An Instructional Model for a Radical Conceptual Change Towards Quantum Mechanics Concepts

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ABSTRACT: We believe that physics education has to meet today's requirement for *a qualitative approach* to Quantum Mechanics (QM) worldview. An effective answer to the corresponding instructional problem might allow the basic ideas of QM to be accessed at an early stage of physics education. This paper presents part of a project that aims at introducing a sufficient, simple, and relevant teaching approach towards QM into in-/preservice teacher education, i.e., at providing teachers with the indispensable *scientific knowledge* and *epistemological base* needed for a reform of science education along the aforementioned line. The investigation of teacher–learners' (t-ls') initial knowledge indicated that their main misconceptions appear to be the result of their pre-/inuniversity traditional instruction, which causes *the overlapping/mix-up* of the conceptual frameworks of Classical Physics (CP) and QM. Assuming that these misconceptions form by nature *epistemological obstacles* to the acquisition of QM knowledge, the educational strategy proposed here aims at leading t-ls to form a conceptual structure that includes CP and QM as two *totally independent conceptual systems.* Accepting, furthermore, that the complete distinction of these systems demands *a radical reconstruction* of t-ls' initial knowledge, we present here an instructional model that bases the required reconstruction on *the juxtaposition* of two models that constitute the signal point of twentieth century's "paradigm shift": (a) Bohr's semiclassical atom model, and (b) the model of the atom accepted by modern physics theory. © 2003 Wiley Periodicals, Inc. *Sci Ed* **87:**257–280, 2003; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/sce.10033

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INTRODUCTION

The twentieth century is characterized by the prevalence of a radically new scientific viewpoint for the physical phenomena, a new paradigm in physics, according to Kuhn's epistemological perception. In particular, the viewpoint implied by Quantum Mechanics (QM), not only supports the understanding of modern technological applications, but also forms the cognitive basis for the adequate interpretation of, both, the structure of the matter and the evolution of microscopic phenomena. This forces school curricula to introduce QM topics, such as the atom models, at a very early stage of the instructional process. However, attempting to overcome the sophisticated mathematical background of QM, the traditional teaching methods and textbooks introduce the relevant scientific content in ways that provoke misconceptions, which seem to stabilize even after a specialized educational training (Bayer, 1986; Bethge, 1988). In our opinion, an effective answer to the corresponding problem may be *a qualitative approach* to QM worldview founded on a stable *epistemological* and *cognitive* base. We present here *an instructional model* along the above lines.

CONTEXT DATA

Recently, there have been quite a few interesting teaching proposals attempting to overcome the mathematical background of QM. Some of these relate QM teaching to the use of simple devices or computer interactive programs. These approaches are mainly based on problem solving activities requiring students to explore situations "by putting their hands on" simple experiments (Allasia et al., 1998; Lawrence, 1996; Zollman, 1998). The proposals under consideration offer valuable material for the improvement of science process skills but seem to be based on the assumption that students "find out" the subject under study if they engage in firsthand investigations and observe or measure the results of their laboratory experience. Thus, "the idea of what a model is and what is acceptable based only on what information one has is an important part" (Zollman, 1998, p. 99) of what they are doing.

Other proposals base their instructional strategy on "what is common," emphasizing "the common aspects between modern and classical physics" (Cuppari et al., 1997, p. 302) or on theories-landmarks in the history of quantum physics, such as the correspondence principle, aiming at demonstrating the relation between quantum and classical physics (Hua-Xiang Liu, 1995). An important contribution to the whole task comes from studies that, intending to reveal *the contrasting views* of Classical Physics (CP) and QM, focus, by nature, on philosophical aspects (Hobson, 1996; Pospiech, 1999).

Although all these approaches shape the wider context of our instructional proposal, the elements that mainly affected its formation stem from pedagogical issues raised in *conceptual change* studies. The first impulse for following the relevant research line came from the investigation of teacher–learners' (t-ls') initial knowledge, which indicated that their main misconceptions appear to be the result of their pre-/inuniversity traditional instruction. Such instruction seems to generally cause—as the existing bibliography ascertains—*the overlapping* or, moreover, *the mix-up* of the conceptual frameworks of CP and QM. Indeed, (a) traditional instruction offers multiple *particle* and *atom models* that "mostly are used in unsystemic ways leaving students believing at different times that different models are 'right' rather than contextually appropriate" (Millar, 1999, p. 392); (b) traditional instruction also focuses on atom physics, with *a semiclassical* understanding. Thus, students' knowledge is characterized by a rather *classical perception of quantum physics* (Mashaldi, 1996) that "shows elements of both mechanistic and quantum ideas" (Ireson, 1999, p. 78). Such elements transfer, for example, "macroscopic attributes to the submicroscopic objects" (Seifert & Fischler, 1999, p. 393). In this situation, Bohr's *semiclassical* planetary model of the atom plays a crucial role: *Dominating* students' mental structures appears to be "the contrasting point of reference for each new idea" (Petri & Niedderer, 1998, p. 1079), forming, in this way, a species of students' "stable knowledge" (Fischler & Peuchert, 1999, p. 397); finally, (c) traditional instruction "introduces modern physics without reference to the difficulties of CP, . . . students are not capable of mentioning a single difference between modern and CP . . . [and] this gives rise to serious misconceptions" (Gil & Solbes, 1993, pp. 255–256).

The aforementioned findings indicate that QM ideas acquired during secondary school instruction are embedded in a conceptual structure *incompatible* with the corresponding scientific one. In order to respond to these problems, studies that focus on students' initial knowledge, following rather parallel lines, attempt to bring about knowledge reconstruction by systematically distinguishing macroscopic and microscopic phenomena. Our approach, setting students' misconceptions as the starting point of the whole task, shares common elements with them. Thus, we selected, for reasons that will be later analyzed, (a) the hydrogen atom to function as a key topic of our teaching proposal (in a similar way to Petri & Niedderer, 1998); (b) the electrons (not the photons) to represent the microworld (in a similar way to Fischler & Lichtfeldt, 1992); and (c) the Heisenberg uncertainty relation to be the introducing principle and the axis of our teaching proposal (in a similar way to Fischler & Lichtfeldt, 1992).

In our opinion, the key differentiation of our approach stems from the fact that it considers learners' misconceptions—attributed to the overlapping and mix-up of QM and CP concepts—as being *epistemological obstacles* to the acquisition of QM knowledge. Consequently, promoting an epistemological solution of the problem, our proposal bases its educational strategy on the *direct juxtaposition* of representative models of QM and CP conceptual systems. Thus, following an alternative to Fischler and Lichtfeldt (1992) line, our approach, (a) instead of avoiding the reference to CP, attempts to reveal the totally different worldview and thinking patterns underlying the interpretation of macroscopic and microscopic phenomena, (b) instead of avoiding the Bohr model of the atom, uses it—as a representative semiclassical model "against" the atom model accepted by modern science—in order to make concrete the deep conceptual differences between CP and QM, (c) instead of avoiding the dualistic descriptions, aims at revealing the inner meaning of the complementarity principle. Additionally, following an alternative to Petri and Niedderer (1998) line, our approach, instead of accepting a gradual change toward QM concepts, attempts to bring about a direct *radical reconstruction* of learners' conceptual structures.

Our final aim is to suggest an integrated instructional view of QM teaching that associates a well-defined epistemological orientation with certain general leading assumptions regarding the learning process.

THE LEADING ASSUMPTIONS REGARDING THE LEARNING PROCESS

Our perception on learning science is based on the following assumptions supported by cognitive science and conceptual change studies:

(1) Learning is *a search for meaning*, that is, "learning is fundamentally coming to comprehend and accept ideas because they are seen as intelligible and rational" (Posner et al., 1982, p. 212). Therefore, the instructional process should start with learners' already formed cognitive structures in order to achieve "meaning construction."

(2) Learners' initial cognitive structures might be compared to inaccurate but more or less consistent "scientific theories" (Brewer, 1991), including assumptions and images that provide *the explanatory context* for thinking about the world.

(3) Based on sensory perceptions and widely spread social beliefs, the initial assumptions and presuppositions of learners are strongly held (Bransford, 1979; Vosniadou, 1995).
(4) Meaning requires understanding *wholes* as well as *parts*: parts might be understood *in the context* of wholes, that is, in the context of *knowledge structures* (Vosniadou, 1996) in which they are embedded.
(5) The instructional process should lead learners to "build" their new "scientific-cognitive structures" by means of a *radical* or *weak* reconstruction (Vosniadou, 1987). The kind of reconstruction demanded is defined by the characteristics of their initial knowledge.

There seems to be broad agreement that the above-mentioned cognitive assumptions, which come mostly from the constructivistic point of view, have influenced the research, instruction, and assessment practices of science education. However, we adopt the recent criticism (Matthews, 1998) that some of the general thesis of a constructivistic epistemology is in conflict with the scientific perception and with the methods by which scientists attempt to interpret the natural phenomena. Thus, the basic constructivistic idea that truth is that which conforms to our experiences or is viable (von Glaserfeld, 1995) often leads to the belief that laboratory and hands-on activities are synonymous with scientific inquiry. This stance often results to the neglect of science content.

Our intention is not to defend a realistic perspective of the nature of scientific enterprise. We only wish to emphasize that a major goal of science instruction should be *the replacement* of learners' initial cognitive structures with currently accepted structures of scientific content. We take the view that it would not be possible for students to learn fundamental ideas in science such as, for example, QM ideas through investigation alone; students reconstruct their initial knowledge under the guidance of the teacher who aims at communicating the scientific content, that is, a structure that *embodies* and *reflects* the basic aspects of scientific thinking and practice.

Consequently, we argue that an adequate design of the educational process should accurately determine the basic characteristics of the structure of the scientific content, which is intended to replace the learners' initial cognitive structures. These characteristics may shape an explanatory context with the potential to offer *an equally persuading* image of the world as the one provided by learners' preinstructional ideas.

EPISTEMOLOGICAL FOUNDATION OF THE CONCEPTUAL CHANGE PROCESS

In order to include the aforementioned requirements in the design of the project, we carried out wide epistemological research on the various ways in which scientists study natural phenomena and propose explanations. Thus, we came to accept that the educational process, following real science, has to communicate the contemporary "*scientific paradigm*" (in Kuhn's sense, (1970)) that includes *the scientific content*, i.e., the body of knowledge accepted by the scientific community, and *the scientific inquiry*, i.e., the research questions, methods and activities that lead to the acquisition and development of scientific knowledge. The scientific content of the contemporary paradigm, reflecting the *unified perception* of modern physics, consists of *both* classical and modern physics and it constitutes the accepted knowledge of today's "normal science." However, modern physics came to be accepted after a "crisis" period during which scientists had been obliged to question the conceptual system of CP and to adopt a totally new worldview. In other words, modern physics was accepted after a "scientific revolution" that led to a "paradigm shift."

Considering that the instructional process might mirror that situation, we were led to the formation of an epistemological-instructional structure of the scientific content called "Levels of Reality" (Hadzidaki, Stavrou, & Kalkanis, 2000). This structure, (a) suggesting a *context approach* to physics' teaching/learning, classifies physical phenomena into distinct levels, for example, the "Newtonian Physics Level" (NPL) and the "Quantum Physics Level" (QPL) that represent two *totally independent conceptual systems*; (b) intending, at the same time, to make visible the accepted by contemporary physics *unified image* of the natural world (this issue is essentially promoted by Wanderlingh in a proposal addressed to a higher instructional level, 1996), suggests "appropriate" links between the different levels. Thus, the "Levels of Reality" structure presents the following basic characteristics:

(1) Each level forms a distinct *conceptual network*, (Brown, 1977, pp. 196–197) *that is*, a system of concepts (*nodes*) and of relations among them (*constraints*), corresponding to a particular *scientific theory*. Each concept acquires its meaning only in terms of the relations that the system itself *as a whole* institutes between it and the other concepts. For example, in NPL, which corresponds to Newtonian physics paradigm, the concept of "force" acquires its meaning through its intrasystemic relations to the concepts of "material point," "mass," "momentum" and so on.

(2) As each level forms a totally independent conceptual network that imposes on the concepts a precisely determined meaning, classical analogies cannot be used for the interpretation of microscopic phenomena.

(3) The theory of each level adapts natural objects into a particular *ontological status* lending them special properties and behavior. Later in this paper we proceed to a detailed description of the *ontological properties* of "Newtonian objects" and "quantum objects" belonging to NPL and QPL respectively.

(4) The level of reality that corresponds to modern physics theory defines *the limits of validity* of the others levels. In such a way students have the opportunity to estimate the *internal consistency* of contemporary physics' scientific content. For example, modern science *knows*, from the vantage point of its present knowledge, that the Newtonian objects constitute a misrepresentation of the world but, at the same time, it determines precisely the series of natural phenomena and the boundary conditions for which Newtonian physics offers a rather correct—and simpler—description.

(5) As the conceptual systems of the different levels are essentially incompatible, their association becomes possible through the understanding of the "crisis process" that led to the abandonment of the older conceptual system and the acceptance of the modern one. For this purpose, the "Levels of Reality" structure uses as *rationality elements* the basic aspects of the nature and the historical evolution of science. In this way, it additionally promotes the understanding of the values and assumptions of scientific knowledge and of the processes, which led to the creation and development of that knowledge; it promotes then what is recently called the "Nature of Science" (NOS).

An integrating attempt of the aforementioned cognitive and epistemological premises led us to accept an educational strategy that treats conceptual development as a *complex process*, which "includes issues that may be described in terms of conceptual growth and issues that may better be interpreted within a framework of radical change perspectives" (Duit et al., 1998, p. 1060). More specifically,

(a) in case that the learners' knowledge indicates a conceptual mix-up of two paradigms, the instructional process should provoke *a cognitive conflict* corresponding to the

Kuhnian period of *crisis* in science. The whole process has to lead to a complete distinction of the conceptual systems of CP and QM, and a parallel explicit clarification of the contextual meaning of the concepts. The expected result is the construction of a self-consistent new "theory" which is relevant to the scientific theory that arises after a "scientific revolution," and which possesses the characteristics of the described structure of "Levels of Reality." In this case, the cognitive change that takes place corresponds to *a radical reconstruction* of learners' knowledge.

(b) as long as learners acquire a new way of "seeing" phenomena, they will probably be able to add new information in a way consistent with their new conceptual structure. That procedure, including activities relevant to the scientific ones during a period of "normal" science, corresponds to learners' *weak* conceptual reconstruction.

OBJECTIVES OF THE INSTRUCTIONAL PROCESS

It has been suggested and supported empirically that modern science courses failed to achieve some of their declared goals because of "inadequacies in the philosophical stance underpinning course design" (Hodson, 1988, p. 35) or because "prospective teachers have limited knowledge of, and experience with, the processes by which scientific knowledge is generated" (Gallagher, 1991, p. 127) or because there is lack of teachers' understanding of NOS (Hodson, 1988; Lederman, 1992). Thus, "teachers' answers [to questionnaires and interviews] show the concurrent existence of beliefs and metaphors pertaining to different epistemologies" (Sperandeo-Mineo, 1999, p. 250). Under the light of these conclusions, our proposal aims at leading teachers to acquire new knowledge, new teaching methods, and a deep insight to NOS.

AN INSTRUCTIONAL MODEL AIMING AT *A RADICAL* CONCEPTUAL RECONSTRUCTION

The central point of the proposed instructional model is the foundation of learners' radical reconstruction on *the juxtaposition* of representative models of the two *competitive paradigms*. Although the design of the instructional process concerns training courses of pre-/in-service teachers', it also concerns all learners whose initial knowledge is characterized by the overlapping and mix-up of incompatible conceptual systems. The model consists of five interactive components.

1st Component: The first component intends to explore learners' preinstructional knowledge. A key topic, selected under the light of data collected during preliminary investigations or offered by the existing bibliography, is used in order to (a) reveal the microstructure and the sources of learners' misconceptions, and (b) to subsequently provide representative models capable to cause the required cognitive conflict.

2nd Component: The second component includes a hermeneutic-analytical process that intends to evaluate the educational significance of the concepts/phenomena included in a concrete scientific area in relation to the already established learners' misconceptions. This process aims at accurately determining the subject matter of the particular course.

3rd Component: The third component intends to identify the special learning needs of the particular learners in order to find or create instructional tools capable to effectively promote their conceptual change.

4th Component: The fourth component concerns the design of such instruction that will put learners in a situation of (re)-constructing knowledge and, at the same time, of getting acquainted with NOS.

5th Component: The fifth component emphasizes views at meta-levels as views about NOS and meta-cognitive views about learning.

EMPIRICAL IMPLEMENTATION

The Sample—The Research Sequence

The instructional module outlined below was developed for prospective/in-service teachers' courses. Two groups of students were selected for study. Each group included three classes of students:

- The first group (*test group*, 98 students in all) consisted of 28 students attending QM courses in the pedagogical department (first class) in their second year of their undergraduate work (approximately, 20% of the whole population of the second year's students), 26 students in the department of history and philosophy of science (second class), also in their second year of their undergraduate work (approximately, 20% of the population of the second year's students), and 44 elementary school teachers (third class) following further training courses (approximately, 50% of the relevant population). Most of the first and second groups' members will probably become elementary and secondary schoolteachers in history and philosophy of science, respectively.
- The second group (*control group*, 102 students in all) consisted of 30 students of the first class (approximately, 20% of the whole population of the second year's students), 32 students of the second class (approximately, 25% of the whole population of the second year's students), and 40 students of the third class (approximately, 45% of the relevant population).

All three classes in each group had acquired their knowledge in physics only through secondary school instruction. In Greece, traditional courses in secondary education include issues related to atom physics (the structure of the matter: Atoms, molecules, orbitals, chemical bonds, and so on) encountered in chemistry courses, as well as issues related to what is called "modern" physics (X-rays, photoelectric effect, introduction of the wave-particle duality through a brief description of the double-split experiment) encountered in physics courses. Hence, the groups under consideration included students whose initial knowledge consisted of a rather limited perception of QM. For our research purposes, the responses of the two groups of students, in all stages of the process, were simply combined and analyzed as though they were one group of 98 (first group) and 102 (second group) independent students. This, although expected in virtue of students' common knowledge background, was also justified *a posteriori* on the grounds that there was no obvious difference between the three classes. The research followed the steps below:

A series of semistructured or open preliminary interviews were conducted with randomly selected students of the *test group*. The interviews were audio taped and their content was initially roughly analyzed in order to provide a preliminary insight into students' initial ideas, but, mainly, in order to indicate the key-topic that would demonstrate the required potential for the instructional process. These interviews were also reevaluated through a second analysis conducted under the light of subsequent data, and their content was taken into account in the final evaluation of the project.

After the selection of the atom model as the key-topic of the instructional process, we gave a questionnaire to all students in *the control group*, under the assumption that the members of both groups possessed similar initial conceptual patterns. This questionnaire was designed on the basis of indications from the preliminary interviews and from the already described conclusions of relevant studies. As it will be subsequently shown, the form of the included questions was defined by the specific aims of the instructional intervention.

The analysis of students' responses, the detection of the possible sources of the established misconceptions, as well as the association of the empirical data collected from the interviews/questionnaires with the theoretical framework of the whole study, led us to define the necessary instructional tools, as well as to explicitly design the teaching unit. The design foresaw 12 lessons of 45 min each. Video recordings were taken of all 12 lessons in four classes (the third class of students in the test group was divided into two equal sections of 22 students each), in order to obtain additional verifications for the conceptions established during the preliminary interviews, and in order to closely observe students' learning trajectories.

Two weeks after the end of the teaching unit, the same questionnaire (the one previously answered by the control group) was given to all four classes taught through the proposed instructional model. This was done in order to obtain—through the comparison of the results of the two questionnaires—a rather reliable insight into the differentiation, if any, between the patterns of students' initial knowledge (control group) and the patterns of students' knowledge after the reconstruction process (test group).

One week after the end of the teaching unit, four personal semistructured interviews were conducted with one randomly selected student, who had attended one of the *test group* classes. The interviews were audio taped and their content analyzed in the light of experience gained during the classes, in order to gain a deeper insight into students' conceptual differentiation.

Written statements were gathered from a total of 102 students in the control group and 98 students in the test group. The verbal answers given by the students during the teaching unit and the pre-/postinstructional interviews were transcribed from the videotapes/audiotapes. The conclusions of the whole task were based on (a) the qualitative analysis of the transcribed material with the use of relevant research methods (e.g., Erickson, 1986). The authors met for daily discussions and interpretation of issues that arose from the transcription of the videotaped lessons. These meetings led to initial assertions about students' learning difficulties, which were tested in the entire database and subsequently addressed during the teaching unit; (b) the comparison of students' conceptions (by means of their written statements) in the two groups (test and control group), which, apart from revealing students' conceptual development, offered some quantitative elements indicating the differentiation between their initial cognitive structures (control group) and their cognitive structures after the reconstruction process (test group). We proceed now to an analytical description of our model's empirical implementation.

1st Component

Preliminary Investigation of Students' Initial Knowledge

Selection of a Key-Topic: The Atom Model. In accordance to our research plan, we carried out nine interviews: (a) Four 60-min semistructured interviews in small groups of seven randomly selected students from each class (a sample of about 30% of all students attending the courses) for about 60 min; (b) four 45-min semistructured interviews with one randomly selected student from each class; (c) one 60-min rather open interview/discussion with all students of each class (four interviews in all).

Each interview was conducted by asking the students to answer questions or discuss experts' texts and pictures associated with QM scientific content and related epistemological issues. Special attention was paid to conceptions/reasoning pathways/items, which, while used by the interviewees to explain phenomena, revealed misconceptions related to a large extent to the intermixture/overlapping of QM and CP conceptual systems. A representative sample of the questions posed and discussed is the following:

(1) We accept that electrons, protons, neutrons and such, are particles. What would you say are the simplest "particle-like" properties that one of these objects could show?
(2) Would you say that the aforementioned particles could also exhibit "wave-like" properties? If yes, which of the defining properties of a wave could an electron exhibit while it moves in the atom?
(3) As we know atoms consist of a central nucleus (composed of protons and neutrons) and electrons. Please comment: "If we decompose the atom into its constituents, we can attain complete knowledge of the atom properties through the determination of the properties of its constituents (protons, neutrons, electrons)." Mention some of the atom properties that could be determined (if possible) by using the properties of its constituents.
(4) Give a rather rough description of two elementary particles collision.
(5) Science textbooks often offer multiple representations of the atom. Which one "remained in your mind"? Which one would you say is the "correct" representation? What could the word "correct" mean in this case?
(6) Would you say that the aforementioned representations could be labeled atom "models"? Is there any difference between a scientific theory and a scientific model?
(7) After scientists have developed a scientific theory that successfully interprets phenomena, does the theory ever change? Support your answer with examples.
(8) Please comment on the following: "To give the history of a concept is at the same time to make a logical analysis of it." (Duhem, 1954, p. 269)

The preliminary results of the interviews are analytically described in Hadzidaki, Stavrou, and Kalkanis (1998). Here, we simply present the conclusions that led us to select *the hydrogen atom* as *the key-topic* of the instructional process.

The ruling idea of students' answers seemed to be that the microscopic world has the same characteristics as the macroscopic everyday world. Thus (a) they constantly applied *the analytical method* for describing the physical world: The particles, which are the result of a division process, are considered to have the same properties as the macroscopic object itself. For example (Question 1), elementary particles appear in students' answers as "tiny" objects possessing inalterable identity/"intrinsic" properties, which remain unchangeable even when they move or interact with other particles. Elementary particles are also considered to possess certain physical quantities (position, momentum and so on) that can be precisely determined at any moment. On the other hand, students often assumed (Question 3) that the properties of the whole system are explicitly determined by the properties of its constituents. For example, "the velocity of an atom can be calculated by means of the velocities of its electrons" (student's answer). (b) They generally used CP deterministic reasoning in interpreting phenomena: they assumed an unambiguous and inflexible link between present–future and past–present. For example (Question 4), they adapted strict predictability (precise values of momentum, energy, well defined trajectories and so on) to the subatomic process of two particles' collision.

An element characteristic of students' stance is that they appeared to believe that the scientific content they have learned during their previous physics and chemistry instruction was "scientifically correct." In this way, epistemological aspects of the scientific knowledge, such as its tentative character (Question 7), seemed concealed or, at least, overlooked. For example, it seems that secondary school instruction fails to offer students an appropriate understanding of models' and theories' characteristics (Question 6). Furthermore, students were inclined to regard models as "copies" of reality (Question 5). Students' answers made also apparent the fact that they have learned physics/chemistry scientific content as a rather static, sound knowledge beyond time and place. Thus, they generally failed to give persuading arguments for supporting the thesis that the history of science contributes to the understanding of concepts' meaning (Question 8). Furthermore, they proved unable to give a reliable account for theory change (Question 7). Most of them ignored concepts like "crisis" in science, "paradigm change," and so on.

As regards students' initial mental models, Bohr's "planetary model" appeared to be deeply anchored in their cognitive system: It was the atom model mainly remembered from secondary school chemistry classes. Additionally, this model was generally considered as "the correct" one, the atom model that "mirrors reality" (Question 5). Furthermore, they were unable to associate knowledge acquired in physics courses with knowledge acquired in chemistry courses. For example, they could not find a single reason that could relate "wave-like" properties of particles to the behavior of electrons in the atom (Question 2).

The above conclusions led us to select the hydrogen atom as a key-topic of the instructional process because (a) it appeared the focus of serious misconceptions, and as such it has the potential to reveal the fine structure of the students' initial knowledge; (b) it can be used as *the reference point* of teachers' thinking as it is a subject familiar to them; (c) it associates physics subject matter (uncertainty principle, wave-particle duality and so on) with the fundamentals of chemistry (structure of the matter); (d) it lays the foundations of QM on *a "matter-based*" perception; (e) it associates the scientific content with the history and philosophy of science: indeed, the rejection of Bohr's model and the acceptance of the contemporary model of the atom might be considered the turning point in twentieth century paradigm shift in physics. Furthermore, (f) since it is included even in the elementary school curriculum, it is a subject that teachers will be called to teach, and finally, (g) it allows for a qualitative approach to QM basic concepts.

Preinstructional Ideas

The Questionnaire. The questionnaire was designed to offer additional data, this time exclusively concerning t-ls' conceptions related to the hydrogen atom. The rationale behind the content and form of the included questions was two-fold: first, they should be rather simple so as to offer measurable results of t-ls' conceptual progress, and, second, they should elicit answers that would reveal if and how t-ls' conceptions were associated with a general explanatory context/worldview. Finally the questionnaire was formed as follows:

(1) Draw the model of the atom you have in mind. Describe your drawing.
(2) What is the meaning of the concept "orbital"?
(3) What is the meaning of the uncertainty principle? In your opinion is there any connection between the uncertainty principle and the concept of orbital? Support your answer.
(4) If a measurement process detects an electron possessing a certain position in space, indicate three future possible positions of the electron under consideration. Justify your answer.

Analysis of Responses—Results: An Overview. A detailed description of the performed analysis as well as of its conclusions appears in Stavrou, Hadzidaki, and Kalkanis (1999a). Here we present a general description of our findings in order to offer a rather integrated view of our model's implementation.

The 1st Question. The analysis intended, first, to classify t-ls' mental models associated with the hydrogen atom, and, subsequently, to investigate, through the exposed verbal descriptions, if each sketched image corresponded to a "well discriminated" or to a rather "confused" mental image. With regards to models' classification, it was immediately obvious from t-ls' sketches that four categories appeared: (a) Bohr's planetary model: electron moves on specific orbits (circles, ellipses or both) around the nucleus; (b) orbitals' model; (c) electron cloud model; and, finally, (d) the atom model accepted by modern science (a large number of "points" representing the possible positions of the electron). Each of these categories was divided into two sub-categories in accordance to "the clarity" of the preferred model.

T-ls' answers confirmed and, at the same time, exemplified the findings of the preliminary interviews. Indeed, Bohr's planetary model emerged as the t-ls' favorite atom model (94% of the gathered sketches), the solar system model (circles) coming first (72%), with the orbits' model (22%, circles and/or ellipses) coming second. In the rest of the sketches a cloudy image appeared, described as "electron cloud" (6%), interpreted, in certain cases, as "a set of orbits" (2%) or "something that visualizes the orbitals" (1%) or a "probability cloud" (1%). However, the most interesting results stemmed from t-ls' verbal descriptions, which brought into light a series of rather "confused" images probably springing from *coexisting* indiscriminate mental models. Actually, 75% of all answers were classified into the category "unclear," whereas the remaining 25% corresponded to a "clear" perception exclusively concerning Bohr's solar system model. Phrases like "the electron orbits create an electron cloud" or "the electron orbitals are enveloped by a shell" are characteristic examples of t-ls' answers.

The 2nd Question. The analysis intended to investigate, at first, the "correctness" of t-ls' knowledge with regards to the concept "orbital" and, further, any kind of reliable connection, if any, between their preferred model and the concept in question. The responses were classified as "true" of "false" depending on whether they appeared in the "ideal" mathematical or qualitative answer approved by the authors. Thus, in the authors' opinion, an adequate mathematical definition of the concept "orbital" should approximately correspond to a statement arguing, "an orbital is the wavefunction of an electron in an atom," whereas an adequate qualitative answer should approach the meaning of the sentence, "an orbital represents the region of space where an electron—that occupies the orbital under consideration—is likely to be found." Then, the category "true" was subdivided into two categories to match the distinction between the "appropriate" or "nonappropriate" association of the concept "orbital" with the atom-image presented in the first question.

As it was expected in virtue of the t-ls' cognitive background, no answer was found offering a mathematical definition of the concept "orbital." The interesting element that actually appeared was the reestablishment of the fragmentary character of school knowledge: although 30% of the answers were classified under the category "true" (offering an approximately reliable qualitative description), only 1% of them revealed an "appropriate" connection between the concept "orbital" and the atom image presented before. Indeed, most of the t-ls who recognized the orbital as a "probability space" had previously sketched Bohr's atom model that by nature contradicts a "randomness" perception.

The 3rd Question. The analysis had targets similar to those of the second question, which implied a relevant classification. The responses were classified again as "true" of "false" depending on whether they appeared in the "ideal" answer that, this time, corresponded to a more or less formal expression of the statement, "the product of the uncertainties in the simultaneous specifications of two complementary quantities (observables) can never be less than a small quantity of the order of h (Planck's constant)." Here, 18% of t-ls' answers belonged to the category "true," of which only 1% appeared to be coherently connected with the atom image presented before.

The 4th Question. As this question sought to offer a deeper understanding of t-ls' explanatory framework, the answers were initially classified into two categories, "deterministic" and "nondeterministic," in accordance to the relevant pathways followed by t-ls' reasoning. Once again, t-ls' answers confirmed the conclusions of the preliminary interviews. Thus, they indicated a perceived absolute predictability concerning the electron future positions that, being associated with a well-defined path/orbit, were mostly placed on the same circle (77%) or ellipse (14%) around the nucleus. Apparently, such a view reestablished the extremely limited coherency of t-ls' perceptions (only 2% of those who had previously correctly described the principle of uncertainty proceeded to predict random future positions).

In summary, we could say that, on the special basis of the selected key-topic, the results of the questionnaire reconfirmed two essential aspects of t-ls' initial knowledge: first, a remarkable confusion created by the intermixture of nondiscriminated models/theories, and, second, the indisputable domination of deterministic reasoning imposed by Newtonian mechanics on t-ls' conceptions.

Possible Sources of the Ascertained Misconceptions. Attempting to get to the roots of t-ls' misconceptions, we proceeded to compare our findings to the conclusions of relevant studies. Thus, in the existing bibliography, we meet a rather wide agreement with regards to the ambiguous results of analogical reasoning in science teaching (for an overview, see Duit, 1991). Indeed, as the conclusions of empirical studies have made apparent, in certain cases, analogies may deeply mislead students' learning processes. For this reason, the instructional use of analogies has been compared to a "double-edged sword" (Glynn, 1989). If we now limit our scope to QM teaching, we find two types of analogies usually used:

First, traditional teaching uses *classical analogies*, which describe quantum phenomena by means of *mechanical analogues*. For example, most traditional teaching methods, treating electron as a classical object, use Bohr's model that is founded on the analogy "planetary system-atom and planet-electron" for defining QM concepts like stationary states. In accordance with the conclusive results of other studies, we conjecture that this type of analogy reinforces students' deterministic (mechanistic) way of thinking, because (a) it conceals the totally different viewpoints of CP and QM, (Fischler & Lifchtfeldt, 1992), and (b) it preserves the "*mismatch* or *incompatibility* between the categorical representation that students bring to an instructional context and the ontological category to which the science concept truly belongs" (Chi, Slotta, & Leeuw, 1994, p. 34). In the present case, the categorical representation that students bring to the classroom context corresponds to material objects of everyday experience, whereas the ontological category to which QM concepts truly belong corresponds to what might be called "quantum objects" that possess their own specific properties. Thus, traditional teaching methods using mechanical analogues without discriminating the different ontological status of each concept, lead students to treat elementary particles as usual material objects.

Second, traditional teaching also uses *exegetical or pedagogical* analogies/metaphors, which refer to everyday life images. For example, the spatial localization of bound electrons in the atom, which is often described in terms of an "electron cloud" or "sea shell," represents this type of analogy (for an overview, see Harrisson & Treagust, 1996). It has convincingly been shown (Vosniadou, 1994) that, in this case, learners, attempting to reconcile the scientific aspects of the analogy with their initial images coming from everyday experience, tend to construct misleading *synthetic models*, which, in the sequel, are strongly held. We may then argue that process, being extremely strong in QM field where students' sensory experience is totally missing, has actually caused the confused mental images that emerged from t-ls' descriptions.

2nd Component

Associating Theory With the Sources of Misconceptions—Educational Evaluation of Subject-Matter Concepts. As already mentioned, the epistemological and learning framework of our research presented at the beginning of this paper, has been gradually formed during a forth and back process: Substantial feedback from investigating t-ls' ideas has been an essential part of our project. We believe that the nature and the sources of students' misconceptions enlighten the reasons that led us to form the structure of the subject-matter scientific content, which was labeled "Levels of Reality."

Thus, that structure, consisting of totally distinct levels—conceptual frameworks—ensures the clarification of concepts' meaning in relation to the level in which they are included. Furthermore, the theory corresponding to each level offers a *covering law* or a limited number of covering laws that form the explanatory framework of that level and impose adequate *reasoning pathways* for the interpretation of physical phenomena. We selected as covering laws of CPL and QPL the Newtonian laws and Heisenberg uncertainty principle respectively. The selection of the latter is justified by the role it actually plays as it sets the limits of our feasible knowledge of a microscopic system. Still, "uncertainty" is a word the meaning of which is particularly context sensitive: In CP it concerns the error caused by the limitations of the measurement process, and in QM it reflects an *in-built* consequence of the quantum formalism concerning the *limit* to the sharpness with which one could simultaneously measure paired observables.

Each level also contains *secondary laws* that particularize the covering law(s) and associate them with *concrete aspects of reality* by forming the appropriate *theoretical models*. For example, in NPL, Newton's inverse square gravitational law, stemming from Newton's covering laws, forms the theoretical model of the planetary system. In QPL respectively the Heisenberg uncertainty principle leads to the probability density for the electron's possible positions, which shapes the modern image of the hydrogen atom.

Furthermore, the theory of each level adapts natural objects into a particular *ontological status* lending them special properties and behavior. Thus, the proposed structure combines t-ls' radical reconstruction with *an ontological shift* concerning quantum objects. Intending to provoke such a shift, we selected electrons, not photons, to represent quantum objects, because in such a way learners' initial matter-based perception is not altered. But, at the same time, learners become conscious of the fact that matter displays a different behavior depending on the assumptions implied by the theory of each level. Thus, after estimating the educational validity of each assumption, we came to determine the special properties and behavior that characterize the objects belonging to NPL and QPL respectively, as follows:

- *Ontological status of Newtonian objects*. In NPL classical physics' theory implies: (a) A rigidly fixed "state" of an object/system, that is, a set of numbers that measure the physical quantities possessed by the system; (b) *The mutual independence* of the observed system and the observer-measuring instrument; (c) *The invariable identity* of the isolated objects; (d) *The analytical method* of studying systems and phenomena; (e) *A deterministic perception* of natural world: the predictability of the physical phenomena evolution, which stems from the time-reversible Newtonian laws, permits the complete—under the ideal conditions—determination of particles' future behavior (for example well-defined orbits); and (f) *The distinguishability* of physical objects: it is accepted that material objects can be alike but never undistinguishable.

- *Ontological status of quantum objects*: (a) As the Heisenberg uncertainty principle determines *the maximum accuracy* with which two complementary observables, as, for example, position-momentum can simultaneously be observed, the "state" of a quantum object/system cannot be determined in classical physics' sense: being formally described by the superposition principle, the quantum "state" offers information only for the *potential properties* of the relevant object/system; (b) the measurement process *transforms the potential to actual*, realizing one of the possibilities of the system; (c) the impossibility of precisely determining initial conditions (as, for example, position-momentum), introduces the element of *chance* even in the behavior of an *individual microparticle*; thus, the uncertainty relations, establishing and determining the *limits of our feasible knowledge* of nature, mark *a final break of QM from classical determinism*. For example, the partial unpredictability for the future situation of a quantum object eliminates the possibility of determining its orbit; (d) The uncertainty relations lead to *the rejection of the classical individualization* of an object; the impossibility of precisely determining initial conditions makes two microparticles of the same type absolutely *identical*; (e) Planck's quantum of action h, attributing to any atomic process *an essential discontinuity,* introduces *the holistic character* and *the nonseparability* of quantum phenomena (Karakostas, 2001); (f) the nonseparability of quantum phenomena makes *the analytical method invalid for describing quantum systems/processes*; finally, (g) the complementarity principle, revealing the necessity of using *mutually exclusive pictures* for exhausting conceivable knowledge about the object of observation, sets the requirement for *a contextual description* of physical objects/phenomena.

The explicit clarification of the meaning of different level concepts is expected to result from *the juxtaposition* of two representative models of the corresponding "competitive" paradigms. The characteristics of t-ls' initial knowledge led us to select Bohr's semiclassical model and the atom model accepted by modern physics as representative models of CP and QM conceptual systems.

3rd Component

Instructional Tools. Intending to attain *a qualitative approach* to the scientific content in order to overcome t-ls' restricted background in science and mathematics, we decided to support the whole task by drawing on *instructional tools* from two fields: the field of *history and philosophy of science* (Stavrou, Hadzidaki, & Kalkanis, 1999a) and the field of *modern technology* (Hadzidaki, Stavrou, & Kalkanis, 1998; Stavrou, Hadzidaki, & Kalkanis, 1999b).

The History and Philosophy of Science. History of science offers valuable insight into how experimental data led—during the crisis period—to a clash with established principles of CP, and how experimental research, combined with mathematical reasoning and philosophical thought, opened entirely novel perspectives. Thus, we estimated that the appropriate use of those elements might lead to the communication of QM viewpoint and, at the same time, might offer an efficient insight into the nature of science. Indeed, it is the history of science that provided the hydrogen atom as a key topic of the instruction process.

Modern Technology. Modern technology can provide representations of the microscopic phenomena that might replace the missing sensory experience of the "quantum world." Based on Shrödinger equation, we created (Appendix) a simulation/computer visualization of the hydrogen atom's orbitals (Figure 1), aiming to offer an adequate technology-based environment (Kalkanis, 1996).

4th Component

The Instructional Design. As mentioned before, we selected (a) as representative models of *the competitive paradigms*: Bohr's semiclassical model and the atom model accepted by modern physics; (b) as covering laws of CPL and QML the Newtonian laws and Heisenberg uncertainty principle, respectively. The successive steps of the teaching proposal aim at leading learners to construct their own knowledge by following the different reasoning pathways imposed by the covering laws.

The Presentation and Analysis of Bohr's Atom Model. The fixed electron orbits, foreseen by Bohr's model, are presented on the PC screen. Bohr adopted Newton's proof for Kepler's planetary system to which he pasted the hypothesis of angular momentum quantization. Thus, (a) the Newtonian equations of motion can be written; (b) we can define, at the same moment, the position and the momentum of the electron, i.e., we can define the classical "state" of the system; (c) the quantities that determine the state of the system can be measured at the same time, and the error of the measurement exclusively depends on the precision of the instrument; (d) as we can predict the orbit of the electron, its future behaviour is one-way defined. Thus, the deterministic character of classical physics appears.

The Presentation and Analysis of the Hydrogen Atom "1s" Orbitals. The possible positions where the electron might be detected are presented on the PC screen. The electron seems to appear at random positions. The visualization illustrates the following

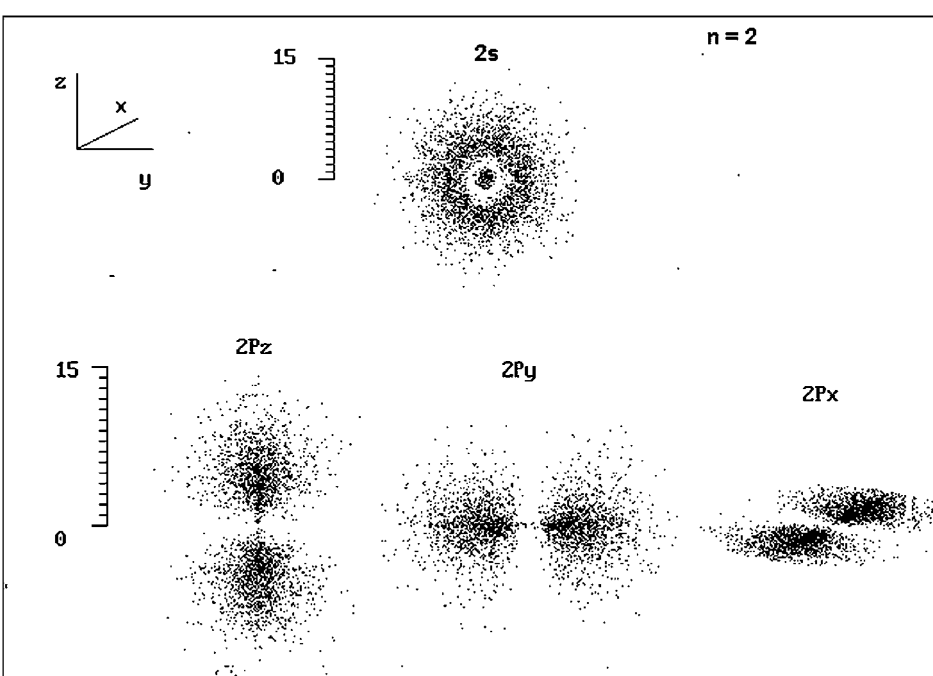

Figure 1. A sample of the hydrogen atom orbitals.

facts: First, there are limits to our feasible knowledge for a microscopic object/system (Heisenberg uncertainty principle: $\Delta x \Delta p \geq h$). Thus, (a) the concept of "state," as it is defined by classical physics, disappears; (b) if we detect the electron at a certain position, we cannot determine the position it occupied before a time interval Δt. Consequently, *reversibility*, *as it is accepted by classical physics*, *does not exist*; (c) as we cannot simultaneously define the position and the momentum of the electron, we cannot predict its future motion, and the concept of the "orbit" disappears. Thus, *predictability*, *as it is accepted by classical physics*, *does not exist*. Second, the impression of a restricted number of the possible electron positions forms an image that *lacks a concrete structure*. Although the image appears to be different every time its formation is repeated—as it consists of different "points"—the final image has always the same general shape. Thus, (a) "orbital" is a picture formed by the possible positions of the electron; (b) these positions follow *a statistical law*. This is the reason why a large number of "points" is necessary to form the final structure; (c) we cannot predict the next position of the electron but we can calculate *the probability* of finding it at a particular position in space; (d) the density of the "points" per unit volume visualizes *the probability density* of finding the electron inside this volume; (e) as the distance from the nucleus increases, the probability density decreases, but it never becomes zero. Thus, the space wherein we can find the electron extends, theoretically, to infinity. Consequently, there are no space boundaries, "outlined spaces," and "coverings."

The Presentation and Analysis of the Hydrogen Atom "2s" and "3s" Orbitals. We used the empty regions of the hydrogen atom "2s," "3s" of the hydrogen atom as a spur to creative thinking. These regions are parts of the probability space where the probability to detect the electron is zero. Thus, the visualization illustrates the following facts: (a) as probability density is, in our case, a time-independent entity, it is plausible to think about a "*probability standing wave*" that determines the "appearance density" of the electron. We arrive then at the conclusion that the quantum mechanical wave is just *a mathematical tool* that, being connected with the concept of probability, is used for explaining the final statistical image; we also come to what *wave-particle duality* really means; (b) furthermore, *the wavefunction* of the electron is the function that describes the evolution of the relevant probability wave and as such it contains all the information about electron's dynamical properties; (c) integrating the aforementioned elements we conclude that the wave-like representation is the appropriate one when the phenomena it has to interpret owe their appearance to a large number of individual events or to the behaviour of a large number of indistinguishable quantum objects. Thus, the potentiality of two complementary descriptions of a physical system appears: the wave-like description corresponds to a holistic point of view and "observes" the collective properties that become nonobservable if we focus on the corpuscular ones. In this way, the *complementary character* of the description of atomic phenomena comes to light; (d) the orbital 1s corresponds to the minimum possible energy value of the hydrogen atom. As atom energy increases, taking only concrete values, the shape of the probability space changes and the images that correspond to the 2s and 3s orbitals appear. Thus, *quantizantion* means acceptability of only certain values of a quantity, called eigenvalues, and, at the same time, acceptability of only certain wavefunctions, called eigenstates, those that correspond to the different orbital images; (e) Before a measurement takes place all possible images (for example, 1s, 2s, 3s) occur as *potentialities*. We consider then that the state of the electron inside the hydrogen atom is determined by a combination of its individual eigenstates (orbitals). This fact is mathematically expressed by the linear combination of the relevant wavefunctions, and thus, we come to the definition of what we call "state" in QM and to a qualitative approach to *the superposition principle*; (f) finally, as t-ls become conscious of the fact that it is *the measurement* that transforms the potentiality to reality, the function of measurement in QM comes to light.

5th Component

Evaluation and Meta-Cognition Processes. As already described, about 2 weeks after instruction, the same questionnaire that had been used to detect the initial ideas of the t-ls in the *control* group, was given to the *test* group. The results of the questionnaire analysis revealed a clear differentiation between the two groups. Thus, with regard to

The 1st Question. Almost all t-ls (99%) who were asked to sketch the image of the hydrogen atom they had in mind, sketched the model accepted by modern physics. Furthermore, the overwhelming majority (90%) of the verbal statements describing the atom image revealed a satisfactory understanding of the concepts related to the intrinsic probabilistic character of QM. Thus, according to t-ls' descriptions, the sketched atom image "represents the probability density of finding the electron at each point around the nucleus," or "is the probability space of the electron" or "shows the points at which future measurements will locate the electron" and so on. Above all, most of t-ls' answers (88%) were classified under the category "clear," as they revealed no signs of confusion nor of different models' overlapping.

The 2nd Question. Almost all t-ls' answers (97%) were classified under the category "correct," and of those answers, most (92%) fell under the subcategory "appropriate," as they revealed a remarkable consistency with the atom image given in the first question.

The 3rd Question. T-ls provided answers, which, apart from demonstrating a remarkable convergence (91%) to the "ideal" answer given by the authors, revealed an "appropriate" connection (97% of the "true" answers) with the reasoning patterns followed, first, in answering the second question and, second, in verbally presenting the atom image of the first question. For example, t-ls stated that "the orbital is nothing other than the image implied by the Heisenberg uncertainty principle that imposes random positions," or that "the orbital represents the probability space predicted by the Heisenberg uncertainty principle," or that "if measurement locates the electron at a specific point, we can tell nothing, at this moment, about its momentum; thus, we can only talk about the probability of finding it at another point of space in the future. All these probable positions form the electron's orbital."

The 4th Question. Almost all t-ls (97%), appropriately applying the Heisenberg uncertainty principle, indicated random future positions, the central point of their justification being that "the way an electron moves from one position to the other cannot be sketched or described, as it is not possible for its position and momentum to be simultaneously identified."

We may claim that the results of the questionnaire analysis offered clear evidence establishing a significant change in t-ls' worldview. However, the final conclusions of our model's first implementation were also based on data collected by closely following t-ls' learning pathways during the development of the whole process. In this way, we had the opportunity to simultaneously focus on data illuminating an issue of particular importance in the present study, that is, to investigate to what extent the association of learners' conceptual reconstruction with the epistemological aspects of the scientific content promotes conceptual change. The whole data base, as already described, was finally formed by elements collected from the pre-/postinstructional interviews, from the discussions conducted with t-ls during the instructional process, and, above all, from the consciously promoted *meta-cognition analysis*.

What we set out to achieve by means of meta-cognitive analysis, was to increase t-ls' "own active and conscious control processing strategies during cognitive processing" (Vosniadou, 1996, p. 98). Actually, during the instructional process, there was strong evidence indicating that t-ls' conceptual reconstruction was essentially promoted when it was synchronized with a gradual increase in their awareness of their own learning difficulties, as well as of their personal attitudes regarding scientific knowledge. A crucial step toward that direction proved to be the association—obtained through the "Levels of Reality" structure—of their own cognitive processes with the development of scientific knowledge in real science: they came to realize that, in a way similar to the "crisis" period in real science, *the classical worldview* reinforced by traditional teaching methods and everyday perceptions, as it is taken for granted, creates the "central metaphysical beliefs" (Posner et al., 1982) or the "entrenched beliefs" (Vosniadou & Brewer, 1992), or the "ideological assumptions" (Baltas, 1986) that oppose the attainment of a radically new worldview.

Thus, such a "meta-cognitive" analysis, functioning, at the same time, as a parallel "meta-scientific" analysis, has gradually led t-ls to recognize the *epistemological obstacles* they had to overcome in order to reach QM perception. We may, then, claim that the "Levels of Reality" structure, associating the meta-cognition processes with views of meta-science, became a powerful *meta-cognition tool* that led t-ls to attain an aspect of what has come to be called *learning with understanding* (Gardner, 1991; Perkins, 1992) in two different domains:

- First, *in QM learning* the "Levels of Reality" structure, using the history and philosophy of science as sources for a rational explanation of the meaning of QM concepts, has effectively supported t-ls' conceptual reconstruction.
- Second, *in the understanding of NOS* the "Levels of Reality" structure, being "built" in a way that reveals how real science creates and classifies its own material, allowed discussion of the following issues: (a) the nature and structure of scientific theories; (b) the tentative character of scientific knowledge; (c) the different views concerning the development of scientific knowledge (continuity–discontinuity); (d) the nature and character of scientific discovery; (e) the Kuhnian terms, "normal science," "crisis" in science, "scientific paradigm," "scientific revolution," "paradigm change"; (f) the different views with regards to the incompatibility/asymmetry of scientific theories; (g) the role of models and analogies in the scientific development; and finally, (h) the limits of scientific knowledge and justification.

Indeed, the postinstructional interviews (during which the addressed questions were similar to those of the preinstructional interviews) revealed *a parallel shift* of t-ls' scientific and epistemological perceptions. Two characteristic statements follow:

> In science, we cannot speak about "correct" representations of physical phenomena. We can only argue that, for example, the atom model accepted by contemporary physics better explains the experimental data. However, we can also use different representations according to the phenomena we intend to describe. Thus, Bohr's atom model is a "correct" representation if we are interested in interpreting certain chemical phenomena (Lisa, Question 5).

> We would not be able to describe the properties of the atom if we knew the properties of its constituents, because the atom is an elementary particle. Thus, it does not behave like ordinary objects do . . . this means that if we measure the value of an entity of, say, a concrete constituent, we disturb the whole atom in an uncontrolled way. If we then sum up the values (of this entity) of all constituents . . . the sum is a disturbed result . . . we cannot claim that (this result) corresponds to reality as happens in CP . . . Through QM theory we cannot reach the whole by means of its parts (George, Question 3).

The above answers reveal the fact that t-ls' reasoning, through QM perception, was closely related to a clear discrimination of CP and QM conceptual systems, as well as to a rather satisfactory awareness of science's justification patterns.

However, from the postinstructional interviews we also came to realize that issues demanding a more sophisticated mathematical background, although qualitatively understood, were not well received. This became clear in the case of subjects requiring fundamental knowledge of wave-mechanics, e.g., the superposition principle, electrons' diffraction, and so on. The following statement illustrates this point:

> All elementary particles have the potential to exhibit wave-like properties—but this can be obtained only in specific conditions. It depends on which measuring device is used . . . when we observe wave-like properties, we miss particle-like properties, this is complementarity. . . . now, with regards to the defining properties of a wave that an elementary particle could exhibit, well, I could say, it could (show) a diffraction pattern due to the overlapping . . . I can not further explain how this happens (Lia, Question 2).

As it will be later explained, on-going courses included in the framework of the whole project attempt to lead t-ls to enlarge their background knowledge of wave-mechanics through a weak reconstruction process.

DISCUSSION—PERSPECTIVES

The explicit question that the present article set out to explore was whether there is a teaching strategy that can lead students who lack a sufficient mathematical background to attain a qualitative approach to QM worldview. Indeed, we might claim that the results presented above can be judged as satisfactory. However, the special characteristics of the whole task raise certain questions, which need to be addressed.

One such question is whether it is worthwhile to teach QM to students who are not willing to attend specialized science training. We take the view that the answer should be positive, because a qualitative approach to QM basic ideas (a) might allow an educated person to reach the core ideas of a theory that introduced radical modifications into human thought; (b) might allow these ideas to be accessed at a very early stage of physics education. This might prevent the introduction of particular items such as the hydrogen atom, which are already included in elementary and secondary school curricula, in ways that provoke serious misconceptions; (c) might be the means of getting in touch with NOS as a result of the historically ascertained scientific inquiry; (d) might also prevent students, who will attend higher physics education, from conceptualizing "QM abstract ideas by constructing mental models that . . . is all mathematics" . . . [a fact] that leads to a "surface learning" that lacks internal consistency" (Johnston et al., 1998, pp. 442–443).

If we accept then that it is worthwhile to undertake such a task, the experience from the courses has clearly shown that the required conceptual reconstruction is feasible as long as the instructional intervention succeeds in increasing t-ls' interest in QM scientific content, disassociating it, to a large extent, from its mathematical formalism, and associating it with the historical and social situations in which it has grown, as well as with the problems in real science, which gave birth to it. We might assume that the whole process presented here along these lines managed to eliminate, at least to some degree, the negative *motivational factors* that seem to impede conceptual change "in areas where students have little interest" (Schumacher et al., 1993, p. 4). This fact was established through t-ls' opinions offered during the postinstructional interviews. The following is a representative statement:

> Well, where NOS ideas came into the instructional process, was that through every step we changed our thinking about how scientific knowledge has to be perceived. This led us to understand how everyday experience can be reconciled with what we really considered irrational or magic . . . For example, everything concerning the uncertainty regarding where an electron is now or where it will be found in the future . . . all this follows from scientific reasoning that attempts to interpret experimental data in a consistent way . . . coming to understand this is a really interesting experience (Maria, postinstructional interview).

Another reasonable question refers to the stage of physics education where QM teaching could be successful, as well as to the required preinstructional knowledge. Our experience leads to the conclusion that t-ls' restricted background in science and mathematics—shared by secondary school students as well—proved sufficient for acquiring a way of thinking that is consistent with QM reasoning patterns. Thus, it is reasonable to expect that secondary school students might produce similar results. Where the elementary school students' physics instruction is concerned, our opinion—supported by t-ls' remarks—is that the carefully selected and appropriately used visualizations of the microscopic phenomena—like the ones we used—have the potential to offer the adequate "images" for the first contact with distinct ontological behavior and properties of elementary particles. Of course, this assumption needs to be well substantiated and carefully tested.

In terms of the learners' cognitive background, we may also underline the fact that the proposed instructional model offers, by its nature, an additional possibility. In case that the development of the instructional process reveals a weak cognitive domain in the learners' "old" knowledge, it is possible, through a back-and-forth weak reconstruction process, to broaden and enrich both the old and the new conceptual structures. For example, in our case, the evaluation process offered evidence that t-ls failed to achieve equally satisfactory results in topics requiring a firm knowledge of classical wave mechanics. Thus, based on the findings regarding t-ls' meta-instructional cognitive state, we proceeded to design a preliminary instructional intervention aiming at expanding their knowledge by means of *a weak reconstruction* process: Selected topics of classical wave mechanics were introduced for enriching the CPL conceptual network. At the same time, the concept of wave-particle duality was reconsidered as an important node of QML, while the deep differences between classical and quantum wave mechanics were enlightened. The first results were encouraging (Hadzidaki, Stavrou, & Kalkanis, 1999), in the sense that they revealed an important increase in the rate of the accommodation process. They seem to confirm our assumption that if the crucial goal of the initial radical conceptual reconstruction is achieved, strong foundations are laid for further enriching the acquired knowledge. The next step of the project, which is in progress, intends to introduce topics of classical wave optics—as part of CPL—in relation to the behavior of photons—quantum objects that belong to QPL—as a special case of wave-particle duality.

In conclusion to the present paper, we may point out that the experience acquired during the evolution of the whole project led us to believe that an effective instructional intervention, aiming at leading students to a qualitative approach to modern physics, demands a *multidimensional* research process in order to achieve an integrated teaching performance. In this paper we attempted to present a possible sample of such an instructional intervention.

APPENDIX

The Simulation-Computer Visualization of the Hydrogen Atom Orbitals

The hydrogen atom is the simplest atom because it contains only one electron. Thus, the Schrödinger equation becomes a one-particle equation after the centre-of-mass motion is separated. The potential of the central Coulomb field with the addition of the repulsive centrifugal barrier reads

$$V(r) = -e^2/r + l^2/2\mu r^2$$

Here, μ is the reduced mass of the atom, $\mu = m_1 m_2/m_1 + m_2$, m_1 the mass of the electron, m_2 the mass of the nucleus, and l is the eigenvalue of the angular momentum, defined by the orbital quantum number L by the relation:

$$l^2 = L(L+1)\hbar^2 \quad L = 0, 1, \text{ and } 2, \ldots$$

The principal quantum number n must obey the inequality $n \geq L + 1$ and defines the possible values (eigenvalues) of electron energy bound states:

$$E = -\mu c^2 \alpha^2 / 2n^2$$

Here, c is the speed of light and $\alpha = e^2/hc$, the fine structure constant. For our purposes, we used the first radial functions (Gasiorowicz, 1995) of the hydrogen atom with the help of which we obtained the equations for the radial probability density. For example, for $n = 2$, $L = 0$ the relevant radial function (R_{nL}) is

$$R_{20}(r) = 2\left(\frac{1}{2a_0}\right)^{3/2}\left(1 - \frac{r}{2a_0}\right) e^{\frac{-r}{2a_0}} \tag{1}$$

Here, $a_0 = h/\mu c\alpha$ is Bohr's radius. Thus, the probability density is

$$f_{20}(r) = r^2 [R_{20}]^2 \tag{2}$$

The probability for finding the electron at a distance between r, and $r + \mathrm{d}r$ from the nucleus is given by the equation

$$f_{20}(r)\,\mathrm{d}r = \frac{1}{2a_0}\left(\frac{r}{a_0}\right)^2 \left(1 - \frac{r}{2a_0}\right)^2 e^{\frac{-r}{2a_0}}\,\mathrm{d}r$$

After the introduction of $y = r/a_0$, the probability for finding the electron at a distance between y and $y + \mathrm{d}y$ from the nucleus is given by the equation

$$f_{20}(y)\,\mathrm{d}y = \frac{1}{2} y^2 \left(1 - \frac{y}{2}\right)^2 e^{-y}\,\mathrm{d}y$$

We want to create a list of numbers that should follow the distribution $f_{20}(y)$ and visualize these numbers by an ensemble of points, whose density in space should be in agreement with the relevant distribution. To obtain that, we calculate the probability function $P(x)$ for finding the electron inside a sphere of radius x. For the case we examine, if we call $P_{20}(x) = Y$

$$Y = \int_0^x f_{20}(y)\,\mathrm{d}y = 1 - e^{-x}\left(1 + x + \frac{x^2}{2} + \frac{x^4}{8}\right) \tag{3}$$

The random variable Y follows a flat distribution and it is connected, by the last equation, to the variable x that follows the distribution we ask for, that is, the probability density distribution f_{20}. As Eq. (3) is not analytically reversible, we proceed to a computer arithmetic solution (Newton's method), which offers the list of numbers we want. We formed a Computer Program, which visualized this ensemble of numbers and the "image" of the hydrogen atom appeared.

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