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THEORIES AS CRUCIAL ASPECTS IN QUANTUM PHYSICS EDUCATION

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Abstract
A lot of difficulties aroused in interpreting quantum physics from its very beginnings up today are still at the core of most educational presentations. In fact, usually people try to grasp theoretical concepts by referring to a blend of ideas taken from scientific, pre-scientific and common sense schemes.
In this paper a pre-condition for every educational approach will be proposed: to rigorously keep to quantum mathematical formalism in order to understand the meaning and the "reality" of quantum physics. It will be argued that the addition to quantum theories of most extraneous concept or common sense scheme comes from an ambiguous idea of nature, scope and aims of science itself.

1. Introduction
Many difficulties faced by most educational reconstruction of quantum theories have epistemological reasons, mainly embedded in the so called paradoxes of the quantum world. Even the educational paths that do not follow a historical (more often a pseudo-historical) approach, often lack a crucial point: that the meaning and the "reality" of quantum physics, just as the meaning of every physics topics, must be read from the theory, i. e.: the meaning and the concept of force should to be stressed from newtonian mechanics and the "reality" of the electric field should, in physics, be understood by Maxwell equations.
In this paper the lack of consciousness about the proper and exclusive nature of physical theories is related to thess well known difficulties and it is proposed that, in order to avoid many misinterpretations, which especially come by connecting quantum theories with classical physics concepts in wrong ways and by trying to reduce it to common sense schemes, a pre-condition is crucial: in quantum physics education please rigorously keep to quantum mathematical formalism (that is that of Quantum Mechanics or that Quantum Field Theory) and its interpretation..

2. Nature of difficulties: theories
First of all our language describes an image. [...] It's clear that, if we want to understand the meaning of what we say, we must explore the image. But the image seems to save us this effort; it already hints at a determined use. So it mocks at us (Wittgestein 1967).
The undetermined “mess" to which we give the name "reality" is subjected to continuous changes because the status of the supposed entities that should form this "reality" is very flexible. Important and very known examples of these changes are the idea of absolute time, that of a luminiferous ether as a medium for the electromagnetic waves and the very idea and structure of atoms (Bellone, 2006).
In fact, it is not possible to separate the object of knowledge from the instrument of knowledge: they must be considered as a whole. And this aspect is one of the main teaching of quantum physics from its very beginning. Theories are but mental constructions that help us find and define reality and utilize its resources. Physics inquiry begins with schemas and concepts that need not to be explained by theories; they come from common notions and language. Then proceeds introducing other concepts by means of what we can call "pretheories", that is already known physics theories stated as granted. Pretheories are unavoidable features and, for instance they are at the basis of our understanding and designing of measuring devices. Finally, our inquiry arrives at physics theories, that are determined by the basic concepts introduced before (common schemas plus pre-theories) plus formalized well defined new disciplinary concepts (Ludwig 2008). Actually we can imagine facts like icebergs, submerged under the surface of the sea of immediate experience that is perceived through common schemas. The submerged part of these facts can only be hypothesized, or, in a sense, imagined. A coherent and formalized imagination of this under-the-sea level of reality gives rise to physics theories. We can even think of these imagined realities as fairy tales; in this sense a scientific explanation is a story about how some entities, that are imagined but considered as real, would, by their very hypothesized nature, have worked together to generate the phenomenon to be explained (Ogborn 2010). A very simple and clear example of what is stated above about the construction of useful entities in theories as fairy tales

can be found in star constellations. They are useful in finding the way on open sea and they are obviously man made constructions. But are they real? In what sense of the word real? Do they form natural entities? (Stenholm 2002). A way to answer to the previous questions is thinking that 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 (Cavallini 2008).
A more physical example can be found in classical mechanics. In the mechanical description of the world, to the word force a reality in sé 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. Newtonian mechanics is not a way to describe forces, but a conceptual schema into which forces, by means of their formal connections with other elements of the theory, become a part of reality. (Cavallini 2008).
Difficulties clearly emerge when we start to believe in the very real objective existence of constellations and of forces as they were natural real entities independent on human scientific schemas. But after all, it could be said that these questions regarding the objectivity of the world have not prevented physicist from regarding their results as objective facts. However it should be clearly stated that when this attitude is put forward even to quantum physics, our understanding of the world explodes into paradoxes.

3. Nature of difficulties: quantum physics

Initially science does not develop by reflecting on its foundations, but with the accumulation of facts and the assimilation of new knowledge. But sometime one meets great contradictions and the greater the contradictions, the greater is the success in overcoming them. One important example of contradictions can be found in the divergence between the classical model of the atom and the studies on the emission of light by substances that eventually brought to the birth of quantum mechanics (Ludwig 2008). We can say that when we face contradictions we are like a paramecium that meets an obstacle: at first he goes backward and then starts again to go forward in a direction chosen at random. One could advise him of a better direction, nonetheless what he knows is correct: He cannot go in that direction! (Lorenz 1973)
In the developing of quantum physics at least three steps can be singled out.
1) Old quantum physics: that is facts and interpretations from 1900 till about 1925. Examples are the problem of black body radiation and the model by Planck; the photoelectric effect with its explanation by Einstein and the various model of the atom, mainly Bohr's atom. It's a set of facts and interpretations with the background idea of the existence of the so called quanta. Old quantum physics is the first response given by physicists to faced contradictions, but by no means constitute a theory.
2) Quantum mechanics: with its formalism given by Heisenberg, Jordan and Born or that given by Schrödinger and Dirac, is a non-relativistic theory with well defined axioms that describes the behavior of a finite number of interacting particles. There are many different formulations of Quantum mechanics i. e. are matrix formulation, wave function formulation, path integral and second quantization formulation and even non orthodox formulations like Bohm's one (Styer 2002).
3) Quantum field theory: it is a relativistic quantum theory and every relativistic quantum theory will look, at sufficiently low energies, like a quantum field theory (Weinberg 1995). The most known example of a quantum field theory is quantum electrodynamics, but even the standard model of particle physics is a quantum field theory.
And here come the problems: popular and even didactic interpretation of quantum physics very often mix these three parts together with great ingenuity. Moreover they often focuse on old quantum physics that, as stated above, is not even a theory and therefore it cannot be a reference for understanding.

4. A pre-step solution for quantum physics education

Instead of working in the general mess of the old quantum physics, before educational reconstruction of the topic, as a pre-step, we should choose a reference theory in one of its formulation, identify the concepts of the theory in this formulation and understand their meanings inside the theory. (Cavallini 2008).

In my opinion the framework of quantum field theory is best suited than quantum mechanics for quantum physics education in general and, more specifically at high school. One of the reason is that only in quantum electrodynamics the concept of photon can be well defined. At the University of Milano we have been working on this subject since 1995 and many encouraging results have come (Giliberti 1996; Giliberti 1997a; Giliberti 1997b; Giliberti 1997c; Giliberti 1998; Bergomi 2001; Giliberti 2002a; Giliberti 2002b; Bartesaghi 2004;Giliberti 2004a; Giliberti 2004b,; Giliberti 2007; Giliberti 2008).

Anyway in general, whatever reference theory is chosen, in physics education one has to try to avoid misunderstanding of ideas and words that are used by the theory, but come from preceding conceptions (pre-theories, or even common sense) rooted in the biased idea that physics reality can be identified even out of a formal theory. A clear example of this can be seen in the idea of particle in quantum physics. When we speak of particles we should clearly state what we mean, what the theory allows us to think of, and what it does not.

We must be careful that with that word we do not implement the idea that particles indicate physics entities in the sense of an ingenuous realism, and that these (ingenuous) entities coincide with the quanta of the theory.

As it has been previously pointed out, in scientific construction, reality comes out of a set of coherent interpretations of the formalism of the reference theory. In this sense the common word "particle" is nothing but a useful metaphor of what is meant by the theory. In quantum mechanics particles of the same "kind" are identical, not only because they have the same charge, the same mass, the same spin,... but also because they are indistinguishable even through their position. They are identical because they have the same physical properties.

We could think of a system with two electrons of different energy. In this situation we can say that one electron has a certain energy while another one has another energy, but it could be impossible to answer to the question "Which electron has which energy?". In more formal terms, the wave function obtained by the exchange of this two particle would yield the same previsions for the measurements of every observable. It is thus clear that the intuitive semantic content of the word "particle" given to the quantum mechanics quanta is, in general not adequate.

From an educational point of view I believe it could be much clearer if we spoke of quanta as linked to the excitations of the normal mode, as it is done in quantum field theory, in this way it would be evident that they are identical and indistinguishable... and have little to do with the "usual" particles. It is the event of revelation of a quantum in a device that drives us to use the word "particle", giving a metaphorical sense to a word coming from classical physics (and from common language).

If one strictly follows the guide of a theory most of the paradoxes (in quantum physics more or less all coming from wave/particle dualism) become not so central, with a great help for teaching.

5. A more deep difficulty

I'm not claiming that keeping in close touch with a quantum theory all difficulties run away. In fact an objective problem remains and it comes from the theory itself. In formulating quantum mechanics (and even quantum theory of fields) the world must be split in two parts; in this way we have a dichotomy: a microscopic quantum physics description for the system we are studying and a macroscopic classical description for measuring devices; experimental context and results must be described in classical terms. Quantum mechanics cannot even be formulated without this distinction. The problem is that the theory gives no indication on how "to cut the world". Quite obviously to get information from a microscopic experiment we must produce an amplification process that leads to a macroscopic change; but, as even the apparatus are in principle describable in terms of quantum mechanics, this leads us to an aporia. Is there a macroscopicity parameter? Not in the theory. Nor it seems in experiments (see for instance experiments of diffraction of macromolecules that show their wavelike proprieties (Arndt 1999) or the quantum macroscopic proprieties of a superconductor). So some deep difficulties are still rooted in quantum mechanics itself: there's really no need of making educational path that instead of presenting difficulties where they are, generate confusion mixing aspects, ideas and words coming from a too ingenuous vision of reality.

6. Conclusions

In conclusion this paper is a call to realism. I would like to stress that, as we already (some time unconsciously) do for classical physics, when dealing with quantum physics education we keep closely to a specific formulation of the theory. We can choose among one of the many formulation of quantum mechanics or one of the formulation of quantum filed theory (we in Milan suggest the latter, for his more easily grasped epistemology, linked to specific space time field instead of the configuration space wave function of quantum mechanics).The path to follow and the results obtained in experimentations are but a secondary problem in this perspective: they come after.
Historical or conceptual presentations and educational reconstructions of the topic cannot in our opinion skip this point, as instead many times they do keeping an eye closer to the path than to the goal.

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