PROCEEDINGS OF SCIENCE

Teaching modern physics in secondary school

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The physics of the last century is now included in all EU secondary school curricula and textbooks, even if in not organic way. Nevertheless, there are very different positions as concern its introduction and students' conceptual knots in classical physics are quoted to argue the exclusion of modern physics in secondary school. Aspects discussed in literature are goals, rationale, contents, target students, instruments and methods. Very different goals, i.e. the culture of citizens, popularization, guidance, education, build different perspectives and aspects to treat selection: fundament, technologies and applications. Methods used are story telling of the main results, argumentation of crucial problems, integrated or as a complementary part in the curriculum. Modern physics in secondary school is a challenge, which involves curriculum innovation, teacher education and physics education research to individuate ways that allows the students to face the interpretative problems and manage them in many contexts and in social decisions. In this perspective, modern physics is an integrated content in curricula involving the building of formal thinking. Our research focus on building of formal thinking is on three directions: 1) Learning processes and role of reasoning in operative hands-on and minds-on phenomena interpretation; 2) object - models as tools to bridge common sense to physics ideas and ICT contribution focusing on real time labs and modelling; 3) building theoretical way of thinking: a path inspired of Dirac approach to quantum mechanics. We developed four different kind of proposals: 1) the physics of modern research analysis in material science: resistivity and Hall effect for electrical transport properties, Rutherford Backscattering Spectroscopy to look to structure characteristics, Time Resolved Resistivity for epitaxial growth; 2) Explorative approach to superconductivity phenomena (a coherent paths), 3) Discussion of some crucial / transversal concepts both in classical physics and modern physics: state, measure, cross section, 4) foundation of theoretical thinking in quantum mechanics.

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[1] Speaker

1. Introduction

Modern Physics is included in the upper secondary school curricula of all countries of the European Union [1] and therefore in the last 10 years it appear in all secondary textbooks, even if in not organic way [2-3]. There are very different positions as concern its introduction: on one side, conceptual knots in classical physics are quoted to argue the exclusion of modern physics by the secondary school; from the other side, there is a wide discussion on goals, contents, instruments and methods, target students. The main research open questions involve: goals and rationale in relationship with its role (culture of citizens, guidance, popularization, education) and aspects to be focused (fundamental, technological, applicative) [2-3].

The different approaches in literature [2-3] leave open many questions regarding the educational strategies: story telling of the main features? Argumentation of crucial problems from the classical interpretation? Integration in classical physics? As a complementary part of curriculum? To whom? All citizens? Only for future scientist or talent students?

Modern physics in secondary school is a challenge, which involves the possibility to transfer to the future generations a culture in which physics is an integrated part, not a marginal one, in a way that allows the students to manage them in moments of organized analysis, in everyday life, in social decisions. It involves different planes: curriculum innovation, teacher education, physics education research [2, 4-5]. Here we present our research approach on modern physics in upper secondary school, exemplifying main contributions and results of research on students learning.

2. Theoretical framework

Our perspective is to design, development and test research based proposals, in cultural perspective focused on foundation of basic concepts, methods and applications in physics research, integrated in physics curriculum and not as a final appendix, offering experience of what modern physics is in active research. Vertical paths are designed, as learning corridor [4-7] for individual learning trajectories and steps by steps concept appropriation modalities [8]. Our Research approaches require that the first step in research task is to rethink scientific content as a problematic issue, to rebuild this with an educative perspective, according to the Model of Educational Reconstruction [5]. This task is often integrated with empirical research on student reasoning and Teaching/Learning (T/L) paths [4, 9-11], DBR: Design based research [12]; action–research in a collaborative dialectic between school and university [4], to contribute to classroom practice, develop vertical path proposals experimented with students [7]. The approaches are not purely based upon disciplinary contents [13] in order to identify strategies for conceptual change [14]. Attention is paid to identify strategic angles, critical details used by common knowledge to interpret phenomena [10], to study spontaneous reasoning paths [4], to find new approaches to physics knowledge [9, 10-11], avoiding reductionism, offering opportunities of learning interpretative solutions and results, becoming able to manage basic concepts and building competences of instruments and methods [4].

Four different types of proposals for a global perspective on modern physics were developed: A) The physics in modern research analysis techniques [15]; B) A coherent educational path on superconductivity [16]; C) Discussion of crucial/transversal concepts, both in classical and modern physics: state, measure, cross section [17], mass and energy [18]; D) Building the theoretical thinking, in a coherent path on the foundation of Quantum Mechanics [19-20]. Here the 1, 2 and 4 types of proposals will be discussed, reporting the main learning students' findings.

3. The physics in modern research analysis techniques

We developed four proposals concerning the research techniques involved in the analysis and characterization of materials and regarding: the optical physics concerning in particular diffraction [21]; the Rutherford Backscattering Spettroscopy (RBS) analysis technique [22]; The Time Resolved Reflectivity (TRR) [23]; Measurement of Hall coefficient and resistivity versus temperature (R&H) of solids to characterize electrical transport properties of materials [24].

3.2 Rutherford Backscattering Spectrometry

The proposal on Rutherford Backscatterig Spectroscopy (RBS) [22] focus on that analysis techniques consisting in collecting the energy spectra of ions (He++ of 2-3 MeV produced by a linear accelerator) backscattered along a direction by the atoms of a target (Fig.3). RBS provides information about the distribution of the constituent elements of the first 500 nm of the surface of a sample, through a semi-classical treatment of data. In our educational proposal students are introduced to RBS discussing the principles of measure, introducing concepts as the cross-section and the stopping power. Student manage and analyse real RBS spectra having the opportunity: to explore the Rutherford-Geiger-Marsden experiment; to understand the role of energy and momentum conservation in the context of research analysis; to understand how microscopic structures can be studied through indirect information; to interpret RBS spectra as problem solving activity [25].

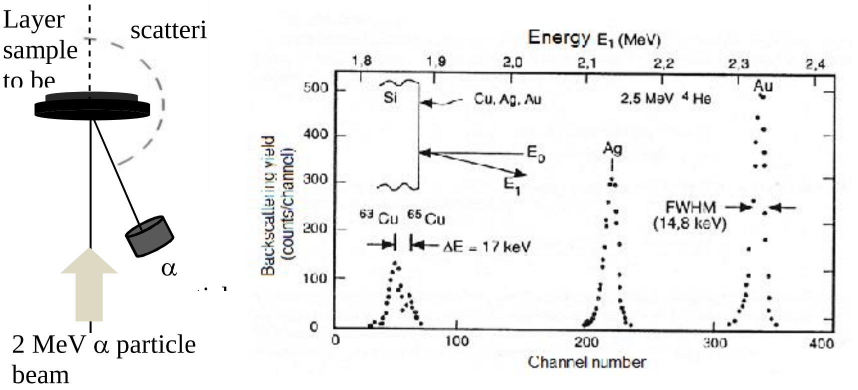

Fig. 3. RBS experimental apparatus schema and RBS spectrum (from [26]): the target is a monoatomic layer of Cu, Ag and Au in equal concentration on a silicon layer. The incident beam is composed by 2.5 MeV α-particles, scattered at θ=170°.

3.3 Transport electrical properties of solids

The characterization of the electrical properties of transport of the materials is based on the measurement of the resistivity as a function of temperature, combined with that of the Hall coefficient (R&H) for identifying sign, number, mobility and energy levels of the electrical carriers, on the base of microscopic models for metals, semiconductors, and materials as silicides [27]. Resistivity measurements in the magnetic field are the basis of the research on superconductors [24]. For our approach to the physics of matter a patented USB probe [34], usable both in high school lab and in advanced lab [29], was developed for the measurement at four points of the resistivity as a function of temperature and Hall coefficient of solids. (Fig. 5).

3.4 Experiments with students

These proposals were experimented in five Summer Schools on Modern Physics held at the University of Udine from 2009 till 2014 with 156 selected students (18-19 aged) from all Italy, and also in curricular activities for what concern the path on diffraction as discussed elsewhere in this volume [30]. Here we consider the main results concerning the RBS approach. From data analysis of the evaluation card filled by students at the end of the summer schools it emerges that the proposal offers to students an engaging and motivating opportunity to test and to enhance their interpretative skills (80%), the capability to transfer their own knowledge to new contexts as those of the Rutherford scattering and the RBS technique (65%). From the analysis of the ways to face the problem solving on the RBS spectra, students shows a functional understanding of the concepts of cross section (85%), stopping power (82%), kinematic factor (76%) [25].

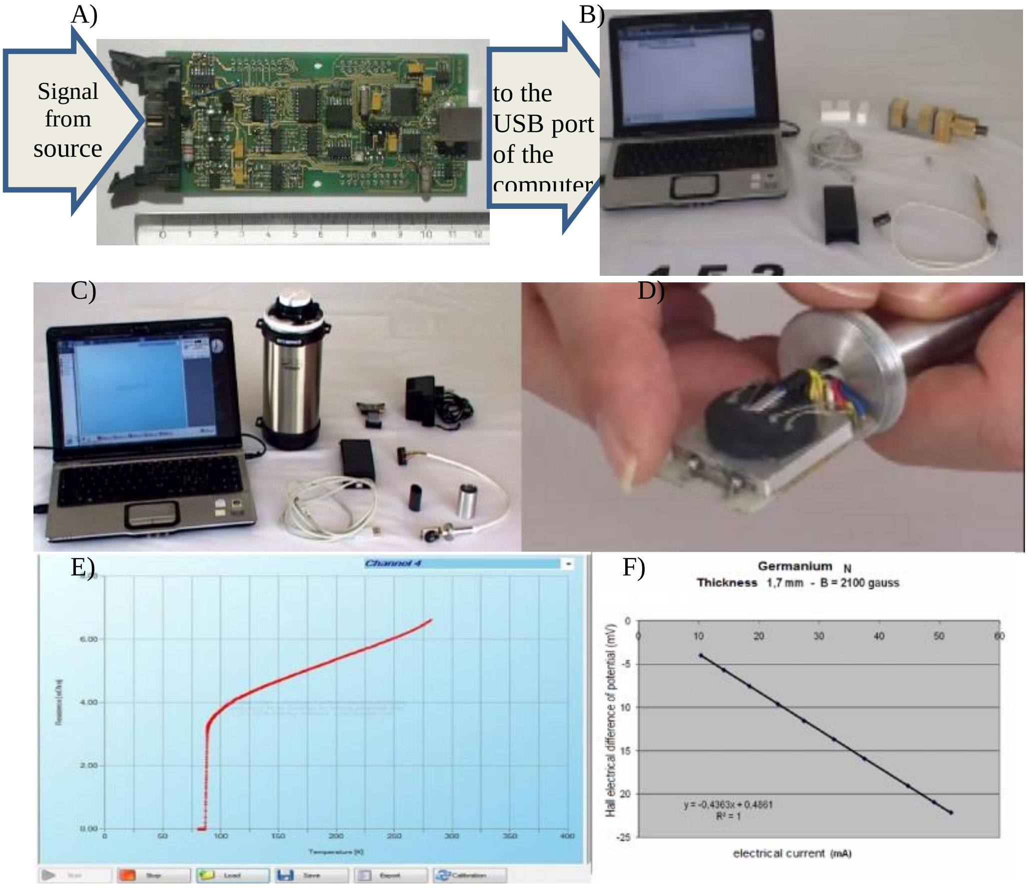

Fig. 5. A) The USB interface developed for the Hall coefficient measurement (B and graph F) for a Germanium N samples) and the resistivity versus temperature (C-D and the graph E for an YBCO disc).

4. A coherent educational path to superconductivity;

The measurement with the R&H-USB [15, 24, 27] is a basic part of an educational path aiming to construct a phenomenological model of the superconductive states, through experiments and explorations of the magnetic property and electrical conductivity of YBCO [16].

4.1 The teaching learning sequence on superconductivity

The educational path [16] approaches the Meissner effect through an experimental exploration [31] of the magnetic properties of a superconductor sample (a disc of YBCO with very weak pinning), aiming: to identify the diamagnetic nature of superconductors; to recognize the role of electromagnetic induction in the persistent supercurrents. Students explore the interaction between an YBCO disc and a magnet, at room temperature To, when it can be observed a weak attraction, and at the liquid nitrogen temperature TLN: posing a magnet over the YBCO disc; pushing the YBCO laterally with the magnet; reversing the magnet and posing it over the YBCO. At T=TNL, in all the cases there is a strong repulsion between YBCO and magnet; the YBCO become diamagnetic; the levitation occurs without any constrain (it is not a magnet suspension).

Students analyse the interaction between an YBCO and a ferromagnetic object recognizing that the YBCO do not manifest his magnetic properties without the magnet. To characterize how change the magnetic properties of the YBCO, changing the temperature it is useful a sandwich formed by a little iron ring, an YBCO disc and a little magnet: at To, the magnet can lift the sandwich; at TLN, the magnet cannot, because the magnetic field do not penetrates the YBCO.

The previous observations shows the (strong) diamagnetic properties of the YBCO, emerging only in presence of a magnet: the YBCO reacts dynamically to the changes of an external magnetic field, motivating to look at a phenomenon as that of electromagnetic induction. Students explore the braking fall of a magnet on a thick metallic layer or inside a metallic tube. The magnet fall at constant speed and that speed changes changing the material of layer or of the tube: it is larger for brass, intermediate for aluminium, minor for copper. The constant velocity of the magnet is due to the balance between the weight force and the one acting between the magnet and the induced current in the tube, showing the role of the resistivity. Extrapolating that result, when the magnet will fall inside a tube with null resistivity, it will "fall" at zero speed (it levitates), being absent the Joule effect. This suggest that a magnet levitates because the YBCO resistivity suddenly becomes zero at T= TLN, as it can be seen with a measurement performed with R&H.

According to the phenomenological model, based on the electromagnetic induction, the levitation phenomenon will not occur, when the superconductive state is created with the magnet over the YBCO. Using an appropriate YBCO disc, it is possible to observe that the magnet is repelled by the cooled YBCO disc even when it was initially over it. An explanation can be constructed minimizing the (free) energy of the system [32]. The phenomenological exploration leads to characterize a superconductor with the conditions: R=0 as well as B=0 inside the YBCO.

The educational path offers to the students the opportunity to analyse also the pinning effect, the correlated phenomenology and technology of Maglev using a model object of the superconductor train, discussing the conditions for a stable levitation.

4.2 Experiments with students

Experiments in school were performed in 44 Italian sites involving students of different age (36 K12-K13; 6 K11), for a total of 1315 students of 292 classes. From the experiments performed in informal activities, it emerges the strong students' involvement in the exploration of superconduction (95%) aims to construct an explanation of phenomena (83%) and of technological applications (75%). Many experiments (20/44) were performed by in service and prospective teachers involved in the Supercomet projects as feasibility test [33]. Other 14/44 are research experiments conducted by PhD students [34-35] or researchers [36], with 412 students, showing that students characterize the superconductive levitation as a repulsion due to the property acquired by the YBCO (81%), representing it with a magnetization vector (57%) or with the global representation of the field lines (24%). Students develop models describing the condition B=0 inside the superconductor (84%), based on the magnet image model (38%) [37] or on the electromagnetic induction one (62%) [36].

5. Quantum mechanics in secondary school.

Quantum mechanics is the paradigmatic theory for the actual interpretation of the world and the theoretical/conceptual base for the development of new knowledge [38-39]. Its implications are very important in many branches of sciences [39] and the "quantum-mechanical way of thinking" is a new cultural approach to physics [38-43].

In the wide scenarios of the proposals on quantum mechanics [38, 41-42] there is no sharing on content to be treated, an unclear overlapping of contents related to the physics of quanta, quantum physics, quantum mechanics and the strategies to be adopted [38, 20]. Among the different approaches, three main can be identified: the reconstruction of the interpretative problems in the historical developments of quantum concepts, the crucial experiments and the birth of the theory of quanta; a wave function formulation and/or in general an approach based on the role of the formalism; a conceptual approach as proposed by Dirac [19,20,40,44]. The first gives a general vision, offering interdisciplinary bridges, but, especially at elementary level, the narrative treatment prevail over aspects related to the subject, being the complete semiclassical treatment too difficult both on the formal plane and on the conceptual one for students [45]. The wave formulation of the quantum theory is a rigorous one, but it demands strong competencies both in physics and in mathematics, only partially decreased by the use of computer [39, 42-43].

5.1 The choices at the base of the proposal

Our proposal includes two plans: A) Crucial experiments for the classical physics interpretation (i.e. Photoelectric and Compton effects; Frank & Hertz experiment; diffraction of light and particles); B) Approaching quantum theory and its basic formalism [19-20, 46], by discussing simple experiments in specific contexts (light polarization, spin, interference), aiming to build theoretical thinking according to the Dirac approach, producing the awareness of the reference assumptions of the theory and on the conceptual role of the formalism.

Crucial aspects considered are: the basic knowledge in physics for the foundation of the new interpretations; the phenomenological analogies to evidence that interpretation; the basic formalism to be adopted to express that interpretation. The core of the proposal is: the construction of the foundation of quantum mechanics theory (not the quantum physics or physics of quanta); the first step toward a coherent interpretation based on the superposition principle and the construction of the formalism supporting it; an introduction to the ideas of the theory through the treatment of crucial aspects, cardinal concepts, peculiar elements of the quantum behaviour, starting to construct polarization as a quantum dynamical property of photons [19, 46].

5.2 The layout of the educational path.

To introduce the phenomenology of light polarization, polaroids are used as explorers on an overhead projector (OHP). When two polaroids have hortogonal permitted directions, the transmitted light vanish. The light filtered by a polaroid (the polarizer) show a property, that is detected by another polaroid (the analyzer). That property is different by the intensity of light and is named (linear) polarization. The phenomenology of (linear) light polarization is resumed by the Malus law, that students can “discover” measuring with an on-line sensor the intensity of the light transmitted by two polaroids versus the angle formed by the permitted directions of them (fig. 6) Repeating the analogous experiments using very week beam, the Malus law emerges as law describing the frequency of photons transmitted. It not depend on collective phenomena of photons, and for that polarization must be considered as a property of each photon.

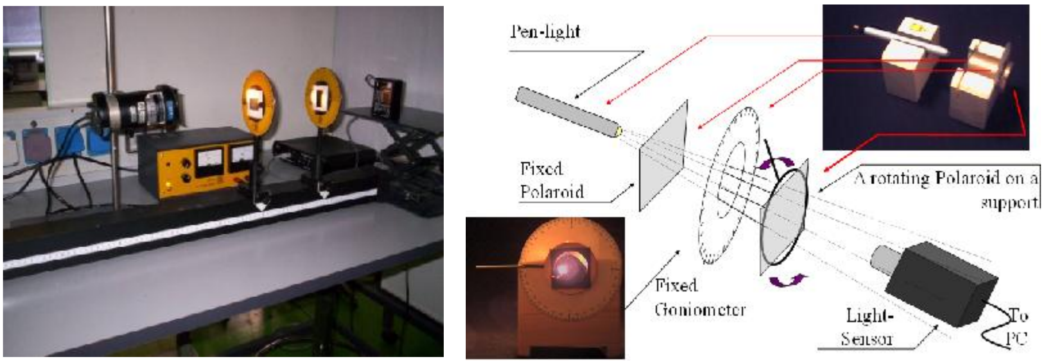

Fig. 6 Lab set up and unexpensive set up for the measurement of le Malus law.

The first part of the educational path focus on the polarization as dynamical property of photons in a well defined state. When, un-polarized light is incident on a polaroid with vertical permitted direction the photons emerging from the polaroid are always vertically polarized. Filtering photons with vertical (horizontal) polarization with one, two, tree (ideal) polaroids with vertical (horizontal) permitted direction all the photon will be transmitted. Due to the certain results of that experiment, it is possible establish that: photons, with vertical (horizontal) polarization, possess a property, that can be represented by a symbol, Δ (*), and are in a well defined state V (H). Analogously photons in the 45° polarization state posses the property Δ.

Photons with property ◊ (property *) in the state V (state H) incident on a polaroid with horizontal (vertical) permitted direction will be never transmitted. For that the properties ◊ and * are said mutually exclusive. In the classical case, the linear polarization is a vector property of light. If the quantum state is assumed as a vector, the vector **w**, representing the state of 45° polarization, can be expressed as the sum **w=u+v** of the vector states **u** and **v** corresponding to the horizontal and vertical polarizations state. It can be seen that photons in the state of 45° polarization with property ◊ behave statistically in a different way with respect to a beam composed by two beams of photons with property Δ end with property *. For that the properties ◊ and * (or Δ) must be considered incompatible.

The following interpretative hypothesis for photons having ◊ property and in the (u+v) state are considered and discussed comparing with experimental results: HP1) It could be thought as an ensemble of photons constituted by a statistical mixture (* and Δ); HP2) It could be thought as an ensemble of photons which have simultaneously two properties, with the same weight (◊Δ and ◊* respectively); HP3) it could be though as an ensemble of identical photons having only a defined property ◊. It emerge that: A) a superposition state must be considered completely different by a statistical mixtures of states; B) a specific polarization property is incompatible with each other properties; C) each photon in a well precise state interacts with the polaroid-analyzer, in a completely random ways. This illustrate the uncertainty principle, as expression of the impossibility to observe simultaneously with arbitrary precision two incompatible properties.

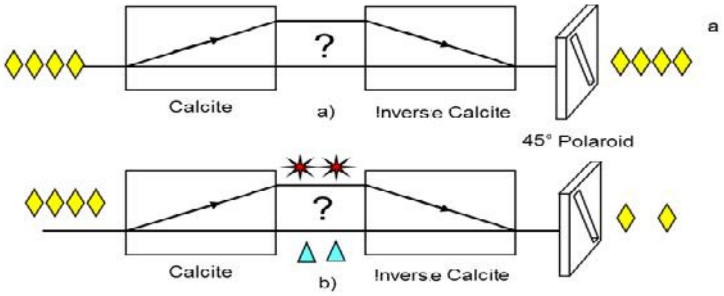

Fig. 7 The interaction of single photon with two calcite crystals is the contest proposed to students to discuss the impossibility to attribute a trajectory to a quantum system.

The superposition principle emerges as the basic principle of quantum mechanics theory. Consequences of that principle, are discussed using two calcite crystals: one direct and the other inverse (Fig. 7). This experiment shows features of the quantum behaviour: as the impossibility to attribute a trajectory to a quantum system; the non-local nature of the quantum processes (a measure on one of the two light path influence suddenly what happens also in the other path); the entanglement (translational and polarization states are entangled); the peculiar character of the quantum measurement process. The renounce to the classical way of thinking open to a new vision and formal description of state. That description could be constructed in the case of light polarization state just posing a vectorial hypothesis on the formal entity representing the quantum state [46]. The layout here synthesized is operatively proposed to students using stimuli tutorial worksheets. These are used to monitor the students learning paths and involve they in an inquiry based educational environment [47]. The applet JQM [48] was developed to help students in the delicate passage from light phenomenology to that of single photon. The proposal is discussed in a research perspectives in different papers [19-20, 46-48] and is also available on the web to be adapted by teachers (http://www.fisica.uniud.it/URDF/secif/mec_q/percorso/teoria.htm).

5.3 Researches on students learning.

Research experiments with high school students (18 years old) were performed since 2000 by school teachers prepared by the researcher team, by researchers in different Italian sites [65-70]. Each experiment last 8-12 hours and was performed using IBL tutorial worksheets, pre/post test [49]. Some main results are resumed, concerning experiments with 250 students from 2004 to 2014. Students appear to be familiar with the meaning of interaction of photons with polaroids (80-90%) and less with calcite crystals (70%). The concept of quantum state is better understood

(70%) than the classical concept of state (40%). A not marginal part of students have difficulties to abandon the classical idea of pre-existing properties to be able to do a prevision (40%). The majority of students was able to explicit consequences only when they have in the hands the formalism (70%). Moreover student profit of the iconographic proposal and discuss in a proper way on mutual exclusive properties (80%) and incompatible properties (55%); the employ of the iconographic representation and formalism facilitate reasoning in the framework of QM; the rigorous reasoning proposed promote the spontaneously used in new contexts (50%); the construction of a coherent framework (80%), even if in other perspectives than that of the Dirac framework. Different analysis of the student profiles was performed using dicotomic index as well in the perspective of the phenomenographic methodology [49].

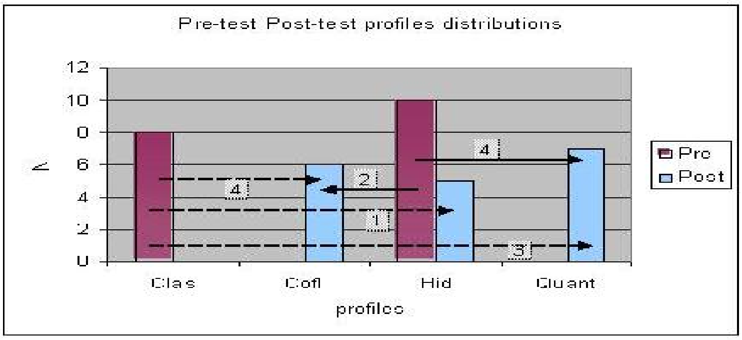

Fig. 10 Phenomenographyc analysis of the students profiles evidenced that the construction of a quantum vision of phenomena often pass through an intermediate state (variables interpretation) [49]

6. Conclusion

Our contribution for modern physics, here discussed and exemplified, may be divided into 4 kinds of researches: A) Research and development for new systems and tools; B) Design based research to support practice with coherent paths; C) Empirical research to study learning trajectories, appropriation and kind of reasoning; D)Teacher education and professional development. It follows different perspectives: 1) The physics in research analysis technics; 2) Explorative approach to superconductivity; 3) Discussion of crucial/transversal concepts both in classical physics and in modern physics: state, measure, cross section; 4) Foundation of theoretical thinking. The experiments with students evidence positive learning progression concerning the crucial knots of the treated topics as discussed in the different sections. It suggest to: A) focus on the coherence of reasoning to create a reference framework, integrating hand-on and explorative work, mind-on interpretation of results, by means of real and ideal experiments and modelling; B) use iconographic representations as conceptual tool; C) use analogies for phenomena interpretation; D) introduce formalism, using it to reinterpret explored situations; E) analyse students ideas in the framework of different interpretative schema; F) integrate modern physics in classical physics developing coherent paths of conceptual understanding.

One of the main fallout at national level of our expertise in research of teaching-learning modern physics is the IDIFO Project (2006-2016), a PER contribution for Innovation in Physics Education and Guidance. That project involves 20 Italian universities cooperating in: Master for teacher formation on modern physics; physics in contexts (in art, sport...), real time labs and modelling; formative guidance, school experimentation; Summer schools for talent students and for teachers; Educational Labs, co-planned with teachers, for innovation in the school [50].

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