RESEARCH BASED PROPOSALS TO BUILD MODERN PHYSICS WAY OF THINKING IN SECONDARY STUDENTS

Marisa Michelini, Lorenzo Santi, Alberto Stefanel
Research Unit in Physics Education, DCFA, University of Udine, Udine, Italy
marisa.michelini@uniud.it

ABSTRACT

Conceptual knots in classical physics are often cited as motivation for the exclusion of modern physics from secondary school, but the physics of the last century is now part of the secondary school curricula in many EU countries and in the last 10 years appear in secondary textbooks, even if not in an organic way and with a prevalent narrative approach. Therefore, a wide discussion is now growing on goals, rationale, contents, instruments and methods for its introduction in secondary school. 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, involving curricula innovation, teacher education and physics education research in a way that allows the students to manage them in moments of organized analysis, in everyday life, in social decisions. In the theoretical framework of the Model of Educational Reconstruction, we developed a research-based educational proposal organized in five perspective directions: 1) the analysis of some fundamental concepts in different theories, i.e. state, measure, cross section; 2) problem solving by means of a semi-classical interpretation of some physics research experimental analysis techniques; 3) the study of phenomena bridging different theories in physics interpretation, i.e. diffraction; 4) phenomenological exploration of new phenomena, i.e. superconductivity, 5) approaching the basic concepts in quantum mechanics to develop formal thinking starting from phenomenal exploration of simple experiments of light polarization. Research is focused on contributions to the practice of developing coherent learning proposals in vertical perspective related to content by means of Design Based Research, to produce learning progression and to find ways to offer opportunities for understanding and experiencing what physics is, what it deals with and how it works in an operative way. Empirical data analysis of student reasoning in intervention modules supports proposed strategies.

1. THE PROBLEM OF MODERN PHYSICS IN SECONDARY SCHOOL

The upper secondary school curricula of a large part of countries of the European Union include contents of the physics of the last century, here named briefly Modern Physics (MP hereafter) [1]. The most recent texts devote chapters to MP topics, even if not in an organic way [2-5]. Although conceptual knots in classical physics are quoted often to argue the exclusion of modern physics from secondary school, the international literature shows a rich debate on how to introduce MP, concerning: goals/rationale (to create a culture of citizens? For guidance? For popularization of recent research results? For education?); contents (what is useful to treat? Fundaments, Technologies, Applications?); teaching strategy: How? (Story telling of the main results? Argumentation of crucial problems? Integrated in Classical Physics? At the end of curriculum as an additional/complementary part?) [4-6]; to whom? (All citizens? Talented students? Lyceum/Gymnasium students?) [2-6]. MP in secondary school is a challenge which involves the possibility to transfer to the future generations the cultural value of physics, building a cultural heritage where physics is an integrated, not a marginal part, in a way that allows the students to manage themselves in moments of organized analysis, in everyday life and social decisions.

Three planes are involved: curriculum innovation, teacher education, physics education research [4, 7]. Here we present our research approach on modern physics in upper secondary school, exemplifying main contributions, presenting more extensively the path on superconductivity and some general results of research on students learning in that field.

2. OUR RESEARCH-BASED APPROACH FOR MODERN PHYSICS (MP)

Our research-based proposals on MP aim to offer a cultural perspective, focusing on the foundation of basic concepts as well as methods and applications in physics research, integrating them into the physics curriculum and not as a final appendix, offering experience of what MP is in active research. Vertical paths are identified as a learning corridor [8-10] for individual learning trajectories and step-by-step concept appropriation modalities [11-13].

Attention is paid to identify strategic angles of attack and critical details used by common knowledge to interpret phenomenology [14, 15], to study a spontaneous dynamical path of reasoning [7], to find new approaches to physics knowledge [14-18]. We avoid the reductionism in favor of offering opportunities of learning and not only understanding of information, interpreting solutions and results (to become able to manage fundamental concepts), competences of instruments and methods [7].

The Model of Educational Reconstruction (MER) is our theoretical reference for the design of research-based educational proposals [8]. According to the MER model the first step in research task is to rethink scientific content as a problematic issue and to rebuild it with an educative perspective. This task is integrated with empirical research on student reasoning and learning progress [7, 16-18], Design-Based Research (DBR) in planning intervention modules [19-22]; action–research [7] in a collaborative dialectic between school and university to contribute to classroom practice and to develop vertical T/L path proposals experimented by means of different interventions in classes [10]. The approaches in our work are therefore not purely based upon disciplinary content [23] in order to identify strategies for conceptual change [24].

The research approach on learning processes focuses on the obstacles that must be overcome to reach a scientific level of understanding and the construction of formal thinking, rather than to find general results or catalogues of difficulties. We are interested in the internal logic of reasoning, spontaneous mental models, their dynamic evolution following problematic stimuli (inquiry learning) in proposed paths, the ways for building formal thinking.

Empirical data analysis is carried out in four main research directions:

1) individual common sense perspective with which different phenomena are viewed and idea organization, in order to activate modeling perspective in the interpretation of phenomena;

2) the exploration of spontaneous reasoning and its evolution in relationship with a series of problematic stimuli in specific situations, in order to formulate activity proposals;

3) finding the modalities to overcome conceptual knots in the learning environment;

4) learning progression from defined low anchor to specific learning outcomes by means of detailed paths.

To monitor the learning progress, data collection is carried out by means of pre/post test, to obtain an overview on the student conceptions and the learning impact of the proposal experienced, IBL tutorials monitoring the students' learning process, often integrated with Interviews carried out according semi-structured protocol and the mirroring Rogersian method and usually also Audio/Video-recording of small or large group discussions and interactions.

The different proposals for MP cover mutually inclusive perspectives, for a global vision on MR: 1) Phenomena bridging theories, as for instance diffraction and specifically light diffraction; 2) The physics in modern research analysis technics, as for instance the Rutherford Backscattering (RBS), Time Resolved Reflectivity (TRR), electrical transport properties of material analysis with resistivity versus temperature and Hall coefficient measurements (R&H) [25]; 3) Explorative phenomenological approach to superconductivity (a coherent path) [26]; 4) Discussion of some crucial / transversal concepts both in CP and MP, for instance the concept of state, the measure process, the cross section concept [27], mass and energy [28]; 5) Foundation of theoretical thinking in an educational path on the fundamental concepts of quantum mechanics and is basic formalism [29-30].

3. EXAMPLES OF MODEL OF EDUCATIONAL RECONSTRUCTION (MER) PROPOSALS

3.1 Phenomena bridging theories: optical diffraction

Optical diffraction is an important context in many perspectives: it is a common phenomenon around us; it has a large use in research analysis, as well as in technological applications useful in everyday life; its interpretation bridges geometric and physical optics, classical physics and quantum physics.

The proposal on optical diffraction is based on the educational opportunities offered by the new technologies. It was designed, set up and experimented parallel to a research and development project aimed to realize the LUCEGRAFO system [31], a patented device connected to the computer USB-port in a R&D research [19-21], which is an evolution of a previous prototype [32]. Through this system, students acquire in real time and then analyse qualitatively and quantitatively the light diffraction pattern produced by a laser beam crossing a single slit, a single hair, a double slit, a grating (Fig.1). The features of light diffraction pattern cannot be framed in the rectilinear behaviour model and motivate students to look for an interpretative hypothesis on the wave nature of light, activated by recognition of similarities that characterize the different diffraction phenomena (the sea waves rather than sound waves). In our approach, students construct a model based on the Huygens-Fresnel principle reproducing the experimental light distribution and fitting the experimental data. A software environment of modelling, now realized also on an electronic worksheet, permits students to implement that model (Fig.1.C), focusing on the physical meaning of the model rather than on the mathematical calculations to obtain an analytical expression for this model [33]. The theoretical model based on the Huygens-Fresnel principle could be interpreted in a classical physics frame as well in a quantum mechanical one, analysing the consequence of the interference of point sources on the wave front.

3.2 The physics in modern research analysis techniques

We developed three proposals concerning the research techniques involved in the analysis and characterization of materials in modern physics and regarding: the optical physics (here exemplified by concerning light diffraction [32]); the Rutherford Backscattering Spectroscopy (RBS) analysis technique [34]; The Time Resolved Reflectivity (TRR) [35]; Measurement of Hall coefficient and resistivity versus temperature of metals (R&H), semiconductors and superconductors to characterize electrical transport properties of solid materials [36].

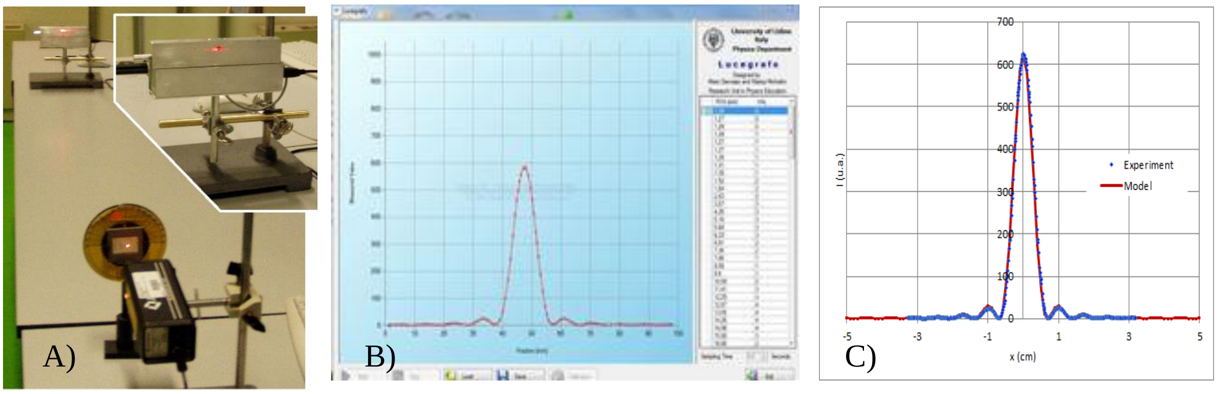


Fig.1. A) Apparatus LUCEGRAFO B) Diffraction patterns from single slit (width 0.12 mm) C) Fit of the experimental distribution with a Huygens-Fresnel based model

3.2.1 Rutherford Backscattering Spectrometry (RBS)

The Rutherford Backscattering Spectroscopy (RBS) measurement consists of collecting the energy spectra of ions (He^{++} of 2 MeV from a linear accelerator) backscattered along a certain direction, after a collision with the atoms of a target. RBS provides information about the depth distribution of the constituent elements of the first 500 nm of the surface of a sample (Fig.2). The principles of the measurement and semi-classical data treatment are discussed with students and real and simulated spectra are analyzed and interpreted as a problem solving activity [34].

Students construct the concepts used for the RBS spectra analysis as the cross-section and the stopping power. They are involved in simple experiments realized with poor materials studying the interaction of spherical projectiles and different shape targets to have an operative experience of the meaning of the cross section concept.

The RBS proposal offers the students the opportunity to: explore the Rutherford-Geiger-Marsden experiment; understand the role of energy and momentum conservation principles in the context of research analysis; understand how microscopic structures can be studied through indirect information and measurements; interpret RBS spectra; have a look of scientific material characterization research methodologies [37-39].

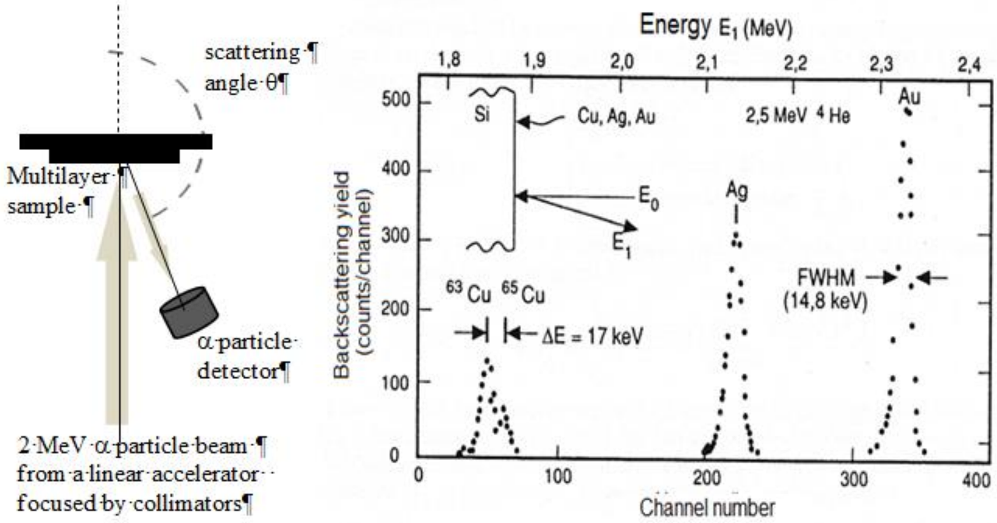
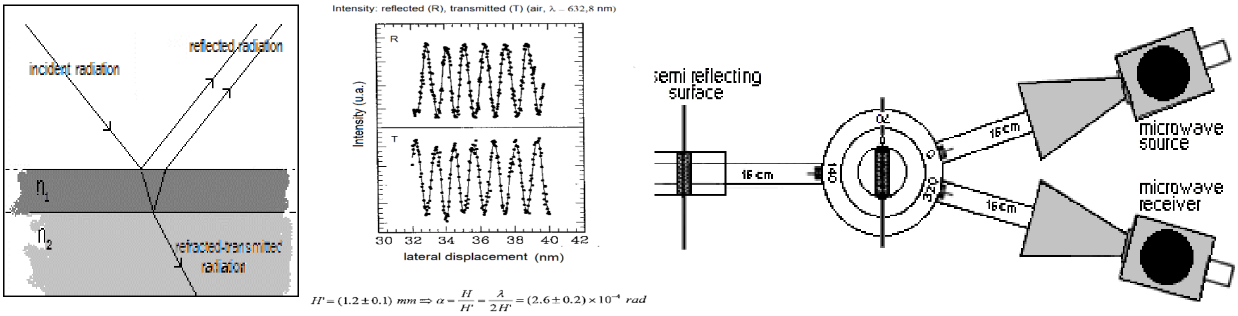


Fig.2. RBS experimental apparatus schema and RBS spectrum (from [39]): the target is a monoatomic layer of Cu, Ag and Au in equal concentration on a silicon layer. The incident beam is composed of 2.5 MeV α-particles, scattered at θ=170°

3.2.2 The Time Resolved Reflectivity (TRR)

The Time Resolved Reflectivity (TRR) technique exploits the interference produced by the light reflected by a double layer, using two visible light or microwave monochromatic sources (Fig.3.) [35]. The TRR techniques can be used to study the epitaxial growth of a sample, analysing the changes in the interference pattern of the two laser beams reflected by changes of the two interfaces, produced by changing one of the two sources. Students carry out measurements with microwaves and laser light, measuring thickness of various thin films of materials, analysing the interference fringes.



$$H' = (1.2 \pm 0.1)\ mm \Rightarrow \alpha = \frac{H}{H'} = \frac{\lambda}{2H'} = (2.6 \pm 0.2) \times 10^{-4}\ rad$$

Fig.3. TRR for visible light (left) and relative fringe pattern (data from [35]); setting in the case of microwaves (right)

3.2.3 Electrical transport properties of solids

In the science of materials, the analysis of the electrical transport properties of materials is based on the measurement of the resistivity as a function of temperature, combined with that of the Hall coefficient (R&H) [36] (Fig.4.). That allows to identify sign, number, mobility and

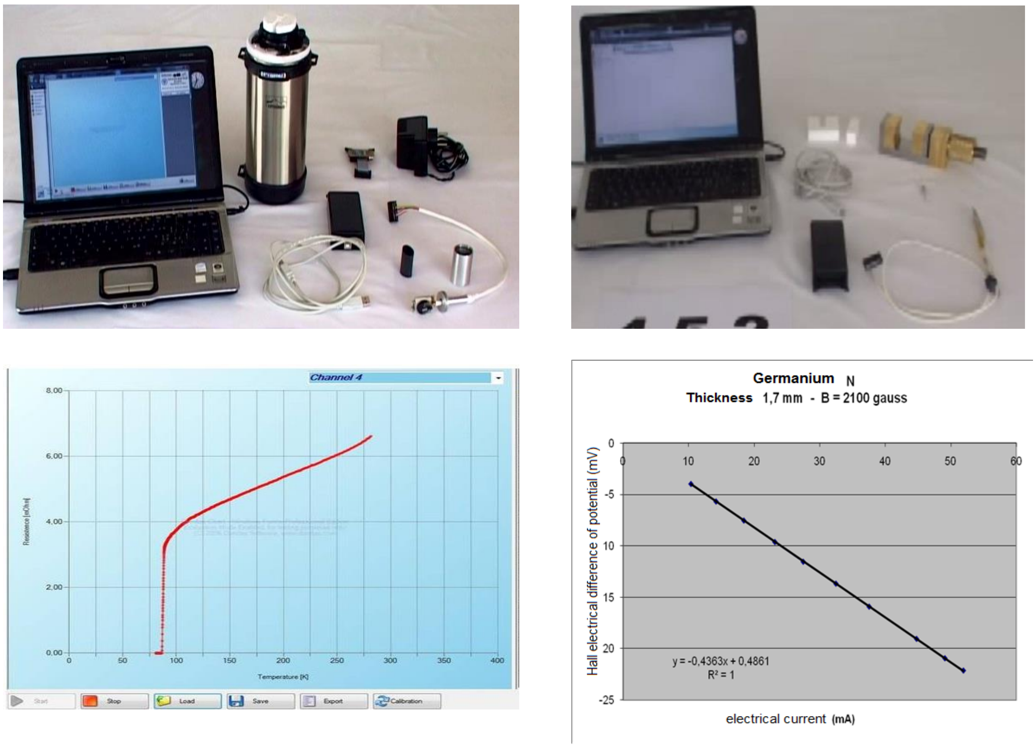


Fig.4. Left: The USB interface developed for the resistivity versus temperature (example of R-T graph for an YBCO sample). Right: Hall coefficient measurements (example of graph for Germanium N)

energy level of the electrical carriers on the basis of microscopic models for metals, semiconductors, and materials such as silicides [25, 39]. The research on superconductors is based on measurements of resistivity as a function of temperature, without or in the presence of a magnetic field [38]. We developed an approach to the matter physics by developing a patented USB probe for the measurement of the resistivity as a function of temperature of metals, superconductors and semiconductors at four points, and one for the measurement of the Hall coefficient of metals and semiconductors (Fig.4.) [36]. That system was designed and developed for a high school didactic laboratory but the constructive characteristics and the reliability of the measurements allow its use even in an advanced laboratory [40].

4. CRUCIAL/TRANSVERSAL CONCEPTS IN CLASSICAL PHYSICS AND IN MODERN PHYSICS (MP)

Some concepts, for instance the concept of system, state, properties are quite general and not related specifically to classical physics or modern one, although the basic theories of the ‘900s gave a new look to all these concepts. In our perspective these concepts could be developed across all the physics curriculum in school offering also insights on how these concepts acquire new meanings in the MP, as presented for instance in the section devoted to MQ. In that perspective, we developed innovative approaches on mass and energy, considered starting with a re-analysis of their classical meaning and then considering the new vision of these concepts given by the theory of relativity [28]. Here we focus on the cross-section, a transverse concept quite important in physics, crucial in the actual research in many fields of physics, but completely neglected in the secondary school.

The concept of cross section is important both in classical physics and in MP, for instance in studying the interactions between elementary particles in nuclear physics at both low and high energies, in atomic collisions, in structure of matter studies (as seen in the brief description of the RBS proposal). It becomes essential in the case of quantum mechanics, because it is impossible to attribute a trajectory to a quantum system. Approaching the construction of the concept of cross-section allows us to move from classical physics to wider and more complex fields using a powerful research tool.

A reductionist approach based on a geometrical interpretation of the concept of cross section might seem to be the easiest approach, but this is not the case. In fact, this interpretation is adequate only in the case of classical rigid spheres. The general concept of cross section is characterized by a probabilistic meaning, and this is what needs to be highlighted in an educational approach.

In the educational approach, students analyze some typical although simple cases of collisions, highlighting the general aspects of the phenomena and showing how to relate measurements and interpretations in a way completely different from the traditional force/equation model of motion/trajectory scheme. The line of the conceptual development of the educational path on cross section is reported in Appendix 1.

5. QUANTUM PHYSICS (QP) IN SECONDARY SCHOOL. FOUNDATION OF THEORETICAL THINKING.

In literature, there are quite different educational proposals [41-44], and a preliminary clarification is necessary to distinguish between physics of quanta, quantum physics and quantum mechanics. In the description of the birth of the theory of quanta the narrative treatment of the discussions on the hypothesis (proposed and not innate to students’ reasoning) usually prevails in the educational approaches over aspects relating to the subject itself. The descriptive dimension if acceptable in a popularization plan does not appear to be satisfactory in an educational plan. There is the need to produce the awareness of the reference assumptions of the new mechanics [45-47] and to offer some indications on the formalism that is adopted, the formalism, in fact, assumes a conceptual role in QM [44-45].

The formal approaches, based usually on the wave formulation of quantum mechanics, are rigorous, but demand strong competencies both in physics and in mathematics [48]. Computer simulation to ‘visualize’ quantum situations helps to overcome the formal obstacles [49-50], leaving the knots open for interpretation.

In our perspective, there is the need to produce the awareness of the reference assumptions of the quantum mechanics theory and to offer a look on the conceptual role of its formalism rather than to stress on the way to use that formalism in problems and applications. Two lines of intervention were developed. The first constitutes a contribution to the traditional approach to quantum phenomena: experiments that are critical for the classical physics interpretation, to focus on the problems (Photoelectric effect; Compton effect; Frank & Hertz experiment; Millikan experiment; normal and anomalous Zeeman effect; emission and absorption spectra; diffraction of light and particles; Ramsauer effect) [51]. The second line, constituting the core of our proposal, is for quantum mechanics (not quantum physics or physics of quanta) in secondary school following a Dirac approach. We chose to approach: the theory of quantum mechanics; the first step toward a coherent interpretation with a supporting formalism; an introduction to the ideas of the theory, through the treatment of crucial aspects, fundamental concepts, peculiar elements to QM [29-30, 52]. Our core proposal for QM may be divided into two levels: on the disciplinary level we have chosen to begin with and focus on the principle of superposition and its implications; on the educational level we have chosen an in-depth discussion of specific situations in a context that allows for the polarization as a quantum property of photons.

Three are the basic elements of the proposal: to explore light polarization on experimental, conceptual and formal levels [53-55]; to discuss ideal simple experiments involving interactions of single photons with polaroids and birefringent materials (calcite crystals) [51]; to describe in quantum terms by two-dimensional vector spaces the states of polarization of light (or spin) [30, 53-54].

The first part is focused on the superposition principle, discussing a series of experiments with polaroids and calcite crystals, and its consequences as the uncertainty principle, the non-epistemic indeterminism, the description of macro-objects and the problem of measuring, the non-local nature of quantum processes, renouncing the classical way of thinking, including trajectory [29-30]. In the second part, each of the conceptual aspects discussed in the first part is formalized with an appropriate mathematical structure, starting from the vectorial representation of the quantum state and the representation of observables with linear operators [30, 52].

The rationale of the educational path includes: the operative introduction of the phenomenology of light polarization, using polaroids on an overhead projector and organizing conceptually through the Malus law, that students can “discover” in a real lab using on-line light sensors; the recognition of the validity of the Malus law in reducing light intensity, polarization is identified as a property of a single photon; exploring the interaction of polarized photons with polaroid, they identify mutually exclusive properties, incompatible properties and the uncertainty principle; the identification of the state of the polarized photon by a vector and the superposition principle can be written as: $\mathbf{w}=\mathbf{u}+\mathbf{v}$; distinction between state (vector) and polarization property, identified by icons living in different spaces; identification of the QM measurement as a transition of the polarized photon to a new state (the precipitation of the system in those measured and its genuine stochastic nature; interaction of polarized photons with birefringent crystals to understand entangled state, impossibility to attribute a trajectory, non-locality of the quantum processes; introduction of basic formalism starting from the transition probability from state u to state w as a projector, expressing the probability of transition with a scalar product:

$$P_t = N_t/N = \cos^2\theta = (\mathbf{u} \cdot \mathbf{w})^2.$$

These aspects can be discussed also in a very similar way considering the more usual case of the two-slit interference, where it can also be discussed what kind of picture emerges from the quantum behaviour when a hidden variable framework is assumed.

All the steps of the proposal are implemented in stimuli worksheet tutorials, aiming to monitor the students' learning paths and to involve them in an inquiry-based educational environment [55]. The different situations proposed in the educational path as well as allowing the pupils to explore their own hypotheses can be realized virtually in a gym of simulated ideal experiments using the applet JQM [51] (free access at: http://www.fisica.uniud.it/URDF/secif/mec_q/percorso/avv_11.htm). Fig.5. shows an example of JQM experiments and tools available.

All the proposals, discussed in a research perspective in different papers [29-30, 52], are also available on the web to be used and adapted by teachers in schools (http://www.fisica.uniud.it/URDF/secif/mec_q/percorso/teoria.htm).

Memory: free 167440.0, total 1048568.0

Direzione di Pol. (gradi) 0.0

N fotoni 100

Fig.5. The tools and the environments used by students to explore the phenomenology in single photon of light interaction with polaroid and birefringent crystals

Extensive research experimentations were carried out with more than 300 students [56-59]. From these it emerged that students profit from the iconographic representation and discussion in a proper way on mutually exclusive properties (80%) and incompatible properties (55%). The employment of the iconographic representation (85%) and formalism (60%) facilitate reasoning in the framework of QM. The rigorous reasoning proposed promotes the spontaneity used in new contexts (50%), the construction of a coherent framework (80%), even if in a different conceptual perspective. In fact the students' learning paths show evolution toward quantum concepts, where some typical hidden variables assumptions often bridge them from classical to quantum way of thinking [57].

6. FROM ELECTROMAGNETISM TO SUPERCONDUCTIVITY

The explorative approach to superconductivity is integrated in a vertical path on electromagnetism [26, 60]. It uses the experimental kits developed in the European projects SUPERCOMET and MOSEM [61], including more than 100 simple low-tech experimental activities on electromagnetism and electrodynamics and 8 high-tech apparatus on superconductivity, computer modelling proposals, 20 simulations. In our approach, secondary school students explore and explain superconductivity first in classical physics and then they have a look at the quantum mechanism that can take into account the transition from normal conductor to a superconductor. The research-based path includes an inquiry-based learning (hands/minds-on) approach to SC using the theoretical framework of classical electromagnetism; ICT learning-based, integrated measurements carried out by sensors, modelling, simulations. The focus is on reasoning for the interpretation of the phenomena [26].

In developing vertical paths on electromagnetism and superconductivity from primary to upper secondary school, our research involved: T/L proposals development by means of DBR [19-22]; Learning process analysis by means of Empirical Research [7, 14-18] and in the perspective of Conceptual Change [24]; R&D of new ICT system [20-21]; Teachers' professional development; Micro-steps of Conceptual Lab of Operative Exploration (CLOE) are carried out to build the formal quantities characterizing the magnetic field B [13].

In experimenting with the same explorative path in secondary school (l8 schools, N=160 students, 17 years hold), magnetic field lines assume the roles of a conceptual tool: to interpret magnetic interactions (65%); to distinguish between magnetic field (direction of orientation) and force (direction of starting motion) (55%); to produce reasoning in terms of flux, individuating that it is a constant quantity in field line system (80%); with related consequences, such as that magnetic field lines are closed (68%), the non-separability of poles (50%) or div=0, interpretation electromagnetic induction (76%), identification of the related applications (56%) [60].

The rationale of the path on superconductivity and the results of the school experimentation are reported in Appendix 2 and 3.

7. CONCLUDING REMARKS

From our research in physics education we developed five different perspectives of proposals mutually inclusive for the Modern Physics to build in young people:

- physics identity
- physics as a cultural issue
- the idea of physical epistemic nature

Avoiding the reductionism our aim is to offer opportunities to:

• Experience the quantitative exploration of crucial phenomena (diffraction), individuating laws, fitting data and testing basic principal ideas and results with experimental data

• Understand the crucial role of classical physics in modern research techniques (RBS, TRR, R&H) manipulating data and interpretation like in a research laboratory

• Focusing on reasoning to conduct the exploration of a phenomenon (superconductivity) understanding the role of analogies for finding explanations

• Reflect on the physical meaning of basic concepts in different theories (state, measure, cross section) revising meanings in classical physics and understanding the different perspectives of new theories

• Approach to the new ideas of QM theory: the first step toward a coherent interpretation with a supporting formalism experiencing aspects, cardinal concepts, elements peculiar to QM

One of the main follow-ups at national level of our expertise in teaching-learning modern physics was the IDIFO Projects (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 (162 cts articulated in clusters of 3cts courses on the following area for (60cts) on: Modern Physics; Physics in contexts (in art, sport...); Real time Labs and modelling; OR- Formative guidance; SPER – School experimentation); Summer school for talented students; Educational Labs, co-planned with teachers, to experiment with innovation in the school [62].

APPENDIX 1. THE OUTLINE OF THE EDUCATIONAL PATH ON CROSS SECTION.

To approach the concept of cross section, students compare first the quite simple case of the collision of two spheres (or two circular disks) and the case where the target sphere is substituted by an object with an irregular shape, measuring the dependence of the scattering angle θ from the impact parameter b. In the first case it is simple to reconstruct the analytical relation between b and θ, including the radius $R1$ and $R2$ of the two spheres [$b = (R1+R2) \cos(\theta/2)$], in the second case the work becomes harder immediately by considering an ellipsoidal shape of the target system, both in the mathematical perspective and, much more important, in the physics perspective, because the dynamics of the collision becomes immediately strongly dependent on the initial condition: a very small variation in b can cause variations of any order of magnitude in the scattering angle. A consequence of this is that by driving the two bodies against each other a number of times with a poor control of initial conditions, the individual results (final states) obtained are significantly different. Does this mean that such an experiment does not give any kind of information about the collision or the geometry of the two bodies?

Students can recognize, using both experiments and simulations when a beam of symmetrical projectiles impact on a target system of arbitrary shape, that the asymmetry in the target shape can be associated to the specific asymmetry in the distribution of the scattered projectiles [27, 37]. The relation between *distribution asymmetry* and *asymmetrical shape* shows to students that it is possible to extract information on the collision phenomenon trough a statistical analysis of the distribution of scattering angle. In general, a complete characterization of the collision requires the knowledge of the probability P_i for any given measurement outcome S_i; these probabilities can be obtained from the average $P_i = \langle N_i / N_{tot} \rangle$, where N_i is the number of outcomes S_i for N_{tot} observations carried out. That probability still depends on the details of the measuring procedure. For instance, increasing the width of the distribution of the impact parameter of projectiles, there will be a greater number of cases in which the projectiles will not interact with body 2 at all. In order to avoid this, it is necessary to consider more in detail a general situation like that represented in Fig.6. A uniform beam of (identical) particles colliding with a target of evenly distributed (identical) particles. So an incoming particle, wherever it crosses the panel (a), meets, on average, the same target distribution. Therefore the total number N_i of scattering events having a certain final state S_i will be proportional to the number of incident particles (there are no border effects due to the 'width' of the beam).

On the other hand, given the limited range of the scattering phenomenon, a certain incident particle will only interact with the particles of the target within the range of action of the force (represented in Fig.6. by the small rectangle of area A on the surface of the target (panel (b)).

The probability that any incident particle of the beam interacts with a target particle within area A, creating a certain result S_i, will be: $P = P_1 \cdot P_2 \cdot P_{int}$, where P_1 is the probability that the incident particle will cross A, P_2 is the probability that there will be a target particle in that area and P_{int} the probability for that type of interaction. With two sufficiently sparse distributions, P_1 and P_2 will be given by: $P_1 = \langle N_1 \rangle = n_1 \cdot A$, $P_2 = \langle N_2 \rangle = n_2 \cdot A$, where n_1 and n_2 represent the surface densities in a projection transversal to the axis of the beam. The average (total) number of interactions with outcome S_i will be obtained by summing up all the small rectangles, of number N_A, into which the section A_{tot} effectively crossed by the beam can be divided:

$$\langle N_i \rangle = N_A P_1 P_2 P_{int} = (A_{tot}/A)\,(n_1 A)\,(n_2 A)\,P_{int} = A_{tot}\, n_1\, n_2\, (A\, P_{int}) \quad .$$

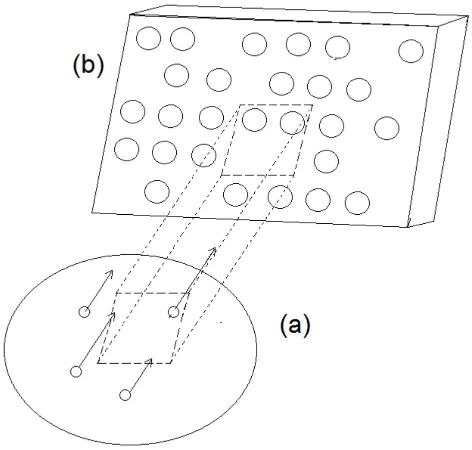


Fig.6. A beam of particles (panel (a)) colliding with a target (panel (b)).
The dotted lines represent the active volume of a beam particle (that is, the region in which it can interact with a target particle)

The factor $s_i = (A \cdot P_{int})$ is related to the characteristics of the observed interaction. The factor has the physical dimensions of an area and for this reason it is called cross section (for the reaction channel considered). The geometrical meaning of the cross section could be easily recognized by applying the previous results to the case of rigid spheres. The information given by s_i is on the intensity of the interaction (or, alternatively, on its range), due to its nature of integral quantity.

To obtain a similar quantity able to offer a deeper insight into the interaction phenomenon considered, it is necessary to consider explicitly each possible result S_i of the collision. If N_i is the number of the outcomes for which the scattering angle is in the interval $(\theta, \theta + \Delta\theta)$, the cross section σ for the collisions with a scattering angle in such an interval is:

$$\sigma = AP_i \approx A N_i / (n_i A) = N_i / n_i$$

where n_i is the number of incident particles per unit area.

This value depends on $\Delta\theta$ and therefore it is better to introduce the so-called differential cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta} = \lim_{\Delta\theta \to 0} \frac{\sigma}{\Delta\theta} = \lim_{\Delta\theta \to 0} \frac{< N_i >}{n_i} \frac{1}{\Delta\theta}$$

That concept could be easily generalized to a solid angle.

The expression of the differential cross section can be applied to the important case of the scattering of two pointlike bodies with charge Ze , $Z'e$ charge, which interact according to a repulsive Coulomb potential. The dynamics of that interaction is governed by the conservation principles of angular momentum and energy (E) and the following relation between b and θ can be easily obtained

$$b = \frac{ZZ'\,e^2}{2E} \operatorname{cotg} \frac{\vartheta}{2} \,.$$

The differential cross section is immediately obtained:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{ZZ'\,e^2}{4E} \right)^2 \sin^{-4}\left(\frac{\theta}{2} \right)$$

That important result could be used to discuss in detail the historical study of Rutherford and the related Geiger and Marsden experiments as well as we have shown in the section of RBS, or to have a look on nuclear interactions [27].

APPENDIX 2. A COHERENT EDUCATIONAL PATH TO SUPERCONDUCTIVITY

The path on SC is structured into two parts: 1) Magnetic properties of a superconductor, Meissner effect, electromagnetic induction and eddy currents for interpretative analogy, the pinning effect [26, 38]; 2) Resistivity vs temperature using the R&H USB system (described in section 3.2.3) to find the critical temperature for a superconductor at the breakdown of resistivity [25, 36,39]. We use different perspectives: Historical, Phenomenal exploration, Applications [60, 63-64].

Let us follow the reasoning path proposed, starting from the Meissner effect, focused on understanding correctly the effect in the framework of the magnetic interactions, and focusing on how students face the main interpretative knots. The educational path [26] approaches the Meissner effect through an experimental exploration of the magnetic properties of a superconductor sample (a disc of YBCO with very weak pinning effect). Students analyse the diamagnetic nature of a superconductor constructing step by step a phenomenological interpretation based on production of persistent supercurrents produced by electromagnetic induction that are at the base of the levitation phenomenon due to the Meissner effect.

The first step of the educational path aims to individuate the change in the magnetic properties of an YBCO disc at room temperature and then at the temperature of the liquid nitrogen (LN hereafter). It could be inspired by an exploration of the magnetic properties of a set of different objects of different shapes, weights and materials (aluminium, copper, water, wood, graphite) by means of a home-made simple torsion balance, by hanging these and see if they are attracted, repelled or not affected by a “strong” magnet. A phenomenological classification of magnetic properties of material can show three main types of properties: ferromagnetic materials (that are strongly attracted, almost in any condition, by a magnet and present often that property also after the interaction with a magnet), paramagnetic materials (that are very weakly attracted by a magnet); diamagnetic materials (they show “magnetic repulsive properties” only in the presence of a magnet). Also the paramagnetic properties of the YBCO at room temperature are analysed by putting two discs of YBCO at the ends of a homemade torsion balance. At T_{LN} temperature, when the YBCO is at thermal equilibrium in a bath of LN (77K), a levitation phenomenon appears due to a strongly repulsive interaction between the YBCO disc and the magnet, or, in other words, the YBCO disc shows strong diamagnetic properties.

The change in the magnetic properties of YBCO (quite evident) happens so suddenly when the temperature reaches T_{LN}, that is we are in the presence of a phase transition. This will be confirmed in the educational path analyzing the breakdown of resistivity.

Before proceeding, it must be emphasized here that the levitation stability of the magnet on the YBCO disc is guaranteed by a residual of pinning effect, which is always partially present in this type of superconductors. However, this does not affect decisively the conclusions that will be gradually drawn.

The diamagnetic properties of the YBCO can be explored by moving the magnet, rotating the magnet or going close to the YBCO from different directions (from lateral side for instance). It is clear that the levitation phenomena is not a suspension of two repelling magnets, constrained for instance in a tube, for two reasons: the magnet on the YBCO levitates without any constrains; by changing the pole of the magnet closer to the YBCO, the repulsion appears anyway. Moreover, if an iron clip is put on the cooled YBCO, no interaction is observed, showing that the diamagnetic behavior is induced only by the presence of the magnet, or in other word the magnetization of the YBCO is not permanent. This aspect is similar to that of other diamagnetic materials, in the case of the superconductor the diamagnetic effects are very intense (comparable to that of ferromagnetic systems) contrary to the ordinary diamagnetic phenomena, which are usually very weak. To understand something more on the diamagnetic properties of the YBCO, it is possible to perform a simple exploration of the magnetic field inside the disc of YBCO, analysing whether the external field of the magnet penetrates the YBCO. This test can be performed using a sandwich of a YBCO putted between a magnet and an iron slab. At room temperature you can’t lift the sandwich pulling the magnet, it remains a compact structure. At T_{LN} this effect disappears, that is, the magnet is unable to lift the YBCO and the iron ring (Note: this is not completely true if there is some pinning effect). At room temperature: the YBCO is transparent for the action of the magnet on the iron, the B field of the magnet “arrives” on the iron passing through the YBCO, a magnetic field can exist in YBCO. At T_{LN}, the B field of the magnet does not reach the iron clip, evidencing that it is really small or negligible through the YBCO.

To appreciate the Meissner effect, producing the repulsive effect between the magnet and YBCO and at the base of the levitation of the magnet over the YBCO disc, the levitation of the YBCO can be observed, when it is cooled in presence of a magnet. When the temperature of the YBCO goes below the critical values, the magnet lifts levitating over the YBCO.

The phenomenology described shows that the magnetic behaviour of YBCO appears to be induced by the presence of the magnet, or better by the magnetic field produced by the magnet. An analogy can give the instrument to interpret the phenomena.

A falling magnet on a copper bar decrease its velocity gradually. A magnet falling inside a copper tube falls at constant velocity. In that phenomenon, the electromagnetic induction and the eddy currents have a crucial role. The interpretation of the falling magnet in a copper tube requires as conceptual tools: the field lines (in our perspective an operative definition of that lines); the flux of B ($\Phi(B)$), defined operatively); The Faraday-Newman-Lenz law. To interpret how the eddy currents arise in the tube, we can ideally slice the tube in rings standing one over the other. The eddy currents arise because the change in the flux of B when the magnet passes from a ring to the ring below: in the first ring that current produces a B field in the same direction of the magnetic field of the falling magnet; in the second ring that current produces a B field in the opposite direction of the magnetic field of the falling magnet. Applying the Lorentz force law, it can be seen that a net force emerges, directed vertically opposite to the direction of the weight of the magnet and producing the braking effect on the magnet. Repeating the experiment with geometrically equal tubes of different materials (bronze, aluminium, copper…) it is possible to correlate the falling velocity and the resistivity of the material of the tube. The analogy between the “braking” of the magnet in the presence of a “real” conductor and the levitation of the magnet over the YBCO disc appear to work if the conductor is “perfect” ($R=0$). The currents initially induced by the magnet never stop, because the Joule effect is not present in the case of a $R=0$ conductor even when the electromagnetic induction ends ($v=0$).

Effectively a superconductor, such as the YBCO at T_{LN}, shows this property. Students can explore that effectively in a lab analysing the behaviour of the resistivity as a function of the temperature, characterizing a superconductor as a system with $B=0$ and $R=0$

The interpretation of the perfect diamagnetism of a superconductor as an electromagnetic induction effect in the case of an ideal conductor (that is $R=0$) can be extended to also include the situation when YBCO becomes superconductor in the presence of an external field.

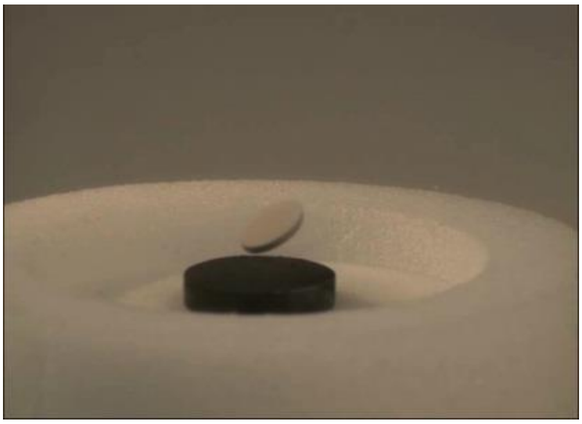


Fig.7. The Meissner effect

Fig.8. The pinning "train" on the magnetic track

The explorative part of the educational path of superconductivity includes also the analysis of the pinning effect, characterizing the superconductor of type II and at the base of the functioning of the MAGLEV train. This effect manifests itself in the fact that the magnet remains anchored to the superconductor at the distance at which it was when it made the phase transition. The pinning effect is due to the penetration of the magnetic field inside the SC sample inside the vortexes created by supercurrents and at the same time the repulsive effect due to the Meissner effect (Fig.7). The analysis of the stability of the train on the magnetic track (Fig.8) offers the opportunity to discuss the conditions needed to obtain a stable levitation.

To interpret how the phase transition occurs in a superconductor it is necessary to consider a quantum approach to solid state physics. We set up a minimal treatment based on energy levels. We usually start discussing the (discrete) equilibrium energy levels of a chair, to give an analogy for the atom levels. When isolated atoms are combined to build a crystal, the energy levels of electrons change dramatically. Using simulations as that of Visual Quantum Mechanics [49] students can understand how the level of one atom splits (http://phys.educ.ksu.edu/vqm/html/eband.html) into 2….n levels close to the other forming bands when 2…n equal atoms go close to one another as it occurs in a crystal lattice.

Electrical transport properties of a solid, and in particular its nature of insulator or conductor, depend on the band structure and on electron states. These states and their occupation are determined by the Pauli exclusion principle. When the superconductive state is created a great change occurs. Due to an effective attractive interaction between electrons, mediated by the lattice vibrations (phonons), the formation of the so called Cooper pairs is favoured because of energy reasons. The Cooper pairs are particles of spin 0 and therefore they can all occupy the same state, that is, the fundamental state that is separated by an energy gap. The existence of that gap assures the stability of the superconductive state and the vanishing of the resistivity of a superconductor [26].

APPENDIX 3. EXPERIMENTS WITH STUDENTS

Experiments in school were performed in 44 Italian sites involving students of different age (29 K13; 6 K12-13; 1 K12; 6 K11), for a total of 1315 students of 292 classes of about 150 schools. 5/44 experiments were performed in informal educational contexts organized in the limit of university-school projects involving 275 students. From these experiments it emerged that students are strongly involved and motivated in the exploration of phenomena such as superconductivity because: it is very surprising and engaging (95%), of the great interest in the technological application of the superconductors (75%), of the general interest in the construction of an explanation of that phenomenon (83%) [60]. These results were confirmed also by the other experiments done in very much different contexts and in formal setting. The majority (20/44) of these experiments were performed by service teachers and in two cases by prospective teachers involved as experimenter of the material of the European projects of the Supercomet family [63-64]. These experiments constitute positive feasibility tests of the introduction of superconductivity in different contexts and types of school, gives as outcomes that teachers individuated four different educational paths to introduce superconductivity in school: Introduction to superconductivity - approach through the magnetic properties; Approach to superconductivity through the exploration of the resistivity of materials. The energy transformations and superconductivity, Approach to superconductivity starting from the exploration of its technological applications. From that experimentation emerged also the positive evaluation of students' learning performed in standard ways by teachers and as unresolved educational problem as treated in school the Cooper pair formation, an aspect remaining open also in their formation [60, 63]. 5/44 experiments were performed by PhD students as part of their research project with 125 students [60, 65]. From these works it emerges that prevalently (81%) students characterize the superconductive levitation as a repulsion consequence of the diamagnetic properties acquired by the YBCO, characterizing that with a magnetization vector (57%), or using a global representation using field lines (24%) explaining also in some cases (22%) that the sample becomes a superconductor or that its resistance falls down to zero. In a few cases (19%), students just describe the system of forces acting. (YBCO repels the magnet with a force that is equal to the weight force). Students were able to distinguish the features of Meissner effect from that of the pinning effect (87%), but without developing different models for the two effects [66].

Nine of these research experiments (9/44) in school were research-based activities conducted with 287 students (66 students were 17 and 261 students were 18) to understand how students learn superconductivity and to validate the didactic material prepared to monitor students' learning paths and were performed in curricular activities, with entire school classes, or in summer schools organized at the University for selected students from all Italy [66]. The models of students are mainly centered on the concept of the magnetic field and the magnetic properties of the systems involved (68%). The static models underlying how students initially describe the superconductive levitation, was substituted at the end of the educational path in the majority of cases (84%) with models describing the condition B=0 inside the superconductor: 63% that the YBCO at $T=T_{amb}$ was passed by field lines (was paramagnetic) and at $T=T_{NL}$ it expels the field lines, in 1/3 of cases adding that this is due to surface currents; 25% the field lines do not cross the YBCO, the YBCO screens the field lines; 12% field lines are trapped. That models are supported by causal explanations based on an intuitive magnet image model (38%) [67] or on the induction electromagnetic role in the superconductive levitation (62%).

REFERENCES

1. http://teachers.web.cern.ch/teachers/archiv/HST2001/syllabus/syllabus.htm
2. Aubrecht G. (1989). Redesigning courses for the 21stcentury. AJP, 57, 352-359.
3. Gil D. P., Solbes. J. (1993). The introduction of modern physics. IJSE, 15, 255-260.
4. Hake R.R. (2000). Is it Finally Time to Implement Curriculums? AAPT Announcer 30(4), 103.
5. Ostermann F., Ferreira L.M., Cavalcanti C.J.H. (1998).Tópicos de física contemporânea no ensino médio. Revista Brasileira de Ensino de Física, 20, 270-288.
6. Ostermann F., Moreira M.A. (2000). Física Contemporânea em la escuela secundaria.

Revista de Enseñanza de las Ciencias, 3 (2), 18, 391-404.

7. Michelini M (2010). Building bridges between common sense ideas and a physics description of phenomena, in Menabue L, Santoro G eds. *New Trends in Science and Technology Education*. (pp. 257-274) Bologna: CLUEB.
8. Duit, R., Gropengier, H., Kattmann, U. (2005). Toward science education research that is relevant for improving practice: The model of educational reconstruction, in: H. E. Fisher (Ed) Developing Standard in RSE. (pp. 1- 9). London, UK: Taylor and Francis.
9. Di Sessa A. (2004). Contextuality and conceptual change, in Proceedings of the Enrico Fermi School, Course CLVI, E. Redish & M. Vicentini (Eds.). (pp. 137-150). Bologna: Italian Physical Society.
10. Meheut M., Psillos D. (2004) Teaching–learning sequences: aims and tools for science education research, International Journal of Science Education, 26 (5) 515-535.
11. Bradamante F., Fedele B., Michelini M. (2005). Children‘s spontaneous ideas of magnetic and gravitational fields, in CRESILS, Pintò R, Couso D eds., Barcellona: ESERA publication.
12. F. Bradamante, M. Michelini (2006). Cognitive Laboratory: Gravity and Free Fall, in Informal Learning And Public Understanding Of Physics, Planinsic G, Mohoric A eds. (pp. 359-365). Ljubjana: Girep.
13. M. Michelini, S. Vercellati (2012) Pupils explore magnetic and electromagnetic phenomena in CLOE labs, In Latin-American Journal of Physics Education, Vol. 6, Suppl. I, 10-15.
14. Viennot L. (1996) Raisonner en physique, Ed. De Boeck Université, Paris, Bruxelles.
15. Viennot L., Chauvet F. O., Colin P., Rebmann G. (2005). Designing Strategies and Tools for Teacher Training: The Role of Critical Details, Science Education, 89 (1), 13-27.
16. Tesch, M., Euler, M., Duit, R. (2004). Towards improving the quality of physics instruction. In M. Michelini (Ed.), Quality development in teacher educ. and training. (pp. 302-306), Udine: Forum.
17. McDermott L. C. (1991). Millikan Lecture 1990: What we teach and what is learned — Closing the gap, Am. J. Phys. 59, 301-315.
18. McDermott L. C. (2008) Physics Education Research: the key to improving student learning, in Frontiers of Physics Education, Rajka Jurdana-Sepic et al eds. (pp.11-23) Zlatni, Rijeka.
19. Lijnse P. L. (1995). Science Education, 79 (29, 189–199.
20. Beichner R. J. (2006). European Journal of Engineering Education, 31 (4), 383-393.
21. Wang, F., Hannafin, M. J. (2005). Educational Technology Research and Development, 53(4), 5-23.
22. Anderson T., Shattuck J. (2012) Design- Based Research. American Educ. Research Association.
23. Fischer H. (2006). Video based analysis of surface- and deep structure of science lessons - power and limits, Esera Summer School 2006.
24. Vosniadou S. (ed.) (2013). International Handbook of Research on Conceptual Change, II edition. London: Routledge.
25. Corni F., Mazzega E, Ottaviani G, Michelini M, Michelutti GL, Santi L (1996). A Problem for educational research: The updating of the curriculum, in Teaching the science of condensed matter and new materials, M. Michelini et al eds. (p.455), Udine: Forum,
26. Michelini M, Santi L, Stefanel A (2014) Basic concept of superconductivity: a path for high school, in Frontiers of Fundamental Physics and Physics Education Research, Burra G. S.,Michelini M, Santi L, eds, (pp. 453-460). Springer, Cham.
27. Corni F, Michelini M, Santi L, Soramel F, Stefanel A (1996). The concept of the cross

section, in Teaching the Science of Condensed Matter and New Materials, M. Michelini et al. eds. (p.193). Udine: Forum.

28. Michelini M., Pugliese E., Santi L. (2014) Mass from Classical Physics to Special Relativity: Learning Results, in Tasar F.ed., Proceedings of the WCPE - 2012, (pp. 141-154). Ankara: Pegem Akademie.
29. Ghirardi G C, Grassi R, Michelini M. (1996). A Fundamental Concept in Quantum Theory: The Superposition Principle, in Thinking Physics for Teaching, C. Bernardini et al eds. (p.329) Aster: Plenum.
30. Michelini M (2008). Approaching the theory of quantum mechanics: the first steps towards a coherent synthesized interpretation with a supporting formalism, in Frontiers of Physics Education, Rajka Jurdana-Sepic et al eds., (pp.93-101), Rijeka: Zlatni.
31. Gervasio M., Michelini M. (2009) Lucegrafo. A Simple USB Data Acquisition System for Diffraction Experiments, MPTL14 Proceeding, CD-ROM and http://www.fisica.uniud.it/URDF/mptl14/contents.htm
32. Corni F, Mascellani V, Mazzega E, Michelini M, Ottaviani G (1993). A simple on-line system employed in diffraction experiments, in Light &Information, L.C. Pereira et al.eds (pp.381-388) Braga: Univ. do Minho.
33. Santi L, Mazzega E, Michelini M (1993). Understand radiation Interference by means of computer modelling, in Light and Information, L C Pereira et al. eds. (pp. 361.366) Braga: Univ. do Minho.
34. Corni F, Michelini M, Santi L, Stefanel A (1997). Rutherford Backscattering Spectrometry: a technique worth introducing into pedagogy, in Teaching the Science of Condensed Matter and New Materials, M. Michelini et al. eds (p.266). Udine: Forum.
35. Corni F, Mazzega E, Michelini M, Ottaviani G (1993). Understand time resolved reflectivity by simple experiments, in Light and Information, L C Pereira et al. eds. (pp. 372-380), Braga: Univ. do Minho.
36. Gervasio M., Michelini M. (2009). A USB probe for resistivity versus temperature, MPTL14 Proceeding, CD-ROM and http://www.fisica.uniud.it/URDF/mptl14/contents.htm
37. Mossenta A. (2010). La tecnica RBS in classe: un ponte tra la ricerca e la scuola per insegnare alcune delle basi della fisica, Frascati Physics Series – Italian Collection, Collana: Scienza Aperta Vol. II
38. Chu W. K., et al. (1987). Electrical Transport Properties of Transition Metal Disilicide Films, J. Appl. Phys. 61(3), 1085.
39. Nicolet A. (1978) Back Scattering Spectrometry, NY: Academic Press.
40. Greczyło T, Michelini M, Santi L, Stefanel A (2010). Measuring and Analyzing the resistivity break down of high temperature superconductors in a didactic laboratory, Il Nuovo Cimento, 33 C, 3, 147-155.
41. Hadzidaki P, Kalkanis G and Stavrou D (2000). Quantum mechanics: a Systemic component of the modern physics paradigm, Phys. Educ. 35 (6), 386-392.
42. Am. J. Phys. 2002, Special Issues 70 (3).
43. Phys Educ. 2000, Special Issues 35 (6).
44. Pospiech G, Michelini M, Stefanel A, Santi L, (2008). Central features of quantum theory in physics education, in Frontiers of Physics Education, Rajka Jurdana-Sepic et al eds. (pp. 85-87). Rijeka: Zlatni.
45. Sakurai J.J. (1985). Modern Quantum Physics, Menlo Park, CA: Benjamin/Cummings (2nd ed. rev., 1990, Reading: Addison-Wesley).
46. Müller R, Wiesner H (2002). Teaching quantum mechanics on an introductory level, Am. J.Phys. 70 (30), 200-209.
47. Fischler H and Lichtfeldt M (1992). Modern physics and students' conceptions Int. J.

Sci. Educ. 14 181–90.

48. Born M. (1969). Atomic physics,VIII ed., Glasgow: Blackie & Son, New York: Dover.
49. Zollman D A, Rebello N S and Hogg K (2002). Quantum mechanics for everyone: Hands-on activities integrated with technology, Am. J. Phys. 70 (3) 252- 259.
50. Cataloglu E, Robinett RW (2002). Testing the development of student conceptual ad visualization understanding in quantum mechanics through the undergraduate career, Am. J. Phys. 70 (3) 238-251.
51. Michelini M, Santi L, Stefanel A, Meneghin G (2002). A resource environment to introduce quantum physics in secondary school, Proceedings International MPTL-7, http://informando.infm.it/MPTL/
52. Michelini M, Ragazzon R, Santi L, Stefanel A (2000). Proposal for quantum physics in secondary school, Phys. Educ. 35(6), 406
53. Cobal M, Corni F, Michelini M, Santi L, Stefanel A (2002) A resource environment to learn optical polarization, in Physics in new fields, Girep International Conference proc., Lund.
54. Michelini M., Stefanel A. (2014) Proposte didattiche sulla polarizzazione ottica, Università di Udine, Lithostampa, Pasian di Prato, [ISBN: 9788897311089].
55. Michelini M, Santi L, Stefanel A (2008) Worksheets for pupils involvement in learning quantum mechanics, in Frontiers of Physics Education, Rajka Jurdana-Sepic et al eds. (pp. 102-111). Rijeka: Zlatni.
56. Michelini M, Ragazzon R, Santi L, Stefanel A (2004) Discussion of a didactical proposal on quantum mechanics with secondary school students, Il Nuovo Cimento, 27C, 5, 555-567.
57. Michelini M, Stefanel A (2008) Learning paths of high school students in quantum mechanics, in Frontiers of Physics Education, Rajka Jurdana-Sepic et al eds. (pp. 337-343), Rijeka: Zlatni.
58. Stefanel A., Michelini M., Santi L. (2012) Upper secondary school students learning pathways through quantum concepts and basic formalism, in The ESERA 2011 conference e-book, http://lsg.ucy.ac.cy/esera/e_book/base/ebook/strand1/ebook-esera2011_STEFANEL-01.pdf
59. Michelini M., Santi L., Stefanel A. (2013) How students link quantum concept and formalism, In 12th International Conference APLIMAT 2013, Szarková D., Richtáriková D., Záhonová V. (eds.). (pp. 423-434), Bratislava: Institute of Mathematics and Physics, Faculty of Mechanical Engineering, Slovak University of Technology in Bratislava, Curran Associates, Inc.
60. Viola R: (2010) Innovazione didattica nella Scuola Secondaria: una proposta curricolare sulla superconduttività, unpublished PhD Thesis, University of Udine, pp.171-173.
61. Greczylo T, Bouquet F, Ireson G, Michelini M, Engstrøm V (2010) High-Tech-kit – the set of advanced activities from the MOSEM project, in Il Nuovo Cimento, 33 C, 3, 221-229.
62. Battaglia R O, Cazzaniga L, Corni F, De Ambrosis A, Fazio C, Giliberti M, Levrini O, Michelini M, Mossenta A, Santi L, Sperandeo R M, Stefanel A (2011) Master IDIFO (Innovazione Didattica in Fisica e Orientamento): a community of Italian physics education researchers for a community of teachers on modern physics, in Physics Community and Cooperation Vol. 2, Raine D, Hurkett C & Rogers L eds. (pp. 97-136). Leicester: Lulu.
63. Viola R., Michelini M., Santi L., Corni F. (2008). The secondary school experimentation of Supercomet in Italy. In Frontiers of Physics Education. Ed. RajkaJurdana-Sepic et al. (pp.190-196). Rijeka: Zlatni.
64. Corni F., Michelini M., Santi L., Stefanel A., Viola R. (2009). Curricular Paths in the

Supercomet2 Experimentation in Italy. In Physics Curr. Desig. Constantinou C. P., Papadouris N. eds. http://lsg.ucy.ac.cy/girep2008/intro.htm

65. Michelini M., Stefanel A., Vanacore A. (2014) Exploration of students' ideas about superconductivity, in Active learning – in a changing world of new technologies, Leoš Dvořák L. and Věra Koudelková V., eds, (pp. 541-551). Prague: Charles University in Prague, Matfyzpress publisher.
66. Stefanel A, Michelini M, Santi L (2014) High school students analyzing the phenomenology of superconductivity and constructing model of the Meissner effect, in Tasar F. ed., Proceedings of The WCPE 2012, (pp. 1253-1266), Ankara: Pegem Akademiel.
67. Arkadiev V. (1947). A floating magnet, Nature, 160, 330.