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To cite this article: Marco Giliberti and Giovanni Organtini 2021 *J. Phys.: Conf. Ser.* **1929** 012046

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Reconsidering Physics Education for better understanding of modern physics

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Abstract. Most current educational presentations of quantum physics still propose the same difficulties that emerged in the early twentieth century, often as a mean to engage students. Those difficulties emerged among physicists mostly because the lack of a suitable meaning of what “reality” has to be considered. Instead of engaging students, those difficulties leave them confused because they lack the awareness of what a physical theory is and its relationship with the experiments. We will discuss this problem, both from the epistemological and the educational point of view and give indications to provide an increasingly solid foundation for the educational reconstructions of quantum physics starting from classical physics that must be reconsidered in view of the final objective rather than opposing it to modern physics.

1. Introduction

Understanding modern physics is universally recognized as important for the education of the future citizens (see for instance [1]). Conceptual and technical understanding of modern physics is then one of the hottest research topics in physics education, as evidenced by the general theme of the GIREP-ICPE-EPEC conference 2019 whose title is “Teaching-learning contemporary physics, from research to practice”. On the other hand, despite the large presence in textbooks of modern physics topics, the didactical quality of most presentations is clearly unsatisfactory. Almost all the authors, in fact, just added chapters about modern physics, especially quantum physics, to already consolidated books, with no or little attempt to create a bridge between classical and quantum physics, insisting, indeed, on the (apparently) paradoxical character of the latter.

The results coming from Physics Education Research (PER) are sufficiently unambiguous and known for at least twenty years: many students (even graduate and master degree students in physics) show great difficulty in understanding the relevant aspects of quantum physics. In 2002, at Mount Holyoke College, one of the prestigious Gordon Research Conference was entirely dedicated to this problem and a whole issue of the American Journal of Physics [2] has put in light the learning difficulties of university students in quantum mechanics. Even in Europe (for instance in Italy where modern physics is a compulsory topic at high school level) the problem has been tackled by most PER groups [3][4][5][6]: it emerged that, often, secondary school teachers do not have a coherent picture of quantum physics.

The traditional approach to quantum physics is, in our opinion, responsible of profound misunderstandings and, therefore, to solve the problem it is not enough to have a coherent set of teaching instructions limited to the specific topic. We need to revisit the way in which classical physics is taught, in order to introduce modern physics more smoothly.



2. Background questions

Among the questions that need to be answered, in order to design a new learning path to modern physics the following are preeminent. What basic conceptual aspects of quantum physics should the average citizen know? Why should citizens be aware of quantum physics? Is it possible to present quantum physics in secondary school in a honest and meaningful way? What cultural and disciplinary goals coming from quantum physics can be proposed to secondary school students? Do we need to change the way in which classical physics concepts are taught and understood? If so, which of them have to be revised?

3. A disciplinary framework for quantum physics education

We already observed that most of the didactic presentations of quantum physics show interpretative difficulties that date back to the early years of the last century. In fact, many teaching paths, even those that do not follow a (pseudo) historical approach, are extremely lacking on a crucial point, that is, that the meaning and the “reality content” of quantum physics must be sought in the theory that describes the physics of the topic itself [7]. This is an obvious feature, shared by any other theory.

For example, in the mechanical description of the world, to the word force a reality per se is often associated, as if forces were independent and external elements of reality. On the contrary, in physics, they find their meaning in the context of the Newtonian theory with its three principles. It is not a coincidence that many aspects of the force concept are completely misunderstood, as we observe below, talking about the force concept inventory.

Newtonian mechanics is not a way to describe forces, but a conceptual scheme in which forces, by means of their formal connections with other elements of the theory, become part of the reality. There is no need, for Newtonian forces, to be compatible with the intuitive concept of force that is manifestly completely different.

As well, the “reality” of the electromagnetic field can only be understood by Maxwell’s Equations.

Just as the concept of “force” gets its meaning from the mechanics of Newton and that of “electric field” is inseparable from the equations of Maxwell, the concepts of particle, of state or of quantum evolution are not a priori aspects of reality, but have their foundation in quantum mechanics.

Moreover, as it is well known, forces and fields are not easily understandable and straightforward concepts, as proven by several observations. For example, the Force Concept Inventory [8] is a well-established compilation of misconceptions of the “force” concept that is not intuitive at all, despite many consider Newtonian physics much more acceptable than modern physics. There is then no reason, to a priori believe that fundamental quantum physics concepts as those of state, operator, etc., should not be learnt with an effort that is comparable, if not lower, than that of classical concepts.

Many of the observed educational difficulties emerge, in our opinion, from the lack of awareness of the nature of the theories, which, we propose, are to be identified with their mathematical formalism together with a coherent physical interpretation that sets the rules of correspondence with possible experiments and their interpretation. On the contrary, physical concepts are often proposed making reference to a mixture of ideas [9] that are uncritically taken from other areas and from other theories, with the addition of pre-scientific or common sense schemes [10]. Manifestly, several secondary school physics textbooks resemble mathematics textbooks, because (almost) only the mathematical formalism is taken as important. On the other hand, textbooks trying to explain physics avoiding mathematical difficulties often fail to provide a clear vision. We propose a different approach, in which the results from experiments are the guidelines for the construction of coherent mathematical pictures, without trying to stick to models based on common sense or everyday experience.

Therefore, to avoid misleading interpretations that often come out when quantum concepts are mixed with classical concepts in common sense patterns, in the teaching of quantum physics, we propose to conceptually start from its mathematical formalism, solidly based on experimental observations and

develop the educational path within this disciplinary framework. Starting from some crucial experimental results one has to induce the basic principles of the theory, that are to be understood in their mathematical and physical meaning and used to describe important real-world properties with no attempt to provide classical analogous of concepts that manifestly cannot exist.

To that purpose, a didactic reconstruction of the contents of the new theory where Newtonian physics becomes a limit theory and not a starting point is essential. We believe that a rethinking in this sense of the teaching of quantum physics is particularly useful, not only for its intrinsic potentiality, but also because it can help to clarify many aspects that are related to key concepts of classical physics, highlighting connections and interpretations that are not always customary.

4. Preliminary answers to research questions

The work presented in this paper has just started. As a consequence, we cannot yet provide a clear set of answers, nor, manifestly, results concerning the effectiveness of our proposed approach. The current work should be conceived as a work in progress proposal that we intend to gradually test in a near future in secondary schools and to be discussed with interested researchers. Till now we partially tested the new approach in university courses for non-physicists and in the Scientific Degree Plan ¹ with about 40 last year secondary school students and 30 physics teachers. Therefore, some of the statements made below have to be considered as starting points for discussion. Being work in progress, we cannot provide any significant strong evidence yet supporting our thoughts. Our aim, in presenting the work in the current state, is to share our ideas, even if not in the final form, with other researchers that may or may not share a similar vision. In our opinion this could lead to useful discussions that, in the end, will lead to better, shared and widely accepted teaching paths.

4.1. *Why should citizens be aware of quantum physics?*

Quantum physics has generated a revolution of thought and of the man-universe relationship that has influenced and still influences the perception of who we are and what place we have; it is substantially impossible in a school path that discusses philosophy, literature and modern art not to deal with quantum physics in high school in a serious and meaningful way.

In this case the answer is rather simple: our modern life is entirely dominated by quantum physics, despite its apparent distance from reality. Electronic devices, indeed, exist only because we understand quantum physics enough to build diodes, transistors and integrated circuits. Life itself is a quantum physics manifestation, being the result of physical-chemical processes that can be understood only in terms of quantum phenomena. Modern diagnosis tools such as Computer Assisted Tomography (CT), Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) are based on quantum phenomena, not to mention radiotherapy and hadron therapy. Those outlined above, are just few of the many examples of everyday life in which quantum physics is important.

Manifestly, understanding the world in which one lives is one of the objectives of education. Citizens aware of the basic working principles of what they use are relatively immune to fraudsters and profiteers, who often rely on general ignorance about certain subjects.

With respect to this objective, one can clearly see that the current approach to quantum mechanics does not help at all in reaching it. On the contrary, since it leaves a mood of mystery around what happens at quantum level, it reinforces the idea that everything is possible and that scientists do not really understand what they pretend to (in this helped by urban legends).

In fact, no other branch of the physics is as well founded as quantum mechanics. Gravitation, often considered one of the most solid physics theory, is by far less understood than quantum mechanics. In fact, the value of the Newtonian constant G is known to a precision that is by far worse than the Planck constant that, indeed, has been taken as a reference for other measurements [11]. Many quantum mechanical phenomena have been experimentally tested and compared with theory to levels up to parts per

¹ The Scientific Degree Plan is a structural project of the Italian Ministry of Education, University and Research which brings together secondary school and universities for student and teacher science lab activities.

million. For example, the electron anomalous magnetic moment, a purely quantum mechanical manifestation, has been measured to be [12]

$$a_e = \frac{g-2}{2} = (1159.65218091 \pm 0.00000026) \times 10^{-6}$$

that agrees with theoretical predictions within $|a_e^t - a_e^e| \cong 3 \times 10^{-9}$ [13] (superscripts stand for theory and experimental, respectively).

4.2. *What basic conceptual aspects of quantum physics should the average citizen know?*

In order for the citizens to appreciate quantum physics in everyday life, they must understand the basic principles of modern apparatus, most of which are based on the quantisation of the energy levels in solids (e.g. lasers, electronic devices) or on energy loss of particles in matter. A general comprehension of fundamental concepts (e.g. the probabilistic nature of predictions that can be made, the superposition of states, the meaning of operators and states, etc.) is also desirable. Moreover, if we want that physics is experienced as a deeply cultural, formative and fundamental human activity for everyone's life, a certain knowledge of quantum physics becomes indispensable. In particular, the concepts outlined above must be correctly acquired, to avoid misconceptions that frequently lead to fanciful interpretation, often encountered in a large part of the population.

4.3. *Is it possible to present quantum physics in secondary school in a honest and meaningful way?*

We believe that most of the fundamental aspects of quantum mechanics can be reasonably presented in the form of the most consistent class of physics theories: quantum field theory (QFT). In QFT, concepts that remain ambiguously defined in "classical" quantum mechanics, like the concepts of particle and field, are precisely defined and provide a clear enough counterpart in our everyday experience. Most of the physics around us is governed by interactions between charged particles. Quantum ElectroDynamics (QED) thus becomes the reference theory, indispensable for treating the electromagnetic field.

Just to provide an example, the propagation of a laser beam is not very different from the propagation of a beam of electrons. In both cases a field propagates in both space and time and both give rise to interference phenomena. Both can be localized when they interact with something else. Furthermore, there is probably no need for particle-wave duality: at least as it is traditionally presented, since it very often generates misconceptions and confusions.

Often, QFT is considered to be too complicated to be introduced to high school students. In fact, we believe that it is just the contrary: QFT is by far easier to understand with respect to other forms of quantum mechanics. The only complications arise from its mathematical formulation for which, however, it is possible to find strategies aiming at dramatically simplifying the mathematical technicalities without losing the cultural content.

On the other hand, such an approach has been already exploited in teaching classical mechanics. The mathematics of gravitation and electromagnetism is not at all simple. Most teachers, including university professors, are not able to derive the form of the Newton's gravitational force from observations, for example. Moreover, many aspects of electromagnetism are hidden in the reformulation of Maxwell's Equations in terms of rules (e.g. the flux rule for the Faraday-Neumann-Lenz is hardly analyzed, but in terms of its bare application that, by the way, sometimes result paradoxical in certain cases [14]).

We then propose a suitable reconstruction of the theory aiming at presenting just the most important aspects, without sacrificing rigor and the ability to mathematically derive results from basic equations, even if this can be done only in selected, simple enough situations. On the other hand, this is what typically happens in classical physics exercises, where physics laws can be applied to a very small subset of problems.

QFT makes it relatively easy to introduce fundamental interactions, in a way that is by far much more quantitative than is typically done (e.g. Feynman diagrams are often presented as a picture of what really happens at microscopic level, though in a completely qualitative form) [15]. Indeed, QFT, is the conceptual basis of the standard model.

QFT can also shed new light on concepts that, as we all know, are very difficult to understand, like energy. One of us, in fact, exploited this feature in providing a non-metaphoric explanation of the Higgs mechanism suitable to be presented to high school students [16].

The basic concepts involved in QFT teaching are: field, state, creation and destruction operators, waves, scattering, evolution and probability.

4.4. Do we need to change the way in which classical physics concepts are taught and understood?

The basic answer to this question is yes. We need to. We need to make it clear that what we call “reality” is subject to continuous changes because the status of the entities that should form such a “reality” is flexible. Just to provide few examples, think about the concept of space and time, as well to that of atoms.

Theories belonging to the domain of classical physics, too, are nothing but mental constructions helping us to find and define reality.

The path followed by physicists in developing a new theory is the following: first, inquiry begins with schemas and concepts not requiring any theory to be explained (common language and notions); then proceeds introducing new concepts that we can call “pretheories” (e.g. the concept of field in electromagnetism); finally arriving at a physics theory after the introduction of a suitable formalism. The truth value of a theory is given by the complete set of its mathematical formalism, by its field of applicability and by the rules of correspondence between these two.

In our opinion the concept of state should be introduced as early as possible. Its concept is still already present in physics textbooks, however we did not find any of them providing a definition of what a state of a physical system is. Moreover, the concept of a physics law as a way to express the evolution of a state by means of an operator transforming the state of the system at time $t=0$ to the state at a later (or earlier) time t , must be introduced quite early. Even the measurement processes must be carefully discussed. There is a widespread idea that physical quantities are represented as continuous functions of continuous variables. As such, we use mathematical analysis to derive results from differential equations. However, this is clearly a very crude approximation. Our data are always affected by uncertainties and these uncertainties, as it is made clear by quantum mechanics, is intrinsic to physics data and are no longer intended as a technological limitation. There should then be a clear separation between mathematics and the mathematics used for physics. As an example, the velocity is often defined as the derivative of the position. However, such a definition implies the possibility to take the limit for the interval of time to zero that is physically impossible to reach, just because of measurement uncertainties. In other words, the velocity, in physics, is always defined as the ratio of finite quantities and we just find that, assuming that position is a continuous function of time, such a ratio can be treated as a derivative.

We must make it clear what is part of the physical system under investigation each time and define concepts, without being pedantic, of any part of it, including those that are often taken as obvious, such as the concept of particle. This is one of the most critical concepts to be discussed, since in quantum mechanics particles are really identical, not as in classical physics in which they can be “labelled”.

In summary, we need an approach to classical physics that is redesigned such that it leads the student to quantum mechanics in a natural way, rather than continuing to insist on the apparent obviousness of classical physics as opposed to the paradoxical behaviour of quantum systems. In order to do so, we believe that only minimum, though relevant, changes must be applied to the way in which we teach classical physics.

5. Schematic idea of our path

5.1. Classical physics

Revision of the presentation of classical mechanics such that a law of temporal evolution (typically given by $a=F/m$) is put in evidence and the idea of state is explicitly given by those specifications of a system that must be known in order for the physics laws to predict temporal evolution.

The statistical aspect must always be highlighted. The reproducibility of a scientific experiment means that a certain class of properties extracted from a suitable statistical set must be reproducible. In the case of mechanics, and considering simple examples, this is almost trivial; in nonlinear systems it becomes more complicated and in thermodynamics it has, instead, slightly different connotations.

The measurement of physical quantities is carried out through measuring instruments that can be represented, at least in principle by the theory. The results obtained in this way are not necessarily state quantities, although they can be related to them.

5.2. *Quantum physics*

Interference and diffraction of electromagnetic and matter beams (electrons, helium, fullerenes, etc.). Analogies and differences between a beam of light (laser) and a beam of electrons (cathode ray tube).

Importance of quantization (laws of chemistry, photoelectric and Compton effects; granularity in interactions (interactions always go in pairs)).

From these experiments the need for a linear theory of fields that interact through quanta in a statistical way is suggested. At least in the case of matter beams a complex theory should be preferred (in fact, intensities are given by the square of the fields. Matter beams have to have an intensity that is not oscillating while the field indeed is).

5.3. *Quantum mechanics*

From experiments we derive the need for operators acting on initial states to produce final states, where the states are determined by what can be measured. Spin is introduced as an experimental measurable quantity (from Stern-Gerlach experiment and the periodic table).

Creation and destruction operators are introduced. The idea that a measurement results in one eigenvalue of an operator is introduced quite naturally. When observing that energy is a measurable quantity, the Hamiltonian operator is introduced.

Discrete spectra such as those for particles in a well and the harmonic oscillator can then be introduced (for the latter only the ground state is computed: the higher energy states are derived from analogy with simpler potentials). The tunnel effect is discussed.

5.4. *Quantum Field theory*

By an analogy between the electromagnetic field irradiated by a wire and radioactive decays, the concept of a matter field is introduced, much like E. Fermi does in his theory of weak interactions. The mathematics introduced above in Quantum Mechanics can be exploited to introduce amplitude computation and effective Feynman diagrams (no need to introduce formal Feynman rules if only ratios of amplitudes of physical processes are computed).

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