right), respectively.

The students of both cohorts (Group 1 and Group 2) from April 2022 were enrolled in the successive lecture on Physical Electronics (Semiconductors). Table 2 show the distribution of marks obtained at the entry test for both Groups.

Table 2. Distribution of marks obtained at the entry test of the Course of Physical Electronics from both cohorts of students.

Mark	Number of students belonging to the Test Group and percentage	Number of students belonging to the Control Group and percentage
A	9 (33%)	7 (15%)
B	4 (15%)	9 (17%)
C	9 (33%)	11 (21%)
D	0 (0%)	3 (6%)
0	5 (19%)	22 (41%)

The 81% of the students which completed the 5E-based learning path (Test group) passed the entry test, while only the 53% of the students of the Control group obtained a positive mark (A, B, C) at the quiz.

4. Conclusion

An effective knowledge of scientific concepts is achieved when the students are able to apply those concepts to solve problems never encountered before. An appropriate training on problem solving has to be based on the development and strengthening of student reasoning skills. Higher levels of thinking abilities can be achieved by “driving” the students to personally experience the world and struggle for finding solutions to real problems, by involving them in highly interesting learning projects and strongly motivating them to actively participate in the scientific endeavor.

The misconceptions about collisions are a serious challenge for any lecturer in modern physics. We have proven here the utility of a 5E-based inquiry approach for first-year students in Nairobi (Kenya). We believe that the proposed educational framework may improve current education and training at the level Bachelor in Engineering. The labs described require few investments, and apart from the cathode bulb of the Franck-Hertz all other parts can be found on local providers.

Acknowledgements

We would like to express our special gratitude to the communication team of Strathmore University, in particular Mrs. Zipporah Wanjohi our photographer and to Mrs. Daphne Wanjiku our Data Protection Officer that together with BD made possible to match the important requirements in right to the protection of the image of our students

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