

QUANTUM PHYSICS

“THE PROBLEM IS NOT UNDERSTANDING THE THEORY, BUT ACCEPTING IT”: A STUDY ON STUDENTS’ DIFFICULTIES IN COPING WITH QUANTUM PHYSICS

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1 INTRODUCTION

The contribution is focused on the presentation of some results obtained by implementing a *thick path*^{b)} on Quantum Physics (QP) with 18-19 year old students. The same path has been implemented in parallel in two different regular classes of a science-oriented high school (Liceo Scientifico “A. Einstein”), in Rimini (Italy). The teacher was the same (P. Fantini) and both implementations took about 25 school-periods each. The results concern the difficulties expressed by the students in entering QP and, mainly, in accepting the implications of QP on the problematic relation between reality-language-knowledge^{c)}.

2 THE THICK PATH

By thick path we mean a multi-level structure of knowledge organization. Instead of a teaching/learning sequence to be covered step by step, a path is meant to be a complex territory within which students are progressively guided to gain cultural and argumentative tools to travel consciously and contextually along different knowledge levels: conceptual, phenomenological, formal and epistemological level. In other words, the instructional materials shaping the path have been designed so as to facilitate the creation of a learning environment where the concepts meaning could emerge through a complex dynamics between the above mentioned levels [1].

The path has been designed and developed as a progressive reformulation of a “complex” question: *How does the concept of object change from classical to quantum physics?*

Such a question has been chosen since its inner complexity allows:

- secondary specific questions to be generated (and secondary routes to be followed) without losing track of the main path;

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^{b)} The term “thick path” was suggested by P. Guidoni, within research meetings of the Italian project *Fis21*.

^{c)} For a wider, although somehow different, contextualization of the study see [1].

- the main concepts we wanted to address with the students to be analysed at different levels (phenomenological, conceptual/formal, epistemological).

More specifically, the path was articulated in an historical introduction and two parts.

In the *introduction* the necessity of re-thinking physical objects was pointed out. In particular problematic situations have been presented, namely situations where the classical models of object present limits by themselves (e.g. photoelectric effect, Compton effect, electron interference) or where different explanatory schemes clash with each other in border problems (the black-body radiation and specific heat problems) [2].

In the light of the problems put on the table, the students have been encouraged to become conscious that, if the available thinking categories are the classical ones, the main question cannot be formulated otherwise but: “*what is not the quantum object?*” (not a wave, not a particle, but “something” that unifies matter and radiation and that interacts by exchanging discrete quantities of momentum and energy).

Moreover, the students were progressively made aware that the question “what is the quantum object”, in this formulation, is bad set and that the process of reformulating it implies it to be split into more questions at different levels:

- A) what kind of behaviour do we consider in talking about a quantum object? (phenomenological level)
- B) what kind of new interpretative tools are needed? (formal, conceptual level)
- C) what are the background assumptions of the new interpretative tools (and of the classical ones)? (meta-physical, epistemological level)

The first part of the path was focused on the analysis of some important historical debates, with the aim of showing how dramatic giving up the classical image of the world has been. In particular, the students are guided to develop arguments for analyzing the debates between:

- Heisenberg and Bohr about the interpretation of uncertainty;
- Bohr and Einstein about determinism and the relationship between knowledge and reality;
- Heisenberg and Schrödinger about the visualization of quantum objects.

The idea was to arrive to addressing the formalism (**second part**) when the concepts of quantum state, state preparation, operator, eigenstate, eigenvalue, superposition principle, complementarity, uncertainty, measuring process and entanglement had been already introduced through the analysis of historical-epistemological debates as well as experimental situations (in particular experiments à la Stern and Gerlach or double slits experiments). We wanted that the formal structure (in particular, the Pauli’s matrixes [3]) did not appear a complication to the students but rather an emerging synthetic and simplified way of managing knowledge complexity.

3 THE STUDY

3.1 The data sources

During the implementations a lot of data have been collected through:

- Initial questionnaire on “the classical models” of object;
- Intermediate written tasks (qualitative and quantitative problems) on the topics addressed, respectively, in the first and in the second part of the path;
- Classroom videotaped discussions (at the end of the path);
- Final questionnaire about students’ reactions to the experience.

For the purpose of this specific study we have mainly considered the data collected at the end of the path: the videotaped discussions and the answers to the final questionnaires.

3.2 Aims

Aim of the study is to interpret the following two pieces of evidence:

1. *The shift of learning difficulties from intelligibility to acceptability of QP (in both classes).* In other words, students did not find the path difficult for technical reasons. Also the formal part proved to be somehow intelligible for all the students, although not easy for many of them:

“The problem was not understanding but accepting the consequences of the theory” (Michele)

“I found the path very stimulating and interesting (really!); easy ONLY from a technical point of view (calculation, exercises), since the theoretical part requires a lot of reflection and, I think, personal interpretation.” (Francesco)

Therefore the first research question of the study was: What kind of problems did students met in accepting QP?

2. *The different roles attached to the formalism by the students of two classes.* In particular, all the students of class A wrote in the final questionnaire that formalism has been *fundamental* for understanding, in front of most of the class B students who considered it *not particularly useful*.

Therefore, the second question is: Why did the two classes show such a different behaviour? What criteria did they use for evaluating the role of the formalism?

3.3 Some results

The first result of the data analysis is the recognition that each class centered its discussion around one dominant topic:

- The problematic relationship between *languages and thinking* (class A)
- The problematic relationship between *knowledge and reality* (class B)

The reasons why a class focused its attention mainly on a topic can be various, as well as difficult to be identified. A plausible reason can be the role played by the class-leaders who triggered and guided the discussions. However, the issue is somehow secondary for the aims of this study: we will take such a “polarization” as a matter of fact and use it, as the following sections will show, as a key for interpreting the different role attached to the formalism by the two classes.

A. Languages and thinking All the students of class A agree that:

- the quantum formalism is *the key for “entering a new mechanism”* (Stefano)
- entering the quantum mechanism requires a radical change of perspective:
- *“the part concerning the formalism, although complicated, has been useful to establish a clear-cut detachment from the classical view of reality”* (Giacomo)

In particular all the students agree that the formalism supports the idea that, in QP, *visualization* is impossible. Nevertheless, about the problem of giving up visualization the students expressed different positions:

- Luca: *The picture of microscopic reality, in this case, is sufficiently supplied by the mathematical formalism. Therefore, in my opinion, to have a graphical representation is not important for the scientific progress: What’s the use of the graphical representation? It may help explaining the object as it is to children. But mathematics already explains it. [...] In my opinion anyway, the picture of microscopic reality is already described well enough by mathematics. It is enough to have the tools for comprehending it and it seems to me that everyone can do so...”*

[...]

- Jessica: *But for me it is necessary in order to understand....*

- Luca: *Ah, but what if you can’t do it...*

- Jessica: *Because it is impossible to talk about something without trying to have a picture of what we are talking about, even unconsciously. It may help, in my opinion, also to give a meaning to formulas, because otherwise, even if we say that it is nonsense to represent the microscopic object, we give a picture anyway... I think so, although we decide not to draw it because we don’t want to give a model that...[...] it helps me, it helps to remember. [...] honestly I can explain the Compton effect by keeping in mind the drawing. [...] we know that to be untrue but...*

- Federico: *OK, but it is just an icon, you could draw a little star to make a photon.*

- Jessica: *Yes indeed.*

- Federico: *It is not a picture meant to express something real.*

As the discussion shows, some students (for example Luca and Federico) consider visualization as “stuff for children” and mathematical formalism enough to describe quantum phenomena. For other students (for example Jessica), pictures, although conventional, are however necessary to *talk* about something.

Hence, for the students of class A the problem regarding the QP acceptability concerns visualization. The point we consider the most important one is that the students manage to formulate the problem in terms of the cognitive need for finding out a plausible criterion to move from the quantum language to the ordinary and classical ways of thinking:

- Silvia: *In relativity it was different [...] there you have a demarcation line.. If you apply our velocity in formulas, you re-find our formulas.*

Without such a criterion, the quantum formalism risks becoming nothing but a “mechanism”, “a mentality” (Silvia) to jump into.

B. Knowledge and reality Most of the students of class B agree that the quantum formalism is an important emotional support, intelligible, *but only internally clear*:

"The part on formalism helped me from an human point of view, since it is always comforting to count on equations, calculations and mathematical laws. Still, although its inner coherence, mathematics did not contribute to give me an idea about the quantum object more convincing than the physical part. [...] Of course: it was not a complication, since formalism has been easy to memorize and understand, but, I mean, only internally clear. (Simone R.)

In particular, for most of the students, the formalism does not provide by itself all the knowledge resources for answering to the main questions arisen by QP, e.g. what they call "the knowledge problem" which arose in the fall of determinism.

"The hardest point to understand has been giving up classical determinism [...] Deterministic physics was an exact science, at least at a theoretical level. Quantum mechanics is upsetting since it requires facing the knowledge problem, it makes you ask if what we observe is really what it is." (Simone R.)

In front of such questions the mathematical formalism shows its limits whilst a refined epistemological language is needed to address the strong emotional impact:

"Until such questions do not emerge, everything goes on for the best but, when they come to light and we have to answer that we cannot say or foresee what we want to observe, the emotional impact is very strong." (Simone R.)

The students' discussion in class B developed around the questions: Should "real" be synonymous with "known in all detail", "known with certainty"?

- Luigi: *I think that realism is not lost. I mean that what we are talking about is something real and is not metaphysical, therefore realism is not excluded. We are talking about something that, so to say, is undeterminable because it has a non epistemic probability. Realism is not excluded anyway; on the contrary it is defined in another way... let's say on the basis of its probability instead of its certainty. Mathematics (in this case) allows us to explain the superposition principle, the principle of uncertainty. And that's what I found somehow difficult to understand: how mathematics gave us an explanation of how nature is not something exact but is instead undeterminable.*

- Michele: *I think Luigi pointed out that mathematics has never been associated with the concept of realism, it has always been abstraction. Mathematics has always given us certainty, something certain and computable. So mathematics giving here a concept of probability and uncertainty can be a little disconcerting. But when has mathematics ever been associated with realism? It has always been abstraction, model.*

At the end of the discussion, someone arrives at a quite surprising position:

- Michele: *The problem is that macroscopic properties are real to us because we are macroscopic. But if we think about it, it is the contrary indeed because the macroscopic is nothing but a composition of microscopic objects. What is microscopic is more real.*

"We are a composition of microscopic objects...", Michele says. But his strongest argument to support that a world description based on determinism is less real than a description based on a non-epistemic probability is the following:

"In my opinion, determinism à la Laplace creates science-fiction worlds... I understood this when I watched Minority Report." (Michele)

So, quite paradoxically, the non-epistemic probability became for some students the way to accept the quantum description as "realistic".

4 CONCLUSIONS

The analysis allows us to point out three dominant positions concerning acceptability, probably corresponding to students' different cognitive stiles, cultural interests or images of physics, and three different roles attached to the formalism:

- formalism is necessary and sufficient for accepting the results of a "theory that works".
- a well-working formalism is necessary but not sufficient to "have the feeling" of understanding. Comprehension requires the "formal mechanism" to be interpreted also in terms of (smoothed) links to ordinary language and classical description.
- formalism is necessary but not sufficient for accepting a theory. Acceptance requires also a philosophical analysis of the theory implications on knowledge in general.

The results highlight the plurality of the dimensions through which comprehension is reached and the plurality of languages needed to understand. The results hence strongly confirm, in our opinion, the importance of investigating what peculiarities a thick path should have for promoting understanding and what balance between the different dimensions of a path should be advisable in order to make physics teaching able to stimulate and respond to the demand of sense coming from the new generations.

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