Upper Secondary School Students learning pathways through quantum concepts

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Abstract
Researches on how students learn basic concepts of quantum physics document how students change from a classical point of view to a specific vision on quantum processes. We experimented with upper secondary school students a research proposal based on the fundamental concepts and structure of quantum theory. We use a phenomenographic approach and di/trichotomous indices to reconstruct the learning path of students, from pre/post test and the working tutorial. In the evolution of student’s conceptions, from a determinist point of view to a quantum vision of processes, an important role is played by core ideas consistent with hidden variables interpretations of quantum mechanics.

Keywords: Quantum mechanics, high school students learning path.

INTRODUCTION
Basic principles and peculiar aspects of quantum mechanics (QM below) are included in several curricula (Zollman, 1999; Pospiech et al., 2008). Researches on how students learn the knots of QM have focused on the following critical points: A) the ontological status of quantum objects (Johnston et al., 1998; Mannila et al., 2002), B) fundamental concepts, such as the identification of the state, the distinction between the state, its representation and the associated eigenvalues (Niedderer, Deylitz, 1999; Steinberg et al., 1999; Singh, 2001), C) impossibility to associate a trajectory to a quantum system (Niedderer, Deylitz, 1998; Fischler, 1999); D) use of classical or semiclassical models (Steinberg et al., 1999; Fischler, Lichtfeld, 1992; Johnston et al., 1998; Muller, Wiesner, 2002). In the main studies, the analysis of students learning path was performed in the context of research experimentations based on innovative instructional strategies, assuming that students starts from a classical coherent point of view and adopting a defined interpretation of the quantum theory (Zollmann, 1999): the statistical interpretation (Fischler 1999); the dualistic interpretation (Müller, Wiesner, 2002); the interpretation based on the fluid model (Budde, Niedderer, 2005). The ideas of students, not fitting the adopted interpretation of QM, was classified as “Conflicting quantum thinking” (Iresons, 2000), indicator of “cognitive conflict” (Fischler, Lichtfeld, 1992), “non-quantum conception”, “hybrid model” (Bethge, Niedderer, 1997). The history of QM has taught us that it is possible to develop deterministic (non-local and contextual) theories, including the concept of trajectory (De Broglie, 1971; Bohm, 1952). It is important, therefore, to explore the extension of coherence of the initial ideas of students and whether the ideas they developed, not fitting a well-defined interpretation of QM, could be initial interpretive nuclei, consistent with unorthodox vision of QM.

In the context of a research based on MER (Duit, 2006) was design a teaching-learning proposal about QM. It aims: to build the theoretical thinking; to favor the formulation of interpretative hypotheses by students (Ghirardi et al., 1995, 1997; Michelini et al., 2000). It considers the photon interaction with Polaroid and birefringent crystals as reference phenomenology: the students explore the same situations first experimentally, then in ideal single photon context. From previous studies, we observed that several students difficulties in acquiring QM concepts are bound to the deep-rooted and often implicit deterministic and local conceptions of nature, rather a vision coherent with classical physics (CM hereafter) (Stefanel, 2001; Michelini et al., 2004). We hypothesized that some students, such as when trying to preserve the concept of trajectory in the description of a quantum system, are attempting to develop concepts closer to a hidden variables interpretation of QM, rather than a
mixture of confused ideas. Here we present the results of two studies conducted in secondary school classes in 2004/05 and 2005/06 to investigate the hypothesis above.

THE RESEARCH QUESTIONS
The two studies aim to give answer to the following research questions:
R1) which are the typically starting points of students facing QM?
R2) which reasoning follow students in the conceptual reflections and which elements favor the elaboration of new coherent interpretative ideas?
R3) which role in this reflection has the classical schema, the quantum scheme, the hidden variables scheme?

RESEARCH METHODOLOGY
To evaluate the experimentations in school we use the following monitoring tools, designed according to previous researches (Aiello Nicosia et al., 1997):
a) Pre/Post qualitative evaluation of the class (by care of the physics teacher)
b) A Pre/Post-test, concerning (Michelini, Stefanel, 2008, 2010): Q1. Topics characterizing QM with respect to CM (open ended question); Q2. Characteristic of QM measurement (*5 options and explanation*); Q3. Comparison of the probabilistic prevision in the case of a classical process (a tossing coin) and a quantum ones (interaction of photon and polaroid) (*3 options, explanations*); Q4. Physical meaning of the Heisenberg relations (*5 options, explanation*); Q5. Quantum indeterminism and QM state concept (*2 options, explanation*); Q6. Trajectory attribution to a QM particle (*5 options, explanation*); Q7. Physical meaning of the superposition principle (*5 options, explanation*); Q8. Physical meaning of $\Psi(x)$ (*5 options, explanation*). The Q2-Q6 complete statements are reported in the table 2.
c) PEC strategy based tutorials, challenging students in the analysis of phenomenology, construction of interpretative hypotheses (Michelini et al. 2008);
d) Audiorecording of class discussion and notes written during and after the activity.
The open answers and comments of students was classified in categories and then associated, according to a phenomenographic approach (Marton, 1986; Fischler, Lichtfeld, 1992; Johnstone et al., 1997), to the following a priori profiles:
Clas – Classic profile. Microscopic systems have an analogous nature to classic macroscopic systems. 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 behavior 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 a measure. These properties are in general not compatible with those characterizing the state before the measure. Position and trajectory lost their meaning. The process of measure can be described as a transition between an initial state and a final one (Michelini, Stefanel, 2008, 2010).
In this paper we focus mainly on the global evolution of student conceptions, from the initial to the final status according to tree different representations. A global profile was constructed considering the prevailing classification and a coherence check between related answers of the test and of the other monitoring tools. When the check was negative an a-posteriori category Confl profile was assigned. This check was also supported evaluating a dichotomous QC index (Michelini, Stefanel, 2008, 2010), varying from -19 (total Class profile) to +19 (total Quant profile), according to Müller, Wiesner (2002), evaluated adding: A) -2 for
each answer of Clas-type, -1 for each Hid-type answer, +2 for each Quant-answer in Q1-Q8; B) -1 or +1 for each correlation in the answer pairs Q2-Q4, Q6-Q8, Q3-Q5. To obtain a more effective representation of students ideas evolution we introduced a (X,Y,Z) tridimensional representation of the students answers. The three coordinates are defined weighting the \( n_{\text{Class}}, n_{\text{Hid}}, n_{\text{Quant}} \) numbers of answers associated to the Clas, Hid, Quant profiles as in the follows: 

\[
X = n_{\text{Clas}} \times p_c , \quad Y = n_{\text{Hid}} \times p_h , \quad Z = n_{\text{Quant}} \times p_q
\]

(\( p \) is the weight depending on the number of coherent answers: \( p = 1 \), when no coherent answers are given; \( p = 1,2 \), when \( m = 2 \); \( p = 1,5 \), when \( m = 4 \)). The value of \( m \) was assumed as the coherence radius of the answers.

The two studies were carried out with 18-19 years old students of a same upper secondary school. The first study was carried out in 2004-2005 in a class (04-05/class) of 18 students, (17 females and 1 male). According to the qualitative pre-analysis, the students attended physics courses in the last three years, do not have any previous experience in lab or any knowledge about optics, usually follow a traditional approach to physics with low results. The second study was carried out in 2005-06 in a class (05-06/class), composed by 16 pupils (11 females and 5 male). The qualitative pre-analysis evidenced a middle-good level class, with good experience in connection of data and models, knowledge of light polarization. The bulk of the two experimentations was developed in 9 and 12 hours respectively of laboratory and group activities, conducted by a researcher using tutorial for students (c instrument).

**DATA AND RESULTS FROM THE FIRST STUDY**

Here we discuss the first experimentation (Michelini, Stefanel, 2008). In table 1 are reported the answers in the pre/post-test to the questions Q2, and Q6. In the pre-test and in the post-test, the majority of students give answers to the Q2 question coherent with a quantum profile. The motivations given (7 in the pre-test, 13 in the post-test) are summarized in the following categories, evidencing also the main changes: Cat-1, characterizing a Quant profile, including B option where the previsions of a measure are probabilistic, because “in microscopic the behavior is not describe by CM”; Cat-2, characterizing a Hid-profile, included B option also, but the previsions of a measurement are probabilistic, because: “of the uncontrolled behavior of the system”, “we do not possess sufficiently precise knowledge”, Cat-3 characterizing a Class profile, as E: “in the measures made by us we obtain values very close one to each other and the result is an average of the results”.

**Q2. Measuring a physical observable, which aspect among the following ones characterizes in a peculiar way quantum mechanics with respect to classic mechanics?**

<table>
<thead>
<tr>
<th>Answer option</th>
<th>Pre Post (04/05)</th>
<th>Pre Post (05/06)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Under some conditions, discrete values of the measured observable are obtained</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>B) Results of measurements are predictable only in probabilistic terms</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>C) In general, systems initially prepared in the same state evolve in a different way when subjected to a process of measure</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>D) The interaction with the measurement apparatus produces a perturbation on the system</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>E) The result of a measurement are affected by an not eliminable indetermination</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Q6. In CM it is always possible to attribute a trajectory to a particle. Which statement can be made as far as a QM particle is concerned (only one option)**

<table>
<thead>
<tr>
<th>Answer option</th>
<th>Pre Post (04/05)</th>
<th>Pre Post (05/06)</th>
</tr>
</thead>
<tbody>
<tr>
<td>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</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>B) it is possible to attribute a trajectory, but it is not experimentally accessible</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>C) it is possible to attribute a trajectory only when a position measurement is performed</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>D) it is impossible to attribute a trajectory to a particle cause to casual perturbations</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>E) it is not possible, even not in principle, to associate a trajectory to a particle</td>
<td>2</td>
<td>3</td>
</tr>
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Table 1. Answers frequencies to the questions Q2-Q3-Q6, in the Pre/Post test. Answers considered: more exhaustive for a Quant-profile are in bold; more coherent with a Hid-profile are in italics. NA: no-answer.
Students in the post test Q6 given answers more related to an Hid profile, as the follows: “D- The particle, for instance electrons, are subjected to movements and collisions against other particles, therefore it is impossible to attribute a well-defined trajectory”; “A- In QM we can hypothesize the trajectory of a particle, but we cannot be sure on the followed path”. The only Quant-profile sentence is: D- “Because the uncertainty principle”. As discussed in the method paragraph, we document the global changes of student’s ideas from pre-test to post-test.

In fig. 1 (left) are presented the two different distributions of the CQ index related to the pre/post-test ($\chi^2=28.5$, p<0.005). In each cases the value of the CQ index increases (mean: 10, $\sigma=4$), from a minimum of 3, to a maximum of 16; 12/18 changes are in the range 7±13. In this first study the final ideas status of students depend strongly from the initial one, but the amount of this change is very close to the mean value, indepently from the initial status. In fig. 1 (right) are reported the gobal profiles emerging from the phenomenographic analysis. Among all examined questions, 6 cases have shown a prevailing of the Clas and Quant profiles at the same time and have been classified in a conflict profile (Confl). The conceptions initially classified as Hid-profile have been mostly confirmed (4 cases) or they have evolved to the Quant profile. Only in two cases they have evolved to conflict ideas.

In fig. 2 the initial and the final status are reported. In the pre-test (fig. 2 – left) the students ideas are represented essentially in the plane X-Y. The baricentrum of the distribution is B1 ≡ (5.2±2.0;1.4±1.0;1.8±1.2). In the post-test diagram the baricentrum is: B2 ≡ (2.4±1.2;1.4±1.1;4.9±1.8). The evolution of the baricentrum of the distributions occurs from the point B1 to the point B2 at constant Hid-Y coordinate ($\chi^2_{Yates}=8$, p<0.005). The three areas evidenced in fig. 2 regards the three different profiles emerged in the post test, and their coherence radius evidenced the dimension along the coherence is (fig.2 right).

The CQ index distributions show that the final ideas of students depend strongly from the initial conceptions but the amount of the changes do not depend appreciably by the initial status. The changes are activated by direct involvement of pupils in the analysis of problem-situations in the real and ideal laboratory. The phenomenographic analysis evidence a coherent evolution toward quantum conceptions nuclei occurs in 7 cases. Ideas compatible with local hidden variables conceptions emerged in 5 cases, 4 of them manifested similar ideas before and after the activities. In particular this students attribute trajectory to systems that have typical quantum properties and behaviour, for what concern other aspects. A conflictual cathegory emerged in six cases. The three-dimensional representation of students conceptions offers a new view of the their evolution from the Clas-Hid plane to the Quant-Hid, that occurs at constant Hid-coordinate. From this emerges an important role of hidden variables conception as intermediate step toward quantum conceptions.
DATA AND RESULTS FROM THE SECOND STUDY

To go deep in the analysis on how students approach quantum concepts a second study was carried out with another class in 2005-2006. Also here we consider the questions Q2-Q6 of the pre/post test. In tab. 2 are reported the students choices. The motivations given to the choices made in the pre-test question Q2 (7 in total) are included in 5 categories: Pre2-1. A- “I think to light and Energy quanta, characterizing electronic orbitals in the atoms: its assume discrete value” (4/16); Pre2-2. “These are elementary particles and therefore we cannot know exactly its position.” (3/16); Pre2-3. B- “We cannot know simultaneously two physical values as space and velocity” (2/16); Pre2-4. C- “We treat low intensity measurements and therefore a perturbation is un-eliminable to observe it” (2/16); Pre2-5. E- “Never, precise, definite and continuous measures are obtained - We need to consider an indeterminacy in each measure” (3/16); 2/16 do not answer. The categories Pre2-1 and Pre2-3 characterize a Quant profile, the categories Pre2-2 and Pre2-4 a Hid profile, the Pre2-5 category a Clas profile.

The motivations in the post-test (13 against 7) can be summarized in 4 categories: Post2-1. “We cannot measure simultaneously two quantities of a system, therefore a measure of one of it disturbs the other” (3/16); Post2-2. C-“The measurement produces a not eliminable effect on the system because the measurement produces the decay the photon in a state or in another state” (5/11); Post2-3. B-“The results are interpretable only in probabilistic way because it is not possible know with certainty the behavior of a single photon” (3/16); Post2-4. E-“Because we don’t know, what happens in the middle” (5/16). Categories Post2-1 and Post2-2 characterize quant-profile, Categories Post2-3 and Post2-4 characterize Hid-profile.

As far as concern the question Q6, the answer categories evidenced in the pre test are the following: Pre6-1: “E, uncertainty principle” (3/16); Pre6-2: “B, We don’t know set up experiments that analyze this phenomena” (5/16); Pre6-3: “C, because we cannot see with eyes a particle and reconstruct the most probably trajectory” (1/16); Pre6-4: “D, the particle is subjected to contact with other systems, that perturb the motion” (3/16). The Pre6-1 category characterizes a Quant profile, the Pre6-2 category characterizes a Hid profile, the Pre6-3 and Pre6-4 categories characterize a Clas profile. (3/16).

The categories of answer related to the post-test are the following: Post6-1 (Quant profile) “E, because the hypothesis $\Delta A=\Delta + \square$ [a pure state is equivalent to a mixture of states] give prevision in contradiction with the experimental results”; “E, because the particle is a superposition of state and only the interaction with the detector, produce the precipitation in one of the possible states.” (11/16); Post6-2 (Class profile) “C, we cannot foresee the trajectory of the particle, we can only search it a posteriori, cause the indeterminacy. This, in any case, does not exclude the concept of trajectory in general” (1/16); Post6-3 (Hid profile) “D, we do not have any possibility to detect the way in which a particle is moving” (2/16).

As in the first study we use three different ways to analyze the global differences from the pre to the post test. The CQ index distributions are reported in fig. 3 (left) ($\chi^2=15.3, \ p<0.1$).
The QC index increases in all cases (mean value of the change: $12 \pm 10$, from a minimum of +6 to a maximum of +34), apart the case of student 11 classified Hid (QC change: -3.5); 7/17 of the changes are in the range $11 \div 15$. From QC distribution related to the second study emerges that the final ideas status of students do not depend from the initial status. The synthesis of the profile related to the pre/post test is reported in the fig. 3 (right) ($\chi^2=15.7$, $p<0.005$).

In the three dimensional representation the students ideas (fig. 4) change from a distribution centered on the point $P_1=(3.7\pm 2.8; 3.5\pm 2.9; 2.1\pm 1.9)$ to the distribution centered on the point $P_2=(0.3\pm 0.5; 3.7\pm 3.3; 6.8\pm 3.6)$, with dispersion only in the Quant-Clas plane. The evolution of the baricentrum ditributions occurs also in this case at constant Hid-Y coordinate ($\chi^2_{\text{Yates}}=8$, $p<0.005$). The coherence radius represented in fig 4 evidence two groups of students completely oriented or on a Quant profile or on a Hid profile and a third group that his radius of coherence define a region on the plane Quant-Hid at $X_{\text{class}}=0$.

The CQ index evidence great changes, apparently not related to the initial status. The phenomenographic analysis shows a prevalent evolutions towards quant profile and minor cases of Hid or Confl profiles. The three dimensional representation evidences a final status of students ideas essentially contained in the plane Quant-Hid. Comparison the three dimensional representations of the two studies (fig. 2 and fig. 4) learning evolutions depending from initial status are more evident with respect to what emerges from the other representations. This representation seems more effective to show the evolution towards Hid ideas, documentated in the sentences of students.

**CONCLUSIONS**

The two studies here presented was carried out to follow the learning paths of students facing quantum mechanics basic knots as proposed in the teacher-learning proposal developed in previous researches. In this approach, students are free to develop coherently their ideas. We use different methodology for the analysis of data: the evaluation of a global dichotomous CQ
index, a phenomenographic classification of the student conceptions, a three dimensional representation, here proposed to follow the evolution of student’s ideas from classic ideas to quantum ideas. Both studies confirmed that personal learning paths and the construction of independent lines of thinking are activated when students are involved in hands-on/minds-on activities, in a specific explorative context, producing a solid understanding of phenomenology and the capability of rigorous argumentation (R2) (Michelini, Stefanel, 2008, 2010). A different familiarity with phenomenology and the competences in the construction of interpretative rigorous argumentations motivate the differences in the two studies (R2).

The starting point of students is characterized prevalently by a mixture of ideas coherent with classical mechanics, generically deterministic conceptions (R1). The trajectory concept plays a fundamental role in the description of students not only in the initial conception (R1). In several cases these nuclei can become stronger and lead logically to develop conceptions coherent with alternative approaches to QM or to play the role as a bridge toward a quantum orthodox vision (R3). In fact, the evolution of conceptual schemes of reference happens following independent lines of thinking, towards typically quantum ideas, when it is recognized the role of the superposition principle and the quantum indeterminism, but also, for a not negligible fraction of students, towards conceptions in which the evolution of a system is described on the basis of hidden variables conceptions (R3). In particular the impossibility to associate a trajectory is associated to a stochastic disturbance acting on microscopic particles (R3). Ideas coherent with alternative vision of quantum phenomena are the true antagonists of the orthodox QM ideas. In our study it emerge in the learning path of students with very different competencies, attitude and previous knowledge.

REFERENCES