LEARNING PATHS OF HIGH SCHOOL STUDENTS IN QUANTUM MECHANICS

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1 INTRODUCTION

As far as the way students face and learn quantum physics is concerned, three main aspects, producing learning problems, are considered in literature: a) the different ontological status of quantum systems with respect to classical ones [1,2,3]; b) disciplinary knots, i.e. concept of state, its formal representation, meaning of eigenvalue [4;5,6], impossibility to associate a trajectory to a quantum system [4;7]; c) use of semiclassical models [1,8-10]. The analysis of learning difficulties is often correlated to the effectiveness of innovative instructional strategies in producing a well defined quantum vision of systems and processes [4,9-11]. The opportunity to analyse developed ideas and the interpretative conceptions build by students is partially lost.

A teaching-learning proposal about Quantum Mechanics (QM hereafter), developed starting from the phenomenology of photons polarization, which aims at building the theoretical thinking favouring the formulation of interpretative hypotheses by pupils to be compared with the results of defined experiment-problems [12-14], allowed four different studies [15-18]. The results suggested that several students approach quantum ideas starting from deep-rooted, often implicit deterministic conceptions of nature, rather than from a coherent classical vision. Moreover, they develop conceptions recalling a local hidden variables description of phenomena, rather than a QM standard ones [17,18].

To acquire information about how students change from classic thinking to a quantum one, we carried out the study here presented and based on the following research questions: R1) which reasoning students follow in the conceptual reflections? R2) which elements favour the elaboration of new interpretative ideas? R3) which are the conceptual schemes of reference: classical, quantum, hidden variables ones?

2 THE CONTEXT

This study was in a last year class of a High School with 18-19 years old pupils (21 females-1 male). Our sample is composed by the 18 students always present in the several activities, listed in the work plan shown in Table 1. During the 1st and the last hours the students filled the pre/post test. In hours 2-4th the students face on the light polarization phenomena, to acquire confidence about the situations re-examined in hours 5-9th, aim to build quantum concepts exploring ideal case of single photon and polaroids/birefringent crystals interaction. All activities were

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conducted by a researcher using inquiring tutorials for students stimulating personal involvement [18-20].

On the basis of consolidated tools to analyze results of teaching-learning instructional pattern implemented in the school [21], used by the school teacher, the class profile can be considered of modest-level with three students of reasonable level and two under the medium level. The students were newer directly involved in laboratory activities before nor made use of the electronic sheet to elaborate data. They also had no previous optics knowledge, nor any notion about the nature of light.

Table 1 Plan of the in-class intervention. Activity.

hours	aims (activities: I individual work; C/G work in groups of 2-3/5-6 students; T the whole class)
1	Pre-Test (I)
2-3	Light-Polaroid interaction: with the naked eye (T-C); by means of light intensity sensors (G)
4	Data elaboration and discussion in computer science laboratory (T and C)
5	From experimental results to phenomenological Malus law, Meaning of the different factors involved (T). Single photon simulated experiments and probabilistic interpretation (C).
6	Operative association of a property to photons and its iconographic representation. Mutually exclusive properties. Hypothesis exploration: superposition of states vs mixed states (T – C)
7	Phenomenology exploration of birefringent crystals (T-C)
8	Impossibility to associate a trajectory to photons (T-C)
9-10	Superposition principles and generalization (T-C); Linear operators and physical observables (T-C)
11	Post-Test (I)

3 RESEARCH METHODOLOGY

Monitoring tools Monitoring tools [21] for the in class intervention were: a) The same pre/post-test, composed by 15 questions, 2 open answer questions, the remaining multiple choice questions and motivation of choice (only one exhaustive answer according to the standard QM interpretation - tab.2 shows 4 of these questions); b) the students answers to the tutorials questions [20,22]; c) notes written by the researcher and the class teacher.

Data analysis methodology In order to classify students answers and comments to the test and tutorials questions, to the stimula offered by the peer interaction, a modified phenomenographyc approach [23] was used according to the following profiles:

Clas – *Classic profile.* Microscopic systems and macroscopic ones have analogous nature. All their observables always own well defined values. In order to describe their evolution, the concept of trajectory can be used, even if it is necessary to use a statistical approach for lack of information about the initial state of the system under observation.

Hid – *Hidden variables profile (local).* Microscopic systems preserve some properties of the classic macroscopic systems, in particular the trajectory even if it is not knowable/detectable. Their non-classical behaviour is due to uncontrollable disturbances, or rather to some their properties that are not directly accessible/measurable.

Quant – *Quantum profile.* Classic and quantum systems have different nature. It is possible to associate dynamic properties to quantum systems only by means of measurements. These properties are in general incompatible with those that characterize the state before the measurement itself. Position and trajectory loose meaning. The process of measure can be described as a transition between an initial and a final state.

The analysis of data, related to each question of the monitoring tools, was: qualitative - classification of answers and choices motivations, made according to one of the three profiles; quantitative - evaluation of frequencies and classified answers distributions, analysis of changing in distributions, crossing data, in particular to perform a coherence check between answers in the pre/post test and in the other two monitoring tools. From this procedure emerged that the questions listed in Table 2 are those that their answers allow to illustrate students initial and final way of thinking, providing an effective picture of ideas changing. In the following, only the answers to these questions are considered. On the basis of the coherent prevailing of one profile among the others, the synthesis profile for each student was defined. A conflicting profile (***Confl***) was a posteriori introduced to classify cases in which different indicators show different results, and to characterize use of contradictory ideas depending on the considered context.

Table 2 Pre/Post test: questions Q2-Q3-Q4-Q6; multichoice answers, frequency occurred Pre/Post. Answers considered more exhaustive for a Quant-profile are in bold. Answers considered generally more coherent with a Hid-profile are in italics, depending from motivations. BA: blank answer.

Q2 - Measuring a physical observable, which aspect among the following ones characterizes in a peculiar way quantum mechanics with respect to classic mechanics?		
Answer options	Pre	Post
A) Under some conditions, discrete values of the measured observable are obtained	3	2
B) Results of measurements are predictable only in probabilistic terms	9	13
C) In general, systems initially prepared in the same state evolve in a different way when subjected to a process of measure	**2**	**0**
D) The interaction with the measurement apparatus produces a perturbation on the system	*1*	*0*

E) The result of a measurement is affected by an ineliminable indetermination	*2*	*3*
BA	1	0
Q3, Consider the following probabilistic previsions: K) the heads outcome in launching a coin has probability ½ to be realized; J) a photon with vertical polarization has probability ½ to pass through a polaroid at 45°.		
Answer options	Pre	Post
A) In the K case we do not know initial conditions precisely enough, in the J case initial conditions are known, but the phenomenon itself has a probabilistic nature.	**5**	**16**
B) In both cases we do not know initial conditions precisely enough.	*0*	*0*
C) In the K case we do not know initial conditions precisely; in the J case we do not know with enough precision how the interaction photon-polaroid happens.	12	2
BA	1	0
Q4. Which of the following statements better outlines the meaning of uncertainty relations?		
Answer Options	Pre	Post
a) there are physical quantities pairs of the same system, which cannot be simultaneously determined with arbitrary precision	**2**	**6**
b) it is not possible to measure with arbitrary precision a physical observable	*2*	*3*
c) it is not possible to make the indetermination of a measurement arbitrary small	2	3
d) it is never possible, even not in principle, to predict precisely measurements	*3*	*1*
e) it is not possible to measure with arbitrary precision posit. and moment. of a particle.	5	1
BA	4	4
Q6. In classic mechanics it is always possible to attribute a trajectory to a particle. Which statement can be made as far as a quantum particle is concerned (choice only one option):		
Answer options	Pre	Post
A) it is possible to attribute a trajectory, but it is not possible to determine with arbitrary precision all the information needed to determine it with arbitrary precision	*8*	*6*
B) it is possible to attribute a trajectory, but it is not experimentally accessible	*1*	*1*
C) it is possible to attribute a trajectory only when a position measurement is performed	2	4
D) it is impossible to attribute a trajectory to a particle cause to casual perturbations	*5*	*3*
E) it is not possible, even not in principle, to associate a trajectory to a particle	**2**	**0**
BA	0	4

4 DATA

Table 2 summarizes the choices made by students in the pre-test/post-test. According to the methodology illustrated in previous paragraph each answer was related to a one of the three profiles, in particular analyzing the choice motivations. Fig. 1 presents the synthesis profiles distribution after the activities for the entire test, indicating changes from pre to post profiles. Among all examined questions, 6 cases have been classified in the ***Confl*** profile. The Clas profile does not appear after the activities.

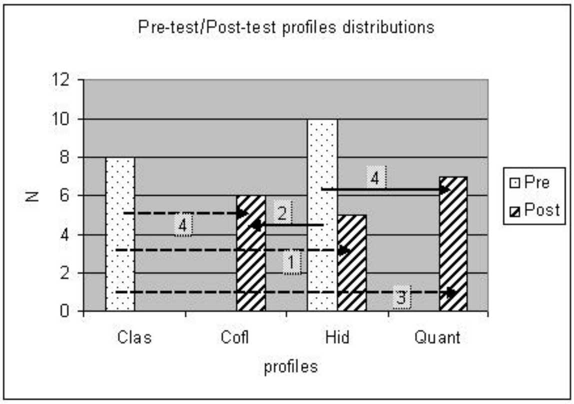

Figure 1 Pre test/Post test profiles distributions, indicating the occurred changes.

An example of a ***Confl*** profile was given by Alexia that answered in the following way: *Q2 her answer changes from D to A; Q3 she chooses the C answer: "other properties need to be known in addition to the starting conditions"; Q4 she does not answer before the activities and after she chooses B: "there will always be non continuous values, subjected to the quantum uncertainty"; Q6 she answers D before the activities, does not answer after.* According to Alexia the main cause to the quantum uncertainty is the existence of discrete observables (Q2-Q4). Probabilistic predictions are made cause a lack of knowledge (Q3). However she does not reply to Q6, because she does not manage to arrange the trajectory knot in her conception.

Michele show a Quant profile. His cognitive organizer is the uncertainty principle: he *chooses Q2-B and Q3-A, recalling in the post-test a specific experimental experience "the probability of transmitting a photon with vertical polarization which passes through a polaroid at 45º is 1/2"; Q4 his answer changes from C to E; Q6 his answer changes from A to D motivating with the "uncertainty principle".*

Federica exemplify a evolution towards hidden variables ideas: *Q2 her answer changes from A to B: "measurements are predictable only in probabilistic terms because the trajectory of quantum particles is not predictable"; Q3 her answer changes from C to B:"the photon transmission has a probabilistic nature, because it is not possible to predict the trajectory (we have experimentally demonstrated this fact)"; Q4 she changes from E to C answer: "this is due to the fact that the measurement of a physics quantity is predictable only in terms of probability"; Q6 her answer changes from A to B: "That is why we can describe the physics observable in terms of probability".* According to Federica the central knot is the impossibility to predict the not accessible trajectory of a quantum system. That is way it is necessary to make probabilistic predictions.

5 DATA DISCUSSION AND EMERGING RESULTS

The synthesis illustrated in Fig. 1, underlines changes in conceptions in 14 cases among 18. These changes have lead from deterministic conceptions to: A) the development of learning nuclei oriented towards quantum conceptions in 7 cases

(Quant profile); B) ideas compatible with hidden variables conceptions in 1 case, to be added to the 4 students that manifested similar ideas before the activities; C) classic and quantum ideas which prevail alternately depending on the considered situation. The students that manifested a Hid profile before and after the activity demonstrated ideas structured and stable enough in order to naturally lead them to a hidden variables formulation of QM.

6 CONCLUSIONS

Personal involvement in hands-on activities, minds-on in a specific explorative context activates personal students learning paths, independent lines of thinking. The changing of conceptual schemes of reference (R2, R3) happens not only towards typically quantum ideas, but also, towards conceptions in which the evolution of a quantum system is compatible with a hidden variables schema. Conceptual nuclei (R1) about an alternative interpretation of QM, constitute the initial ideas with which some students start studying QM. In several cases these nuclei can become stronger and lead logically to develop conceptions coherent with alternative approaches to QM. In some cases, instead, they give rise to conflicting classic and quantum ideas (R1). A tendency in the evolution of ideas of some students, from a completely classic conception of phenomena, to a hidden variables ideas, to a quantum vision, seem emerge (R3). This process is not linear and regards part of the students of the current study (R2). A hidden variable approach is perhaps inaccessible at high school, but here it is important to note how for a not negligible number of students the conceptions coherent with hidden variables theories (and not trivially classic conceptions) are the true antagonists to the orthodox QM ideas.

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