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# An inquiry-based approach to the Franck-Hertz experiment

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**Summary.** — The practice of scientists and engineers is today exerted within interdisciplinary contexts, placed at the intersections of different research fields, including nanoscale science. The development of the required competences is based on an effective science and engineering instruction, which should be able to drive the students towards a deeper understanding of quantum mechanics fundamental concepts and, at the same time, strengthen their reasoning skills and transversal abilities. In this study we report the results of an inquiry-driven learning path experienced by a sample of 12 electronic engineering undergraduates engaged to perform the Franck-Hertz experiment. Before being involved in this experimental activity, the students received a traditional lecture-based instruction on the fundamental concepts of quantum mechanics, but their answers to an open-ended questionnaire, administered at the beginning of the inquiry activity, demonstrated that the acquired knowledge was characterized by a strictly theoretical vision of quantum science, basically in terms of an artificial mathematical framework having very poor connections with the real world. The Franck Hertz experiment was introduced to the 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. The whole activity has been videotaped and this allowed us to deeply analyse the student perception's change about the main concepts of quantum mechanics. We have found that the active participation to this learning experience favored the building of cognitive links among student theoretical perceptions of quantum mechanics and their vision of quantum phenomena, within an everyday context of knowledge. Furthermore, our findings confirm the benefits of integrating traditional lecture-based instruction on quantum mechanics with learning experiences driven by inquiry-based teaching strategies.

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## 1. – Introduction

The fields of nanoscience and nanotechnology are rapidly advancing, together with their significant applications and implications. Several challenges are connected with a full scientific understanding of the world at nanoscale and related concepts; thus, the education of science/engineering undergraduates on these fundamental topics is crucial to the scientific and technological progress [1-3]. The development of the required competences is based on an effective science and engineering instruction, which would be able to drive the students towards a deeper understanding of Quantum Mechanics (QM) fundamental concepts and, at the same time, strengthen their reasoning skills and transversal abilities [4]. On the other hand, a careless simplification of the sophisticated concept of nanoscience could generate misconceptions, lead to superficiality and risk of misrepresenting. At this regard, an instruction based on scientific inquiry represents the natural framework to develop opportunities of learning science concepts in terms of an active construction of meaningful knowledge and to stimulate high levels of critical thinking skills [5].

In inquiry-based learning environments, the students are engaged in identifying scientifically relevant questions, planning investigations, gathering data and evidences in laboratory and/or real life situations, building descriptions and explicative models, sharing their findings and eventually addressing new questions that may arise [6]. Being these activities the same real scientists carry out when perform their investigations, this learning cycle is considered the most effective way for developing scientific knowledge and stimulate the strengthening of reasoning skills. However, depending on the amount of support provided by the teachers, the students may be involved in *structured*, *guided*, or *open inquiry* [7-9]. In structured inquiry both the question and the explorative procedure are provided by the teacher, but students strive to generate their own explanations on the basis of their investigation results. In guided inquiry the teacher provides students only with the research question, and students plan the procedure to test their working hypothesis, design and carry out their own experiments, draw conclusions. In open inquiry the teacher introduces the context by presenting a multidisciplinary view of a theoretical problem or a real-life phenomenon. Subsequently, the students define their relevant questions, design and carry out their own investigations, communicate and share their results. An open inquiry-based instruction seems more efficient to reinforce learners' reasoning skills, also increasing the awareness of the process of scientific inquiry and of the nature of science [10-12].

In this context, the role played by the teacher is fundamental for the achievement of the desired results. In fact, it seems that a more structured/guided instruction should provide the students with competencies more focused on conceptual knowledge, leaving the learners with a not well defined view of how scientific knowledge is produced, while a more open approach would let the students to experience the world with a higher level of autonomy, developing higher-order thinking skills [13]. Despite this, students involved in open inquiry may develop feelings of frustration due to the lack of achieving the desired goals independently from teacher's hints [14].

In this study we address the question of the efficacy of a structured inquiry-based learning approach, with different levels of teacher's guidance, to introduce the students to fundamental aspects of QM in the context of the Franck-Hertz experiment, in order to find the most suitable teaching approach to develop a deeper understanding and comprehension of the QM concepts.

In the following, we briefly introduce the method and research questions addressed in this paper, then describe the details of the Franck-Hertz experiment carried out by a sample of engineering undergraduates and, finally, report and discuss the results. Concluding remarks on the most effective scaffolding structure to be used in order to stimulate and elicit the students' scientific inquiry through their path of exploration are reported at the end of the paper.

## 2. – Method and research questions

This study present the results of an inquiry-driven learning path experienced by a sample of 12 master students in electronic engineering at the Laboratory of Condensed Matter Physics at the Department of Physics and Chemistry, University of Palermo, Italy. Before being involved in this experimental activity, the students received a traditional lecture-based instruction on the fundamental concepts of QM. Despite the efforts of introducing specific technological and engineering-based applications of QM during traditional courses, students' answers to an open-ended questionnaire, administered at the end of the theoretical lectures, demonstrated that the acquired instruction was characterized by a vision of quantum science basically in terms of an artificial mathematical framework, with poor connections with the real world. This could be ascribed to the many difficulties that students demonstrated to hold in order to deal with concepts at scales in which they cannot have a direct experience during their everyday life, especially at microscopic and sub-microscopic scales. Moreover, students still prefer to conceptualize matter as being continuous rather than discrete.

In order to fulfill these lacks, driven by the idea that inquiry-based laboratory experiments exploring quantum phenomena may provide the students with motivation for an effective comprehension of QM concepts, the students were invited to join an experimental activity concerning the Franck-Hertz experience. First, the Franck-Hertz experiment was introduced to the 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. After that, the students were driven by two instructors through a reasoned sequence of experimental steps, carried out within an inquiry-based learning environment, towards the visualization and discussion of the experimental results.

The students were first engaged in a traditional *structured inquiry* [9], then involved in a learning path with a specific process of activation — *Elicited Inquiry* —, consisting of a structured inquiry in which two or more instructors actively participated to the debate on the physics governing the observed phenomena, never providing exhaustive explanations to the students, but giving comments and hints, sometimes expressly incorrect, always leaving the students in a state of uncertainty, stimulating their reasoning and activating their scientific inquiry.

At the end of their inquiry-based learning path the students were asked to answer to a structured interview with questions similar to those proposed by means of the initial questionnaire. Moreover, the whole activity was videotaped for a deeply analysis of the student perception's change about the main concepts of QM.

The results reported in this paper are based on the analysis of videotaped data, analyzed on the basis of an in-context search for keywords or phrases and specific aspects of the student's behaviour (speech and gesture events) that could give evidence of their cognitive processes.

The analysis of all these data allowed us to answer the following two main research questions:

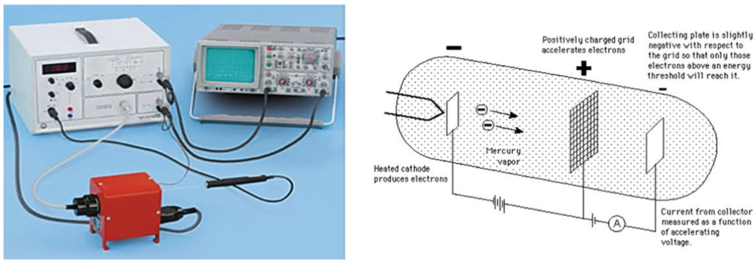


Fig. 1. – Experimental set-up for the Franck-Hertz experiment (left) and schematic representation of the mercury-filled Franck-Hertz tube (right).

- Can an inquiry-based method of instruction be successfully applied to achieve an effective understanding of QM concepts?
- Which is the most suitable inquiry-based teaching/learning strategy for QM?

## 3. – The Franck-Hertz experiment

The famous experiment of Franck and Hertz, carried out in 1914, consisted in bombarding mercury atoms by electrons, and detecting the kinetic energy loss of the scattered electrons. In particular, they showed that electrons could impart energy to a mercury atom only if the electrons had a kinetic energy exceeding 4.9 eV. This was the first direct proof of the quantized nature of energy transfer, postulated by Niels Bohr in 1913, showing directly that quantized energy levels in an atom are real, not just optical artifacts.

The apparatus for this experiment consists of a mercury-filled Franck-Hertz tube, a control unit with power supplies and a DC current amplifier with a shielded cable. The power supply section of the control unit delivers the accelerating voltage (continuously variable from 0 to 30 V), the filament heating voltage for the tube (up to 7 V), and the retarding voltage (up to 5 V). The accelerating potential can be adjusted manually or swept automatically. The apparatus is pictured in the left panel of fig. 1.

Electrons are thermally emitted from the cathode and they are accelerated toward the collector electrode by an attractive potential. A control grid helps to keep the emission current constant as the accelerating potential is varied. Electrons that pass through the control grid are accelerated by the potential added between the cathode and the anode. Electrons passing through the anode with an energy greater than the retarding voltage applied to the collector electrode are collected at the plate and give rise to a plate current that is measured with a sensitive current- to-voltage amplifier connected to a voltmeter (fig. 1, right panel).

The mercury tube should be turned on for approximately 60 min to allow the unit to stabilize at a temperature of about 180 °C. The experiment proceeds by slowly increasing the accelerating voltage from the initial value. The current increases uniformly, reaches a maximum, and then decreases as the accelerating voltage is increased. A reduction in collector current occurs starting at about 4.9 V. This is accompanied by the appearance of a glowing red layer at the anode. As the anode voltage is increased, the collector current decreases and the glow moves toward the cathode. The emission current must be at a low enough level so that gas discharge does not occur. The retarding voltage between anode and collector electrodes should be properly set so that the minima in the current

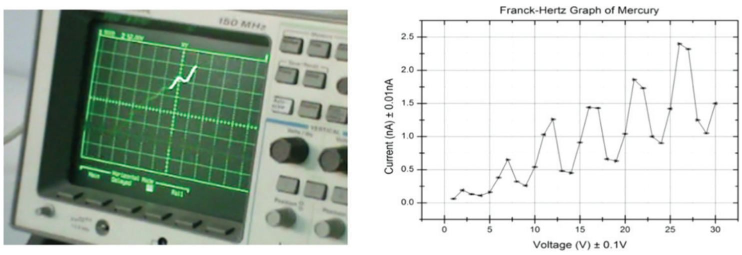


Fig. 2. – Franck-Hertz Experiment: Experimental data gathered by the students manually from the oscilloscope (left) and plotted on a Current-Voltage diagram (right).

voltage curve are clearly recognizable. The data were collected manually by the students reading a digital oscilloscope (fig. 2, left panel) and were plotted on a Current-Voltage diagram (fig. 2, right panel).

## 4. – Results

The students were first invited to perform the Franck-Hertz experiment by following the scaffolding lines of a *structured inquiry*-based learning path of exploration. In particular, the students were introduced into the laboratory, being already prepared by the instructors on the physical problem to address (the same faced by Franck and Hertz on demonstrating the existence of the quantum energy levels), and invited to follow the educators' instructions for what concerns the procedure to carry out, in order to get to the necessary physical conditions (mercury-filled tube temperature and voltages) for the data collection.

By following the lines of a scientific inquiry, the students, working in group, were asked to perform a questioning activity that naturally should have guided them throughout the steps of the Franck-Hertz experiment. However, despite the students' diligence on performing the several steps of this experiment, they encountered many difficulties to generate their own explanations on the basis of their investigation results, and several times they went stuck on a stance. At this stage, the two instructors decided to take part in the discussion with the students, by taking the role of inexpert learners and to actively participate to the debate on the physics governing the observed experimental findings. The instructors never provided the students with exhaustive explanations, but, on the contrary, they expressed personal opinions and comments, sometimes expressly incorrect, always leaving the students in a state of uncertainty. This educators' behavior proficiently elicited students' scientific inquiry — *Elicited Inquiry* —, stimulating reasoned discussions and activating new cognitive resources allowing them to surmount their difficulties and draw convincing evidences of the experimental results.

The whole activity has been videotaped and this allowed us to deeply analyze the students' behavior and perception's change about the main concepts of QM. These data were treated by performing a *discourse analysis* and a *gesture analysis*, which both contributed to highlight the benefits of this integrated inquiry-based strategy of instruction.

## 5. – Discourse analysis

Distributed cognition treats thinking not as an action that takes place wholly inside an individual's head, but rather as a distributed activity among other people and their

TABLE I. – *Percentage of students showing Speech Events (SE) during the performance of the Franck-Hertz experiment.*

| Speech events (SE) | Percentage of students showing SE during the performance of the Franck-Hertz experiment | |
|---|---|---|
| | Traditional Structured Inquiry | Structured Inquiry with activation |
| Critique | 27% | 75% |
| Elicitation of critique | 13% | 54% |
| Awareness of knowledge gained | 34% | 82% |
| Contextualization of research | 17% | 63% |
| Explanation of research | 27% | 67% |
| Negotiation | 12% | 54% |
| Consensus Building | 18% | 68% |

language [15]. By following these basic ideas, we have analyzed the videotaped data gathered during the inquiry-based learning experience carried out by our students, in order to explore their learning process from the widest point of view. To this aim, we have selected seven different kinds of speech events (SE) (adapted from [16]) and recorded the percentage of students showing these SE during the performance of the Franck-Hertz experiment. The data were taken both during the first initial phase of traditional structured inquiry and after the succeeding inquiry with the intervention of instructors' elicitation. In table I we report the observed percentage. The main result of this study is that the students engaged into a tradition structured inquiry show very low percentages of involvement into *Elicitation of critique*, *Contextualization of research*, *Negotiation* and *Consensus Building*, which all remain well below the threshold of 20%. Even other important SEs, such as *Critique* and *Explanation of research* are observed only in less than a third of students. Moreover, only 34% of the students show the *Awareness of knowledge gained* SE. It is important to note how such percentages definitely change when the instructors elicit their scientific inquiry. All the percentages of SEs recorded during the activation phase of the structured inquiry (elicited inquiry) show a significant increase, bringing the *Awareness of knowledge gained* percentage up to 82% of students.

## 6. – Gesture analysis

All the activities of the students engaged into the inquiry-driven Franck-Hertz experiment were videotaped in order to gather information about their attitudes and feelings from their posture and movements. In some cases, this kind of analysis often provides a unique view of students' mental representations of concepts, opening a window on their way of thinking [17]. This may happen, in particular, when the students are not engaged into an active construction of learning, they are "forced" to listen and cannot express immediately all their doubts or questions, such as in a structured inquiry-based case of instruction.

In the following, we show a comparison between the students' gestures observed during the first part of their inquiry-based learning experience, *i.e.* the strictly *structured inquiry*, with those recorded during the *elicited inquiry* phase of exploration. In fig. 3 we

Fig. 3. – A sample picture taken during the traditional structured inquiry.

show a picture taken during the phase of structured inquiry without activation, where many arm-cross events are observed. Usually this kind of posture is a self-comforting posture used mostly unconsciously to alleviate nervous tension and isolate ourselves. In special situations this position might also suggest self-importance or disagreement. Moreover, some students remain focused on the experimental setup, looking at the data appearing on the oscilloscope screen, while others look away, probably lowering the attention towards the experimental results (fig. 3).

The stimulating discussions between students and instructors about the experimental findings coming from the Frank-Hertz experiment produced a specific effect of activation of the inquiry process. In fact, the students showed many more postures associated to

Fig. 4. – Pictures taken during the phase of Elicited Inquiry.

reasoning efforts (fig. 4), demonstrating a clear increase into their involvement and an active participation into the process of knowledge construction. Moreover, during this phase the students also showed many gestures explicative of QM concepts (fig. 4).

In summary, we have found that an *activated* participation to this structured inquiry-based learning experience favored the building of cognitive links among student theoretical perceptions of QM and their vision of quantum phenomena, within an everyday context of knowledge.

## 7. – Conclusions

Student interest in QM can be increased through laboratory experiments that illustrate the inadequacy of classical physics for understanding microscopic phenomena. Quantization is the fundamental concept necessary for understanding the development of QM and the Franck and Hertz experiment reveals that quantized electronic energy levels really exist. This experiment gives the students the opportunity to appreciate the concept of quantization and the field of electron spectroscopy. In addition, it allows the students to follow the historical lines of a milestone experiment in the development of the quantum theory. However, an effective understanding of QM concepts can be achieved only within a process of active learning typical of inquiry.

An inquiry driven experience of an experiment confirming the existence of the atomic quantized states could make the study of QM concepts more meaningful. Unfortunately, the process of scientific inquiry is spontaneously activated mainly for people experiencing everyday phenomena. In students going to understand phenomena not directly related to their everyday experience, such as when approaching the study of QM, *the inquiry process must be explicitly activated*.

In this study, an *elicited inquiry*-based learning path has been experienced by a sample of engineering undergraduates who already attended university-level courses on quantum physics concepts. Despite their previous instruction, students initially persisted to hold a vision of quantum science basically in terms of a mathematical framework and did not actively engage into a traditional structured inquiry. Our results show that scientific inquiry could not always be spontaneously performed by students involved in QM studies. Nevertheless, we have found that a stimulated activation of the inquiry process may constitute an efficient teaching/learning approach both to effectively engage students into active learning and, at the same time, to clarify important experimental and technological aspects of QM. Video analysis clearly demonstrated a great participation and motivation to learn, both in terms of useful discussions and scientifically relevant questions. The reasoning effort asked to the students to perform this learning experience successfully reinforced their understanding of the QM fundamental concepts. This experience definitely favored the building of cognitive links among student theoretical perceptions of QM and their vision of quantum phenomena, within an everyday context of knowledge. We believe that an explicitly activated structured-inquiry approach could support effectively the teaching of QM to students who already have a solid background of conceptual knowledge. Under these terms, the integration of curricular instruction with teaching/learning strategies based on explicitly activated inquiry approaches seems a viable solution to improve the overall understanding of quantum physics.

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