BASIC CONCEPT OF SUPERCONDUCTIVITY: A PATH FOR HIGH SCHOOL

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Abstract

The need for renewed physics curricula, it suggests to include topics of modern physics. The phenomenology of superconductivity is interesting, because: macroscopic evidence of quantum processes; presentable with simple and motivating experiments; involving interesting technological applications. An approach designed to introduce superconductivity in the high school, based on experiments, aimed to recognize the change in electric and magnetic properties of an YBCO sample at phase transition is presented with some results about experimentations with students.

1. Introduction

Teaching and learning Modern Physics is a challenge for Physics Education research involving multidimensional perspectives (PE 2000; AJP 2002, Meijer 2005; Johanssonm, Milstead 2008; Steinberg, Oberem 2000). The results of different international surveys show a diffuse illiteracy in the scientific areas and from different perspectives (PISA 2006), that motivated a diffuse reflection on how physics is taught, how can be proposed in a renewed ways (Euler 2004; Duit 2006). The curricular researches stress the need to reorganize classical physics as physics in context where the technological apparatuses used in everyday life become objects of study to develop concepts and theory, classical principles based techniques used in research offer to the pupils experiences of methodologies of physic (Battaglia et al. 2011; Zollman 2002; Cobai et al 2011). It seeks effective bridges from classical to quantum physics, to create continuity between what the students traditionally faced and the new topics (Cobai et al 1996; Zollman et al 2002; Johanssonm, Milstead 2008; Battaglia et al. 2011) also for education of Quantum Mechanics (PE 2000; AJP 2002). Research experimentations on modern physics evidence the feasibility of the introduction of Quantum Physics in Upper Secondary, particularly when the focus is on the basic concepts (Fischler, Lichtfeld 1992; Zollman ed 1999) or on the integration of physic and technology (Zollman 2002). Empirical studies showed some typical learning difficulties of students in the acquisition of a a quantum mechanical way of thinking and also made clear the effective learning produced by coherent research based teaching/learning sequences (Zollman eds 1999).

In this perspective, superconductivity offers many opportunities to explore phenomena very interesting for students because challenges that stimulate the construction of models, activate a critical re-analysis of their knowledge on magnetic and electrical properties of materials, stimulate links between science and technology, thanks to really important applications (i.e Maglev Trains, supermagnets for physics research and MNR test) (Tasar 2009; Michelini, Viola 2011).

We developed, in the collaboration of the European projects MOSEM 1-2 (Kedzierska 2010), an educational path for high school to introduce superconductivity, integrating it in the courses of electromagnetism. The educational path developed implement an IBL approach using a set of hands-on/minds-on apparatuses designed with simple materials and High Technology, YBCO samples, USB probe to explore resistivity versus temperature of solids (Gervasio, Michelini 2010).

The present paper focus on the rational of the educational path, presenting its main steps aiming the following research questions: Which conceptual elements of superconductivity can be introduced from phenomenology? How to construct a coherent description of the magnetic and the electric properties of a superconductor? How to introduce the main aspects of the BCS theory?

Some general results are also reported concerning the students learning, referring to a future work for a more extensive discussion of it.

2. Superconductivity and classical physics

Superconduction is a quantum mechanical phenomenon to a large extent as implied in the Ginzburg-Landau theory (1950), in the BCS theory (1957), in the Josephson effect (1964). In spite of this, Essén and Fiolhais (2012) pointed that “According to basic physics and a large number of independent investigators, the specific phenomenon of flux expulsion follows naturally from classical physics and the zero resistance property of the superconductor—they are just perfect conductors”. In particular they showed, following de Gennes (1999) and their own work (Fiolhais et al. 2011), that the Meissner effect (B=0 inside a superconductor) can be derived just from Maxwell equation applied for a R=0 conductor. At the same time they stressed on the possibility to use classical electromagnetism (without ad hoc hypothesis) the derivate the London equations, usually framed coherently just in the BCS theory (1957). Badía-Majós (2006), aiming to understand stable levitation when a magnet is posed on a superconductor, proposed a treatment of superconductors of I and II type to give into account Meissner effect as well as pinning where "the main concepts involved are electromagnetic energy, thermodynamic reversibility and irreversibility, Lenz-Faraday's law of induction, and the use of variational principles".

These theoretical results ensure that the phenomenology of superconductive state, almost for what concern the Meissner effect, can be described in the framework of classical electromagnetim. From an educational perspective, the concept of electromagnetism (magnetic field, flux, magnetization) can be used as tools to explore the phenomenology of superconductivity. In this perspective the Meissner effect (B=0 inside a SC) can be explained as an em induction process occurring in an ideal conductor (R=0 Ω). The London equations constitute the theoretical (implicit) reference for the exploration and a possible intermediate goal of the educational path. The attempt to explain how the R=0 Ω condition can be created inside a superconductor bridges toward the quantum mechanical frame for the creation of the superconductivity state.

3. The rational of the path on Meissner effect for Upper Secondary School Students

The educational path approaches the Meissner effect through an experimental exploration of the magnetic properties of a superconductor sample (SC – a disc of YBCO with very weak pinning effect), aiming to the identification of the diamagnetic nature of a SC.

An YBCO disc at room temperature (T_e) does not present magnetic properties. When it reaches the temperature of LN (T_{NL}), the evident levitation of a magnet on it poses the problem to individuate what kind of magnetic property has or acquire a SC when T is close to T_{NL}. A systematic exploration of the interaction of the SC with different magnets and different objects (ferromagnetic objects in primis), with different configurations, put in evidence that a repulsive effect is ever observed when a magnet is posed close to the SC and no interaction is observed when a ferromagnetic object is putted close the SC alone. These exploration leads to the conclusion that: when $T= T_e$, a SC does not evidence magnetic properties; when $T\sim T_{NL}$, suddenly, magnetic properties emerge (there is a phase transition?). Moreover the SC is not ferromagnetic, it do not transmit the magnetic field inside, it is not a permanent magnet, it do not behave like a magnet, it do not become like the mirror image of the levitated magnet. It always shows repulsive effects close to a magnet, like all the diamagnetic objects placed near a magnet. For that a SC at $T\sim T_{NL}$ must be classified diamagnetic. The strength of the interaction between a SC and a magnet, several orders of magnitude greater than those observed with ordinary diamagnetic materials, suggest to give a more detailed characterization of the nature of the diamagnetism of the SC.

Starting from the evidence that the SC shows magnetic interaction only when a magnet is close to it and that the SC do not interact with a ferromagnetic object, it is possible recognize that the interaction with a magnet do not depend on the pole put close to the surface of the magnet, the equilibrium position is always the same. Changing magnet (inside a range of course), the equilibrium position changes but is always the same, for the same magnet. Moreover when $T_{NL}<T<T_e$ the B field can be different by 0 inside the YBCO sample (a magnet interact strongly with an iron ring also when a YBCO disc is putted in between), but when $T\sim T_{NL}$ the magnetic field inside the SC sample must be very little (in this condition the magnet and the iron ring do not interact when the YBCO disc is in between). The magnetization of the SC is always adjusted to react to the external magnetic field, tending to preserve the initial situation. In particular if B=0 when the superconductivity state is created, the system tend to react to an external magnetic field creating a counter field that tend to maintain B=0 inside the SC (Meissner effect). It is possible to find a similar behavior in the case of eddy current produced in the electromagnetic induction. For instance a magnet is evidently braked when falling down on a thick copper layer or inside a copper tube. It is evident however that never can be stopped, as in the case of the SC. In fact If the magnet were to stop, the induced emf immediately ceases and, due to the Joule effect, also the induced current ceases immediately. The magnet would be stopped just falling over a conductor with R=0 Ω (an ideal perfect conductor!). Supposing that an electromagnetic induction process will be at the base of the superconductivity levitation, a link between the magnetic and electric property of the SC is activated. This suggest that the resistivity of the YBCO sample could be suddenly change when $T\sim T_{NL}$ and the levitation phenomena is observed. The experimental measurement of the breakdown of the resistivity of a SC, give quantitative evidence to this link making explicit also

that a phase transition occurs when the YBCO sample changes from the ordinary conductor state, to the superconductor state.
The phenomenological exploration leads to the conclusion that R=0 as well as B=0 inside the SC, aspects that characterize the Meissner effect. The levitation phenomena, that is a phenomenological evidence of this effect, can be described as a fall down of a magnet occurring at v=0 velocity. When the superconductive state is create with the magnet away from the SC, the magnetic flux changes from 0 to the value corresponding to B*S (B* is the mean value of the magnetic field produced by the magnet on the surface of the SC of area S). When the superconductive state is create with the magnet over the YBCO sample, the flux variation is due to the change in the magnetic properties of the SC. So also in this case, where apparently there isn't a flux variation, an electromagnetic induction process is at the base of the levitation phenomenon.
To give into account how this superconductive state can be created, it is possible to start from the analysis of the energy of the electrons system inside of a crystal lattice. In the ordinary conduction state the electrons could be treated as not interacting particles, because of the negligible interaction occurring and due to two part: a repulsive part, due to the coulombian interaction essentially screened by the mean field produced by the lattice; an attractive part, due to an effective potential emerging as results of the interaction of the electron and the lattice. Only the second part is depending from the temperature, so when it is prevalent with respect to the coulombian part, the system of electrons become instable for creation on Cooper pairs, or in other words the formation of pair of correlated electrons is a process energetically favored. The collapse of these Cooper pairs on the same ground state is responsible of the R=0 property of an SC, that is recognized to be at the base of the superconduction behavior.
The discussion of the creation of Cooper pairs ends the exploration of the Meissner effect that is the main focus of the present work. The educational path faces also the other effect evidenced usually by the II type of SC, as the persistent currents, the pinning effect and the correlated phenomenology. This effects are observed when the superconductivity state is created in presence of an external field. The pinning effect, due to the penetration of the magnetic field inside the SC sample inside the vortexes created by supercurrents, emerges as the anchoring of the magnet to the SC. This is at the base of the MAGLEV train.

4. From electron conduction to the superconduction of the Cooper pairs

The Meissner effect is described characterizing the SC state, on the phenomenological level, with the two conditions B_{int}=0 and R_{SC}=0, but do not giving into account how the phase transition can occurs and the processes that produce the change from the initial situation, to the SC state. This change can be described in an educational perspective as follow.
The energy of the electrons inside a solid, that can be written roughly as the following sum:

$$E_{el} = K_e + V_{int} = \Sigma_{(i)} K_i + \frac{1}{2} [\Sigma_{(i\neq j)} V_{coul} - \Sigma_{(i)} V_{2ij}]$$

where:

- $K_e=\Sigma_{(i)}K_i = \Sigma_{(i)}p_i^2/2m^*$ is the kinetic energy of the electrons, p_i being the momentum of the i-th electron and m* is the effective mass of the electron inside the lattice (including in a phenomenological way the interaction pf the main field produced by the lattice)
- $V_{coul} = \frac{1}{2} \Sigma_{(i\neq j)} V_{coul}(r_{ij})$ is the screened Coulomb energy (of the form: $V_{coul}(r_{ij})=V_c \exp(-\beta r_{ij}) (e^2/ r_{ij})$
- $V_2 = \frac{1}{2}\Sigma_{(ij)}V_{2ij}$ is an effective energy potential due to the interaction of electron and lattice (in the case of Sc of I type this can be written in a relative simple way as a phonon-electron interaction).

In an ordinary conductor the electrons can be treated as a system of non-interacting particles, or weakly repulsing particles due to the predominant term V_{coul} in the interaction part of energy V_{int}. When the temperature increases V_{coul} remains essentially the same, V_2 generally change. In the ordinary conductor V_{int} remains greater than zero. Their state is characterized by the values of: energy, momentum, spin. (es. E, $\mathbf{p}_l$, ↑). Many energy level are possible and are one very close in energy to the other. Of course many electrons can possess the same energy but have different values of the momentum. For each momentum two state are possible (one with spin ↑ and one with spin ↓). The electrons, being spin ½ h particles, due to the Pauli principle, (at T=0 K) fill all the energy level till a maximum value named Fermi energy level. When T increases some electrons can usually acquire energy making a transition to excited state and leaving lower state partially empty. The presence of a band of energy level one very close to the other ensure that the system of electron can exchange energy with the lattice. This exchange is at the base of the presence of a resistivity greater than zero in the ordinary conductors.

In the SC this schema changes, because the attractive contribution V_2 can become greater than V_{coul} and the interaction energy V_{int} become negative ($V_{int}<0$) and the electron are subjected to a net attractive energy. For anyhow smalll $V_{int}<0$ the electrons system become instable for production of couple of electrons correlated by the long range interaction V_2. When one of this pair of electrons (Cooper pair) is created the energy of the system decrease of an amount of the order of the main value of $<V_2>$. The pairs of electrons are (quasi) systems with integer spin. For energetic reasons (but not only) the coupling of electrons with opposite spin and opposite momentum is favored. Due to their integer spin, the electron pairs occupy all the same ground state, that is separated from the first excited state by an energy gap of an amount proportional to $N<V_2>$, where N is the number of pairs created in the systems. The same process that produces the electron pairs, produces also the energy gap. The state created is not only relatively stable, but also ensures that the pairs of electrons cannot exchange energy with the crystal lattice. In other words the energy gap ensure that the resistivity of the system becomes zero. The creation of pairs of electrons is a crucial process in the creation of the superconductive state.

In the case of SC of I type the schema described is framed in the BCS theory of superconductivity [ ], being the V2 term of interaction expressed as a potential energy interaction between two electrons mediated by the exchange of phonons. In the case of the SC of II type it is not clear what kind of interaction is responsible of the V2 energy potential.

6. Experimentation with students

Explorative activities with students are carried out in informal learning setting, in four contexts (Udine, Pordenone, Frascati) with 685 students. These activities was important to test microsteps of the path, in particular for what concern the way in which students discuss the distinction between the levitation due to the Meissner effect and the levitation due to the pinning effect. The research experimentations of the educational path on Meissenr effect of SC was performed with students in eight contexts in Italy (Udine, Pordenone, Cosenza, Bari, Crotone, Siena) with 335 students of Italian upper secondary schools (17-19 aged). In these experimentation tutorial worksheets are used to monitor the students learning, analyzing their answers, drawings and schemas after the construction of typical categories. Few results concerning three main conceptual steps are given, referring to further work a more thorough details.

The change in the properties of the YBCO disc when $T\sim T_{NL}$. When student answered to the question concerning the change of the properties of a YBCO sample when the temperature is $T=T_{NL}$, sentencing: a) «the properties of the YBCO have changed», «the diminution of the temperature produced a change in the behavior of the YBCO» (40%); b) «The disc of YBCO changes his properties. It repels the magnetic field» (35%); «The YBCO disc is magnetized» (13%); Re-arrangement of the atoms (7%); other answers (5%). The change in the property of the superconductor is the main focus of about 90% of the students answers, explicitly referred to the magnetic properties in about half of the sample. When the students were requested to represents the magnetic field configuration that can give account of the stability of the levitation configuration, they drawn: field lines do not penetrating the YBCO if $T<T_{NL}$ (55%); field lines around the SC and aroud the magnet (37%); the lines of the magnet penetrate inside the SC at $T>T_{NL}$ (8%). The first two chategories include all the draw where the field do not entry in the SC.

For what concern the intermediate way to resume the Meissner effect indicate that: “It consists in canceling the magnetic field is part of a SC”, “At a certain temperature of the transition to the SC the Meissner effect means that the SC ceases to oppose any resistance to the passage of electricity and being all or almost all internal magnetic fields” (22%); The Meissner effect makes levitating a magnet over a superconductor without any constraint (57%), “an effect which changes the physical properties of objects subjected to cooling” (14%); “magnetic fields are arranged in such a manner (such as jammed) that the magnetysme in air because it has no possibility to deviate) then receives only fields opposite to the magnet.” (7%). In all the students answers the Meissenr effect is identified phenomenologically. It Is also explicitly framed on the conceptual plane by the students of the first group.

7. Conclusion

An educational path on superconductivity for Upper Secondary School was designed. Students are engaged in an experimental exploration of the phenomenology of use the experiments developed in the context of the European projects MOSEM and MOSEM 2. The focus is on the analysis of the Meissner effect to characterize the perfect diamagnetism of the superconductors under the temperature of the phase transition. With an experimental exploration, carried out both with qualitative observations, both with measurements using on-line sensors, students gradually construct the conclusions that B=0 and r=0 inside a S under the critical temperature. The students use concepts of the electromagnetism (the field lines, the magnetization vector, the electromagnetic induction law) as tools to construct a link between magnetic and electric properties of a syperconductor, describing the phenomenology of the Meissner effect, according to the suggestion of many authors, that show the possibility to describe the Meissner effect in the framework of classical electromagnetism. In the phenomenological description of the superconduction the aim is the recognition of the role of the electromagnetic induction in the description of the Meissner effect. How this state is produced or the phase transition occurs, it is described for what concern the role of the creation of the Cooper pairs on the change in the energy of the electrons system of the superconductors. The focus on energy leave open the opportunity to go deep in the quantum description of the energy gap formation.

From research experimentations carried out in eight different contexts with 335 students emerge that the majority of students recognize the change in the magnetic properties of the superconductor under a critical temperature, the B=0 condition, the different nature of the magnetic suspension and the levitation of a magnet on a superconductor sample.

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