Updating the physics curriculum in high schools: a teaching unit about superconductivity

Fernanda Ostermann y Marco Antonio Moreira

Instituto de Física, UFRGS, Porto Alegre, Brasil.

Abstract: This paper describes the implementation and results of high school physics classes on superconductivity. The study was designed as an attempt of updating the physics curriculum at this level through the progressive introduction of contemporary physics topics. Pre-service physics teachers were trained to do so, and the results, in terms of student's learning and teacher preparation were quite satisfactory.

Keywords: high school physics, physics teacher preparation, contemporary physics.

Introduction

The last two decades of the twentieth century have brought about the consolidation of an international consensus concerning the need to include contents of contemporary physics in the high school physics curriculum (e.g., Arons, 1990; Aubrecht, 1989; Cuppari, Rinaudo, Robutti, and Violino, 1997; Fischler & Lichtfeldt, 1992; Gil & Solbes, 1993; Jones, 1991, 1992; Lawrence, 1996; Müller & Wiesner, 2002; Petri & Niedderer, 1998; Stannard, 1990). Physicists, researchers in physics education, and high school physics teachers are taking part in this movement. Such a trend justifies itself, among other reasons, by the need to attract young people towards scientific careers. It is also essential to awaken the students' curiosity and lead them to identify physics as a human enterprise, therefore bringing it much closer to them. Besides, a good scientific background is part of the full exercise of citizenship.

According to a recent literature review (Ostermann and Moreira, 2000 a), it was possible to verify that in several countries, there is an intense movement concerning the revision of the physics curriculum for high schools in order to insert contemporary physics within it (e.g., Barlow,1992; Ireson, 2000; Solbes, Calatayud, Climent, and Navarro, 1987; Swinbank, 1992). New books and other materials have also been produced under a contemporary view (e.g., Contemporary Physics Education Project, 2002; Fermi National Accelerator Laboratory, 2002; Hewitt, 1998; Swinbank, 1997) and some new subjects have been proposed. In accordance with this recent literature review, it has been possible to verify that there is a large concentration of articles in the following areas: relativity, elementary particles and notions of quantum mechanics (Ostermann and Moreira, 2000 a).

The study reported in this paper makes part of the PhD Thesis of the first author and has the aim of contributing towards the updating of the physics curriculum in high schools, exploring a contemporary theme of the actual scientific research: *superconductivity* (Ostermann, 2000). The area of superconductivity has been little exploited as a contemporary physics subject both in Brazil and abroad for use in high school teaching. It was only possible to find three papers that approach this subject in texts directed towards high school teachers (Ostermann and Moreira, 2000 a). Gough (1998) traces the progress made in technical applications in high temperature superconductors in the last ten years. Shukor and Lee (1998) and Guarner and Sánchez (1992) lay out the construction of equipment with the aim of demonstrating magnetic levitation.

The teaching of this subject took place through the work of six pre-service teachers who were enrolled in the subject 'Physics Teaching' Practice", pertaining to the undergraduate curriculum designed to prepare physics teachers at the Federal University of Rio Grande do Sul (UFRGS), Brazil. Thus, what we report is the experience of trying to introduce this topic in high schools via college students plus the results obtained (Ostermann and Moreira, 2000 b). In spite of referring to a Brazilian experience, we believe that this report might be useful for teachers from other countries as well, considering that the area of superconductivity is not exploited in physics education as a subject to be taught in high schools. This idea is therefore both new and original. In relation to the didactic proposals to teach contemporary physics in high schools, we believe that this study could contribute towards a better understanding in respect of the most appropriate methodology in particular contexts. Before elaborating on our approach, we will discuss the main methodological trends presented in physics education literature.

Three representative trends have been considered concerning methodological approaches for the introduction of contemporary physics in high school education: the exploration of the limits of classical physics, the non-utilization of references to classical physics, and the choice of the essential topics. (Ostermann and Moreira, 2000 a).

The first trend – the exploration of the limits of classical physics – is proposed in the articles of Gil and Solbes of Valencia University, Spain. In their papers (Gil et al., 1988), they show from an analysis of fourty two physics text books in Spain that the majority of these make no reference to:

- the non linear feature of scientific development;
- the difficulties that cause the crisis in classical physics;
- the great conceptual differences between classical and contemporary physics.

For these authors, contemporary physics presented in an over-simplified way in high schools causes serious misconceptions. From a questionnaire responded to by five hundred and thirty six students aged between sixteen and eighteen, the authors have verified that the great majority ignored the existence of a crisis in the development of classical physics and did not recognize the difference between classical and contemporary physics. The authors have suggested that the concepts of contemporary physics should be introduced with a constructivist referent of teaching and learning from a view point of conceptual and methodological change (Gil and Solbes, 1993).

The second trend – the non utilization of reference to classical physics – is atributed mainly to the research of Fischler and Lichtfeldt of the Free University of Berlin, Germany. It is for the most part in direct opposition to the first trend. They consider that the learning of contemporary physics is hampered because it is frequently taught using classical analogies. For example, Bohr's atom, once learned can become an obstacle in the understanding of modern ideas (Fischler and Lichtfeldt, 1992).

The third trend – the choice of essential topics – is represented by the contribution of Arons of Washington University, U.S.A. Arons (1990) proposes that few concepts of contemporary physics should be taught at high school level. It is very important in an introductory course of contemporary physics to maintain a firm link with classical physics to cover the modern topics. However, in the teaching of contemporary physics only the essential concepts of classical physics should be considered in relation to the proposed topic to be learned. In a certain way, these pre-requisites are the main feature of the proposal.

To sum up, it can be verified that although there are few papers concerning methodological discussions on the subject of the teaching of high school contemporary physics there is much discord concerning the best route to be taken. This discord is present in, for example, the role of classical analogies for the understanding of modern concepts, the emphasis or not on pre-requisites and the historical or logical approach. This movement of curriculum change is very recent and a great deal of additional research is necessary to understand better this complex problem (Ostermann and Moreira, 2000 b). Bearing this in mind, the research shown here is an attempt to contribute towards a change in the curriculum. It verifies the possibility of adopting the 'third trend' which relates contemporary physics with classical physics as a mean of introducing the subject of superconductivity in high school physics classrooms.

Research methodology

Our design is not experimental. We have not used random selection for the subjects or the schools involved in the research. We have worked with all the students who have enrolled in the subject 'Physics Teaching Practice' and with all the students that have attended physics classes in schools that were willing to receive our students for their supervised teaching practice.

We do not consider that our students or schools were case studies. Our objective has been simply to study these high school students, pre-service teachers and schools within the existing working conditions to introduce a topic of contemporary physics in the curriculum. We have utilized a didactic approach that we consider innovative and which we will describe without any attempt at generalization or overt profundity. Our research methodology will become clearer in both the description of the preparation of instructional materials and teachers and the teaching of the subject in schools.

The preparation of physics teachers at the Federal University of Rio Grande do Sul

At the Federal University of Rio Grande do Sul, high school physics teachers are prepared in a four-year undergraduate course which is parallel (and almost equal in the first two years) to the B.Sc. in physics, which is also a four-year undergraduate course targeted at the preparation of prospective physicists. Both courses are offered by the Department of Physics. The teachers who graduate from this course are prepared for teaching physics to students between the ages of 14 and 18, who are taking the last three years of secondary education. Physics, in Brazil, is a required subject for all students at this level of education.

The curriculum of the preparation of physics teachers at UFRGS is composed of three groups of subjects concerning the specific physics content, the pedagogical training and the integrating subjects. The physics subjects are the same of the first two years of the B.Sc. course. The pedagogical subjects (educational subjects) and the integrating subjects are taught from the third year on. This last group of subjects make up the curricular interface between the physics subjects and the educational ones and are designed to approach the special didactics of physics. The whole course reaches its climax with the subject ‘Physics Teaching Practice’, which is offered in the last semester and basically consists of the supervised practice of the prospective teachers in high schools. The subject is structured in two parts: a) acknowledgement of the praxis accomplished in the school (through three weekly observational hours) and b) the theoretical part developed at the university (a weekly three-hour class). The first part takes three months. At first, the students observe and monitor (during a two month period) the physics teacher of a given group of high school students previously defined and, later, they teach physics to the same group (approximately one month). Parallel to this, they attend classes at the university in order to acquire a better command of the content to be taught, and to shape and organize their knowledge for classroom work. After the conclusion of the practice, students elaborate a final report within a month, in which they describe all the stages of their preparation. All these stages of the subject are developed under the supervision of the advisor-teacher of ‘Physics Teaching Practice’, which includes visits (observation) to the classes of each teacher-to-be.

The teaching of superconductivity in high schools

Out of the twelve students that enrolled in ‘Physics Teaching Practice’, six taught the topic ‘superconductivity’ in two kinds of high schools: a public state school and a public federal one. The other half of the group was in charge of another contemporary topic and their experience is also part of the thesis (Ostermann, 2000) already mentioned.

These six students were assigned to the schools according to their schedule availability and to the possibilities opened by each school:

- two of them worked in two first-year high school groups of a federal school (61 students between the ages of 14 and 15);
- one taught in a third-year high school group of the same federal school (18 students between the ages of 16 and 17);
- three of them worked in three third-year high school groups of a public state school(66 students between the ages of 16 and 17).

The phenomenon of superconductivity has several appealing features that justify its selection as a topic for inclusion in the high school physics curriculum. For instance, it fits quite well in the science/technology/society (STS) curriculum emphasis. According to this emphasis, students should acquire the scientific knowledge in the context of its technological applications and use it in the full exercise of citizenship. Superconductivity is closely related to the incredible technological revolution that has been taking place since the beginning of this century, providing the opportunity of explaining to the students several potentially motivating applications. In addition, this topic, in spite of being a contemporary research topic, can be illustrated experimentally: it is possible to show the phenomenon of magnetic levitation using a superconducting tablet, a small magnet and some liquid nitrogen in such a way that the students can actually "see" the phenomenon instead of relying on purely abstract theoretical concepts. On the other hand, the understanding of this topic requires previous knowledge of classical physics (particularly some thermodynamical and electromagnetic concepts) as well as some basic concepts of quantum mechanics and solid state physics which are not usually taught at high school. Thus, superconductivity might serve as an interesting bridge between concepts that are already in the curriculum and new ones that should be incorporated in order to update the curriculum. Following this line of thought, this study seeks to widen the discussion concerning which methodological approach should be adopted in the teaching of high school contemporary physics. We feel that the trend that proposes a link between contemporary and classical physics is the most appropriate for the teaching of superconductivity. Thus, we decided that we had enough arguments to attempt to teach this topic at high school, especially in the last year because students would have had the adequate previous knowledge in classical physics. However, it was also possible to teach this topic in the first year of one school in which there was a tradition of beginning the teaching of physics with a conceptual and qualitative overview of the subject centered on the concept of energy. Of course, the implementation of high school physics classes on superconductivity implies a review of the classical topics usually taught. For instance, in the last year of high school we have decided to diminish the usual emphasis on eletrodynamic problems in order to include a teaching unit about superconductivity.

The bibliography available to high school teachers and students about this subject is scarce. This being the case, we started the work of preparing materials that would at first be targeted to high school teachers and, later, adapted to high school students. A 74-page text in Portuguese was prepared (Ostermann et al, 1998 a), directed at high-school teachers, based on several references (e.g., Cyrot & Pavuna, 1992; Luiz,1992; Nobel,1996; Pureur, 1996; Rose-Innes & Rhoderick,1988). This text includes the history of the phenomenon, basic properties of a superconductor (zero resistance and Meissner effect), thermodynamics of superconducting transition, London theory, Ginzburg-Landau theory, BCS theory, magnetic levitation, type-II superconductors and applications of superconductivity. In addition, a superconducting tablet (YBaCuO, critical temperature of 92K) the size of a coin, was manufactured in a research laboratory for demonstration purposes.

Considering the instructional material prepared, the theoretical part of the subject ‘Physics Teaching Practice’ was organized in three stages. During one month, the six students attended college classes based on the aforementioned text and illustrated with slides on superconductivity. The goal of this first stage was to present the subject from a didactical point of view, as well as to help the students fill in any conceptual blanks they might still have regarding superconductivity.

The second stage consisted of preparing the topic for its introduction in high schools. During another month, the students prepared a text (‘student's text’), under the supervision of the teacher in charge of the subject ‘Physics Teaching Practice’ (the first author of this paper). This ‘student’s text’ tried to simplify and, in a certain way, adapt the subject for the level of the high school student. The resulting 21-page text is divided into seven parts: revision of classical physics (metal model, current, resistivity, Ampère's Law, Faraday-Lenz's Law), basic properties of a superconductor (a distinction between superconductor and perfect conductor), change of state, magnetic levitation, BCS theory (with analogies to facilitate its understanding), type-II superconductors, and technological applications. The ‘student's text’ has an introductory section designed to review some aspects of (or to fill in some gaps of) student's previous knowledge required for meaningful learning of the superconductors basic properties: a metal model, electric current, Ampère's Law, and Faraday-Lenz's Law. The idea behind the emphasis on the difference ‘superconductor x perfect conductor’ that exists in the text is to show how different the magnetic behaviors of superconductors and perfect conductors are: superconductors react to a static magnetic field (Meissner effect) whereas perfect conductors react only to variations of a magnetic flux (Faraday-Lenz's Law).

The section on changes of state focused on the comparison of the phase diagram of the solid-liquid-gaseous system with the superconductor phase diagram which itself has two phases: normal and superconducting. One of the most interesting aspects of the superconducting state is that it is a phase transition. We discuss with the students that phase transitions are a class of phenomena very common in nature. Examples of phase transitions are the transformation from ice to liquid and from liquid to gas. Certain parameters control phase transitions and each phase transition has its own thermodynamical parameters. In the case of the solid-liquid-gas system, these parameters are temperature T and pressure P. These two variables can be controlled in laboratory that is why they are called thermodynamic variables. So a given value of pressure and temperature determines the state of the system. Well-defined phase boundaries separate one state from the other. We explain that for a fix pressure, the system can pass from one state to the other by the simple temperature change. For example, at sea level, water exists in the gas state if the temperature is above 100^0 C. With decreasing temperature, the gas condensates in the liquid phase. Further decrease of temperature leaves water to the solid state. In the superconducting transition the temperature is also a thermodynamical parameter that control phase transition. The other is the magnetic field. The superconducting state is stable up to a critical field. For fields higher than the critical field, superconductivity is destroyed. The phase diagram has a line with a boundary which separates the normal from the superconducting state. The critical temperature decreases as a function of the magnetic field. All this discussion is done qualitatively in order to help the students to relate something that they already know (change of state) with something totally new, and to compare the molecular organization of water in each phase with the higher degree of electronic organization that happens in the passage from normal state to superconducting state. In the case of the superconducting transition, we can imagine that the order of charges that is involved. We have discussed the absence of electrical resistivity is one of the main properties of superconducting materials. Considering that electric conduction exists due to charges (electrons) which have movement through the material, we can associate the superconducting transition to the electrons set. Actually, the superconducting state is a manifestation of an ordered electronic state. This electronic organization involves an atractive interaction between electrons. In 1957, Bardeen, Cooper and Schifer proposed a microscopic theory of superconductivity, known as BCS theory. According to them, the electrons in the superconductor form pairs called Cooper´s pairs. The atractive nature between two electrons is handled through the use of a figure showing the formation of a Cooper's pair from the attraction of two electrons by the distortion of the crystal lattice. Some analogies are used in the text: the "mattress effect" (which compares the crystal lattice to a mattress and the two electrons with two negatively charged heavy spheres) and the "domino effect" (an analogy for the absence of resistivity in a superconductor due to the ordered motion of Cooper's pairs). This analogy can help students understand the superconductivity as an ordered motion of pairs. On the other hand, in the normal conduction the electrons have a very disorder motion. Of course, a concept like wave function is not discussed with high school students.

Type II superconductors are presented through their phase diagram and three figures showing the three phases of this type of superconductor. Again, several figures and short paragraphs were used. Levitation is also approached qualitatively through the use of figures and short explanatory paragraphs. Finally, some examples of technological applications of superconductivity are presented in the last five pages of the text.

The third stage was the actual teaching period of each teacher-to-be who taught an average of ten 50-minute classes on superconductivity. Adding up the number of the high school students corresponding to each of the six student teachers, the experiment involved a total of 145 high school students.

Theoretical framework for the teaching approach

The theoretical framework of our study is the meaningful reception learning theory of Ausubel and Novak (Ausubel et al, 1983; Novak and Gowin, 1989) which lays out what the conditions are for meaningful learning. The first is that the student must present a predisposition to learn and the second that the materials should be potentially meaningful. This second condition implies that the material has logical meaning and that the student has, in his/her cognitive structure, the appropriate knowledge. Once these conditions are met the learning process can be receptive in the sense that new information is presented to the student in its final form; it doesn’t need to be discovered but processed. No matter how the new knowledge is presented creatively, the learning process is still considered to be reception learning, which doesn’t mean that it takes place passively. Following this theoretical line, the teaching methodology basically utilized lectures and discussions with the high school students arising from the use of the instructional resources which had been prepared (slides and demonstration of magnetic levitation). The ‘student's text’ was employed as a consultation bibliography and as a reference for the deepening of the subject. Its reading was strongly suggested as preparation for the evaluation.

Results of the high school students' learning

The assessment of the high school students' learning results was based on the application of two questionnaires: one at the beginning, and another at the end of the classes. The initial questionnaire consisted of an open question (Have you ever heard, read and/or studied the phenomenon of superconductivity? If yes, which ideas do you have about the subject?) and eight multiple-choice questions about previous knowledge that the students should have in order to learn the phenomenon (referring to the review of the classical physics in the ‘student's text’).

The final questionnaire had two open items and ten objective questions (with three alternatives each and just one correct answer) about superconductivity. The open questions were the following:

1. What have you learned about superconductivity? Use your own words. Discuss the possible technological, scientific applications or uses that you see in this phenomenon.

2. What else would you like to know about this subject? Has superconductivity awoken any special curiosity in you?

The results obtained with the application of these questionnaires are described in the following.

Results of the initial questionnaire

The answers given by the 145 students involved in this research, concerning the open question of the initial questionnaire have shown that 61% of the students had no previous knowledge about the phenomenon at all.

The average obtained in the objective part of the initial questionnaire, considering all the students, was 3.94. This average, to some extent, showed the need to include a review of classical physics both in the lectures and in the ‘student's text’.

Results of the final questionnaire

The answers given by the same 145 students to the first open question of the final questionnaire were organized according to the concepts they used. The main concepts discussed were: zero resistivity, critical magnetic field, the Meissner effect and Cooper pairs. Almost 40% related zero resistivity with the Meissner effect and Cooper pairs. Considering what had been suggested in the question, 56% gave examples of technological applications.

The percentage of answers to question 2 of the final questionnaire has shown that the phenomenon of superconductivity has not only awoken curiosity in 48% of the students but also that 58% of the students would like to know more about it.

The average obtained in the final ten objective questions, considering all the 145 students, was 7.6. The averages concerning teachers-to-be, the school year and types of school were also calculated.

An analysis of variance (Affifi & Clark, 1996) was carried out and has shown that 30% of the variance of the answers in the final objective test is due to the teachers-to-be; 9% to the school year and 4% to the type of school (level of statistical significance, respectively, 0.00, 0.00 and 0.02). One can see, then, that the variable 'teachers-to-be' is the one which best explains the results of the high school students in the ten final objective questions.

It has also been possible to verify that the correlation coefficient between the results of the initial and final objective tests was low (β = 0.09) and without statistical significance. It means that a student who did not have a good previous knowledge for the study of superconductivity did not necessarily present a low performance in the final test. Such a fact might make sense since before introducing new concepts, teachers tried to reinforce classical concepts such as electrical current, resistivity and electromagnetism.

Results of the performance of teachers-to-be

The performance of the future teachers was evaluated through class observation, their final written reports and their interviews that took place at the end of the course. All the class observations were made through written notes without the use of recording or filming. This observation work was carried out through a form of note taking of all relevant aspects. After each class there was feedback between the advisor-teacher and the teacher-to-be in a constructive manner to assist in the progress of general development. The final written reports were detailed works which included a description and analysis of all the stages of the 'Physics Teaching Practice' course. At the end of the semester, each teacher-to-be had to present him/herself at a recorded interview of fifteen minutes where the main discussion point was the difficulties encountered in the teaching of contemporary physics. The analysis of this qualitative data can be summarized in the following manner:

All the teachers-to-be put great importance on the problems of updating the physics curriculum. In general, they considered the necessity of re-thinking the physics curriculum in high school teaching with the aim of including more updated topics.

Concerning the difficulties encountered in schools, the ones most frequently mentioned were the lack of certain pre-requisites of the high school students, a lack of abstract reasoning, and a general sense of insecurity on the part of the teachers-to-be both in the new content and its application.

One positive point mentioned was the fact that they themselves had prepared the student's text instead of receiving it ready-prepared. On the other hand, they considered that the teacher's text helped significantly in understanding the subject and in the preparation of the text and the materials for the students.

Conclusion and discussion

This paper reported the experience of introducing a contemporary physics topic - superconductivity - into two Brazilian high schools through the classroom work accomplished by six prospective physics teachers during their pre-service teaching preparation. There are few papers in physics education literature regarding the potential of this subject as a contemporary topic for high school. In this sense, the research reported here might be a relevant contribution to the growing demand for studies that approach contemporary physics subjects in an adequate form for high school teaching. Besides this, our study has tried to investigate, in a real classroom situation, learning results that make explicit the failures and successes of the experience of introducing the phenomenon of superconductivity. We believe this investigation represents a contribution to the problem of updating the curriculum, since it explores a topic that is in harmony with some classical contents, which are already part of the curriculum, and at the same time, it advances towards up-to-date physics concepts. This study suggests that for the teaching of superconductivity, the methodological trend that emphasizes links between classical and contemporary physics is the most appropriate. Of course, further studies are required for the teaching of other topics to verify how different subjects can be treated using alternative methodological trends.

The evaluation of this study has led us to conclude that the learning of contemporary physics concepts by high school students is not only possible but it can also generate a larger interest in physics. The students can improve their understanding about classical concepts (in our case, resistivity, electrical current, Faraday-Lenz's Law, amongst others) as well as learn new concepts through analogies (as, for example, in the understanding of the formation of Cooper's pairs). Obviously, the problem of updating the physics curriculum cannot be totally solved simply by inserting a contemporary topic in it. Naturally, the inclusion of more modern subjects demands a re-thinking of the curriculum as a whole, bearing in mind that many classical subjects that are currently taught should be excluded. The inclusion of new and motivating subjects in high school physics should not evoke an increase in the extension of the curriculum. We need to eliminate certain subjects and change our objectives. Although the experience related here is treating one particular subject, it opens the possibility of implementing changes through revitalization and updating of concepts in the high school physics curriculum. This study also shows that it is essential to prepare physics teachers to understand the importance of updating the curriculum and to have the necessary tools to implement it in their school practice. It is also indispensable to invest in instructional materials for contemporary physics topics directed towards students and teachers. As a final point, we believe that working with undergraduate students that are going to be physics teachers is probably a very good beginning.

Bibliographical references

Affifi, A.A. and V. Clark (1996). *Computer-aided multivariate analysis*. London: Chapman & Hall.

Arons, A.B. (1990). *A guide to introductory physics teaching*. New York: John Wiley & Sons.

Aubrecht, G. (1989). Redesigning courses and textbooks for the twenty-first century. *American Journal of Physics , 57*, 352-359.

Ausubel, D.P., Novak, J.D. and H. Hanesian (1983). *Psicología educativa: un punto de vista cognoscitivo*. México: Trillas.

Barlow, R. (1992). Particle Physics: from school to university. Physics Education, 27, 92-95.

Contemporary Physics Education Project. (2002). Internet: http://www.cpepweb.org/

Cuppari, A.; Rinaudo, G.; Robutti, O. and P. Violino (1997). Gradual introduction of some aspects of quantum mechanics in a high school curriculum. *Physics Education, 32*, 302-308.

Jones, D.G.C. (1991). Teaching modern physics - misconceptions of the photon that can damage understanding. *Physics Education, 26*, 93-98.

Jones, D.G.C. (1992). Cosmology and particle physics. *Physics Education, 27*, 76-80.

Lawrence, I. (1996). Quantum physics in the school. *Physics Education, 31*, 278-286.

Luiz, A.M. (1992). *Aplicações de supercondutividade*. São Paulo: Edgard Blücher.

Müller, R. and H. Wiesner (2002). Teaching quantum mechanics on an introductory level. *American Journal of Physics, 70*, 200-209.

Cyrot, M. and D. Pavuna (1992). *Introduction to superconductivity and high-Tc materials*. Singapore: World Scientific.

Fermi National Accelerator Laboratory (2002). Internet: http://www.fnal.gov/

Fischler, H. and Lichtfeldt (1992). Modern physics and student's conceptions. *International Journal of Science Education, 14*, 181-190.

Gil, D.P. ; Senent, F. and J. Solbes (1988). Análisis critico de la introducción de la física moderna en la enseñanza media. *Revista de Enseñanza de la Física, 2*, 16-21.

Gil, D.P. and J. Solbes (1993). The introduction of modern physics: overcoming a deformed vision of science. International *Journal of Science Education, 15*, 255-260.

Guarner, E. and A.M. Sánchez (1992). The superconducting bird: a didactical toy. *The Physics Teacher, 30*, 176-179.

Gough, C. (1998). High temperature superconductors take off. *Physics Education, 33*, 38-46.

Hewitt, P. (1998). *Conceptual Physics: a high school program (8th ed.)*. San Francisco: Addison-Wesley.

Ireson, G. (2000). The quantum undestanding of pre-university physics students. *Physics Education, 35*, 15-21.

Nobel, J. (1996). The Discovery of superconductivity. Physics Today, 49, 40-42.

Novak, D.P. and D.B. Gowin (1989). *Learning how to learn*. New York: Cambridge University Press.

Ostermann, F. (2000). Contemporary physics topics in high schools and in the teacher preparation. Unpublished PhD Thesis

Ostermann, F.; Ferreira, L.M. and C.J.H. Cavalcanti (1998a). Tópicos de física contemporânea no ensino médio: um texto para professores sobre supercondutividade. *Revista Brasileira de Ensino de Física, 20*, 270-288.

Ostermann, F. and M.A. Moreira (2000a). Uma revisão bibliográfica sobre a área de pesquisa "Física Moderna e Contemporânea no ensino médio". *Investigações em Ensino de Ciências, 5*, 1-28.

Ostermann, F. and M.A. Moreira (2000b). Física Contemporânea em la escuela secundaria: una experiência en el aula involucrando formación de profesores. *Enseñanza de las Ciencias, 18*, 391-404.

Petri, J. and Niedderer (1998). A learning pathway in high school level quantum atomic physics. *International Journal of Science Education, 20*, 1075-1088.

Pureur Neto, P. (1996). Supercondutividade. Porto Alegre: Curso de Pós-graduação em Física – UFRGS. Unpublished manuscript.

Rose-Innes, A.C. and E.H. Rhoderick (1988). *Introduction to Superconductivity*. Oxford: Pergamon.

Shukor, R.Abd and K.H. Lee (1998). High temperature superconductor levitation motor. *Physics Education, 33*, 47-50.

Solbes, J.; Calatayud, M.L., Climent, J.B. and J. Navarro (1987). Diseño de un curriculum para la introducción del modelo atómico cuántico. *Enseñanza de las Ciencias, 5*, 309-310.

Stannard, R. (1990). Modern Pysics for the young. *Physics Education, 25*, 133.

Swinbank, E. (1992). Particle physics: a new course for schools and colleges. *Physics Education, 27*, 87-91.

Swinbank, E. (1997). Developing resources for astrophysics at A-level: the TRUMP Astrophysics project. *Physics Education, 32*, 40-45.