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Students' Knowledge of Nuclear Science and Its Connection with Civic Scientific Literacy in Two European Contexts: The Case of Newspaper Articles

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Abstract Nuclear science has uses and applications that are relevant and crucial for world peace and sustainable development, so knowledge of its basic concepts and topics should constitute an integral part of civic scientific literacy. We have used two newspaper articles that deal with uses of nuclear science that are directly relevant to life, society, economy, and international politics. One article discusses a new thermonuclear reactor, and the second one is about depleted uranium and its danger for health. 189 first-year undergraduate physics and primary education Greek students were given one of the two articles each, and asked to answer a number of accompanying questions dealing with knowledge that is part of the Greek high school curriculum. The study was repeated with 272 first-year undergraduate physics, physics education, science education, and primary education Turkish students. Acceptable or partially acceptable answers were provided on average by around 20 % of Greek and 11 % of Turkish students, while a large proportion (on the average, around 50 % of Greek and 27 % of Turkish students) abstained from answering the questions. These findings are disappointing, but should be seen in the light of the limited or no coverage of the relevant learning material in the Greek and the Turkish high-school programs. Student conceptual difficulties, misconceptions and implications for research and high school curricula are discussed.

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1 Introduction

Science education research has shown that the learning of science is a hard task for most students (Johnstone 2006). Both cognitive and affective factors are held to be responsible for this. With regard to the cognitive domain, the abstract nature of science makes learning of science concepts difficult for a majority of students. On the other hand, the emphasis on theories and the lack of context, that is, the lack of a consideration of the connection of science with everyday life and society, are added affective factors in the difficulty and unpopularity of science.

Traditionally, school science is made up of, simply, various adaptations to secondary education of university science programs and textbooks (*transposition didactique*). This is what one calls *formalist* school science. Research in science education considers such adaptations and approaches as being unsatisfactory, and recommends that school science should be an entirely new construction that takes into account educational and cognitive psychology, as well as science-education theory (Johnstone 2000).

Formalist approaches to school science did not pay attention to the affective domain. Modern science education, while still placing the emphasis on cognitive objectives of science teaching, considers affective factors of equal importance. One way of motivating students is by adopting a so-called context-based curriculum. Such curricula approach science topics from a real life perspective and/or a scenario, providing applications as starting points from which to develop the subject. Their success is attributed, at least in part, to higher levels of interest and motivation amongst the students, together with their perception of the relevance of the topics (Gutwill-Wise 2001).

2 Rationale and Purpose

2.1 Scientific Literacy

The term *scientific literacy* (SL) has been discussed since the late 1950s. Various definitions and interpretations of SL appear in the literature (Laugksch and Spargo 1996). 'SL for all students' is in current use an umbrella term for the general purposes and aims that school science curricula should promote. It is generally valued among science educators and curriculum designers as a desirable student learning outcome. Project 2061 has been an important contribution to exploring the concept of SL in science education reform (AAAS 1989, 1993; NRC 1996). According to the international research project PISA (*Program for International Student Assessment*), of the *Organization for Economic Cooperation and Development* (OECD), SL is defined as

> the ability of a person to use scientific knowledge, to ask questions and make conclusions that are based on scientific data, so that to understand the natural world that surrounds him/her and to contribute to the taking of decisions about the changes that the human activity brings to it. (OECD, PISA 2005)

A review of the historical and contemporary meanings of SL and its relationship to science education reform has been carried out by Deboer (2000).

Many researchers in science education identify key components of SL (e.g. Miller 1998; Norris and Philips 2003). Lau (2009) considers the following as core abilities for SL: (1) scientific concepts and their applications in real-life contexts, (2) scientific inquiry processes, (3) understanding of the nature of science, (4) understanding of the relationships between science, technology, and society.

There are various levels and expressions of SL (Shwartz et al. 2006, and references therein). One categorization is based on Shen (1975, cited in Laugksch 2000, p. 77) and distinguishes the following three levels (Shamos 1995): *practical* or *functional literacy; civic literacy* (or literacy as power); and *cultural* or *ideal literacy.* For Laugksch (2000), this categorization of SL is not mutually exclusive, but is distinct with respect to objective, audience, contents, format, and means of delivery.

- *Practical* or *functional literacy* is the lowest level, and refers to the ability of a person to function normally in his/her daily life as a consumer of scientific and technological products, such as food, health, and shelter.
- *Civic literacy* or *literacy as power* is connected to the capacity of a person to participate wisely in a social discussion relevant to current scientific and technical issues that are of interest and crucial for society. This capacity will make the person capable of understanding the issues of our time, and being an informed and critical citizen, with the ability to take the right decisions that will or might affect the future of humanity. Shen (1975) has considered civic SL to be the cornerstone of informed public policy. Miller has suggested that civic SL should be conceptualized as involving three related dimensions: (1) a vocabulary of basic scientific constructs sufficient to be able to read competing views in a newspaper or magazine, (2) an understanding of the process or nature of scientific inquiry, and (3) some level of understanding of the impact of science and technology on individuals and on society [Miller (1983), cited in Miller 1998, p. 20]; in addition, it should involve understanding the essence of competing arguments on a given dispute or controversy (Miller 1998) .
- *Cultural* or *ideal literacy* involves appreciation of scientific endeavors and perception of science as an intellectual activity. It is a higher-level, metacognitive capacity that is achieved in part by a minority of students and which develops throughout one's life under the influence of further input from work and society. Shen (1975) has indicated that this category is important and influential because it would reach current and future opinion-leaders and decision makers.

Another hierarchy distinguishes the following five kinds of SL: (1) *Scientific illiteracy*, (2) *Nominal SL* (3) *Functional SL* (4) *Conceptual SL* (5) *Multi-dimensional SL* (Bybee 1997). *Nominal* and *functional* SL is about the ability to use scientific vocabulary. *Conceptual SL* demands an understanding of scientific concepts. Within *multi-dimensional SL* students develop some understanding and appreciation of science and technology in connection with their everyday life, and they are aware of the major issues that constitute a challenge for society. According to Bybee (1997) achieving multidimensional SL in all scientific disciplines is probably impossible or a lifelong target and this might never be attainable.

2.2 Purpose

Students in two European countries, Greece and Turkey, completed a diagnostic instrument designed to elicit: on the one hand, knowledge and thinking related, in principle and in particular, to conceptual SL of upper-secondary-school Greek and Turkish students with regard to fundamental concepts and knowledge of nuclear physics; and on the other hand, knowledge and thinking related to civic SL (see below). The study offers further an opportunity to compare responses and knowledge in two educational contexts, and to explore the extent of similarities and differences. The focus on these two particular countries was simply a matter of convenience, with these countries sharing no special feature(s) to make them characteristic or distinct cases.

Scientific knowledge constitutes 50 % in the PISA framework for testing SL, so scientific knowledge is essential for participating in a relevant social discussion and in decision making about crucial problems such as whether a fusion nuclear plant should be built. Because, however, this knowledge is not taught or debased in either Greek or Turkish high schools (see below), we hypothesized that the relevant knowledge of the Greek and the Turkish students should be weak.

The knowledge of nuclear science covers all three aspects of SL according to the first hierarchy, with more emphasis on the second level (civic literacy). The focus of this study is (1) on the knowledge of the relevant science by the students; (2) on civic literacy, or on multi-dimensional SL according to the second hierarchy, referring to peace and sustainable development. These crucial issues are involved in our study implicitly (by means of the newspaper readings that were used in the study), and explicitly (by means of the questions):

- *Can you cite some of the (significant) advantages of nuclear energy projects over conventional fuels?*
- *Do you know of another non-peaceful use of the nuclear energy?—you can provide relevant historical information.*
- *What is the meaning of the term 'radioactive waste'?*
- *Do you have any idea of how radioactivity affects human and animal health?*
- *Can you think why radiation workers are given higher dose exposure limits than the general population?*

In addition, some questions dealt with the vocabulary of basic nuclear concepts, which were deemed essential for students' understanding of competing views in the newspaper article:

- *What is a nuclear reactor?*
- *What do we mean by the terms radioactive material and nuclear radiation?*

2.3 Review of Related Studies

A number of studies have explored the confusion and partial understanding of radioactivity in general (Durant et al. 1989; Lucas 1987) or in connection with nuclear accidents, such as those of Chernobyl or the Gioania accident in Brazil (Eijkelhof and Millar 1998; Martins 1992; Nunes and Zylbersztain 1990). Millar (1994) focused on the lack of differentiation of the terms 'radioactive-source' and 'radiation'. Kaczmarek et al. (1987) focused on second-year medical students' misconceptions about radiation. A notable finding was that almost 75 % of the students believed that objects in an X-ray room would emit radiation after a diagnostic examination.

Children's understanding of radioactivity has been explored by Eijkelhof et al. (1990). The findings indicated that: (1) the terms 'radiation', 'radioactivity' and 'radioactive matter' tended to be undifferentiated; (2) radiation is frequently perceived to accumulate in living things, objects and closed space, for instance radiation was thought to concentrate in vegetative matter and be released to humans when consumed after the Chernobyl nuclear accident; (3) any situation involving radiation is strongly associated with danger—a reaction that is constantly reinforced by the mass media (Klaassen et al. 1990). Linjse et al.

(1990) used the information presented in the media about the Chernobyl accident to study pupils' ideas about radioactivity. Boyes and Stanisstreet (1994) studied 11 and 16-year old students' understanding about radioactivity and radiation, and reported that relatively few pupils seemed aware of the natural, 'background' sources of radioactivity, but that the majority of children of all ages thought that radioactivity came from nuclear power stations. A high percentage thought that radioactivity could kill or otherwise harm living organisms. Eijkelhof et al. (1990) approached radiation experts in order to get a better insight into (a) lay-ideas that may exist about ionizing radiation, (b) the importance of these ideas for risk assessment, and (c) the relations between the various lay ideas. These relations were expressed in a framework of lay-thinking and were contrasted with the experts' view. Colclough et al. (2011) focused on secondary school pre-service teachers' knowledge of and attitudes towards risks associated with alpha, beta, and gamma radiations, and concluded that their findings raise questions about the extent to which pre-service science and history teachers have the knowledge necessary to teach this topic.

Powell et al. (1994) considered the value of the topics of nuclear energy and of radioactive waste management (RWM) in school science. Integrated science and comparative energy approaches were considered necessary in order to teach these topics. According to the authors, teachers can help students understand the scientific and sociological contexts of nuclear energy and RWM when they teach these topics in the broader context of the needs of society, and when they help students see the interconnections between science, technology, and society. In addition, by comparing the advantages and disadvantages of different energy sources (i.e., nuclear, solar, fossil, geothermal), students can better be prepared to discriminate between them and to appraise critically their value within economic, social and environmental frameworks. Williams (1995) considered safe isolation of nuclear waste to teach science in the context of politics and history. Henriksen and Jorde (2001) developed an exhibition on radiation-related environmental issues for visiting students at the Norwegian Museum of Science and Technology, and identified Norwegian 16-year-olds' prominent features in understanding of radiation. In many aspects these features were similar to those described for students of other age groups and nationalities.

Alsop and Watts (1997) built on Treagust's refinement of the Strike and Posner model of conceptual change by recognizing the important role of affective and social domains beyond the purely cognitive domain. They carried out four case studies concerning informal learning of radiation and radioactivity by members of the general public in a rural village in a geographic area in the UK that has high levels of background radiation through naturally occurring radon gas. Alsop (2001) carried out a quasi-scientific comparative study of two groups of 'recent school leavers' in the UK to explore if people living with the immediacy and relevance of higher than average levels of radiation are more knowledgeable and emotionally detached compared with a similar group removed from this health concern. Although, few conceptual and emotional differences were observed, the participants faced with higher than average radiation levels were found to be more knowledgeable about everyday practicalities of living with increased risk due to elevated radon concentrations.

Finally, Nakiboğlu and Tekin (2006) detailed the types of misconceptions Turkish high school students hold about basic concepts and topics of nuclear chemistry. The misconceptions related to nuclear stability, half-life, binding energy, practical applications of nuclear chemistry, and radioactive decay rate. Students had difficulties with the concept of isotope atom and with the fact that elements can contain different naturally occurring isotopes; they also confused nuclear and chemical reactions. The authors attributed the problems to (1) the highly abstract nature of the relevant concepts, (2) difficulties with basic chemistry concepts that are essential prerequisites for learning nuclear chemistry, and

(3) the fact that nuclear chemistry is usually placed in the last chapters of chemistry textbooks, and as a result it is not given sufficient attention.

2.4 Subject/Problem: The Uses, Applications, Abuses, and Risks of Nuclear Science[1]

Nuclear science has two kinds of uses and applications: (1) peaceful ones directed at producing cheap and 'clean' energy, thus contributing to sustainable development, as well as medical applications; and (2) military ones related to the armaments industry. These uses and applications constitute currently an issue that appears very high in the world political agenda, both in terms of its peaceful uses and its threat to world peace, through the possible spread of the development of nuclear weapons. Of particular importance is the use of nuclear plants for energy production, especially taking into account the current crisis over the high-price of oil and the environmental problems that are associated with carbon emissions. While most people appear to be against nuclear weapons, scientists and politicians are often divided over the matter of the peaceful use of nuclear energy, with one side emphasizing its usefulness and advantages and playing down the dangers, and with the other side being focusing on those dangers.

The recent (March 2011) nuclear accident at the *Fukushima Daiichi* nuclear power plant that followed the devastating magnitude 9 earthquake and the follow-up tsunami that ravaged North Japan initiated another round of heated discussions in the mass media about the safety of nuclear plants and of nuclear power. Of particular relevance to this work is a web commentary entitled "Science literacy and nuclear accidents" (APS Physics 2012), according to which:

> People's reactions (to nuclear accidents or to the specter of a radiological terrorist attack) are not in necessarily line with what the actual risks may be, and that all things nuclear and radiological scare them, sometimes unnecessarily. That lack of scientific literacy is a growing legacy of our educational system, one in which STEM education (science, technology, engineering and math) is no longer valued, emphasized or funded. Add to this the fact that most K-12 science and math teachers don't even have a degree in these fields, and you have a public that can't tell an atom from a neutron. No wonder anything nuclear frightens people. They don't understand it. Suspicion of government secrecy, cover-ups and untoward practices by industry further complicates the mix.

Notwithstanding, the Fukushima Daiichi tragic nuclear accident, as well as previous ones (Chernobyl and Three Mile Island) are a powerful reminder of how limited is our predictive power and even our understanding of the natural world. It follows that the knowledge of basic nuclear science concepts and topics is essential for the modern citizen, and therefore should constitute an integral part of SL.

3 Methodology

3.1 The Material

Informal learning resources are encountered both in school and in out-of-school environments using mass media, such as non-school books, newspapers, magazines, television, the internet, museums, etc.[2] Hofstein and Rosenfeld (1996) have reviewed how informal

[1] For an extended literature about nuclear energy, its uses and abuses, nuclear physics and chemistry curricula, and other relevant topics, see http://www.nriched.eku.edu/bibliogr.htm (accessed 03 January 2013).

[2] See, for example, Collins and Bodmer (1986), Hofstein and Rosenfeld (1996), Kariotoglou and Papasotiriou (1999), Wellington (1990, 1991).

science learning, including press and electronic media, might be better integrated into formal science learning, and concluded that it can make significant contributions in providing diverse learners with appropriate learning opportunities and in motivating them to learn science, both within and outside schools.

Parkinson and Adendorff (2004) reported that popular science articles can play a useful role in the teaching of science and make science more accessible to students; in particular, popular science articles view scientific findings as provisional rather than as incontrovertible fact, as they are presented in textbooks or as they appear to be presented in research articles. Oliveras et al. (2011) identified the difficulties experienced by secondary school students (aged 15–16) with critical reading of newspaper articles with scientific content and found that the activities designed were useful in helping students to read critically. The instrument used enabled the authors to detect those aspects of critical thinking where students had the most difficulties: identifying the writer's purpose and looking for evidence in a text. It was also shown that the stance taken in the articles had an influence on the results.

In informal forms of learning, various science topics are encountered such as health and medicine, nutrition, environment, energy, new materials, astronomy and the space. This kind of knowledge makes a decisive contribution to citizen's scientific literacy and to the attitudes the citizens adopt with respect to science, science issues and scientific problems.[3] Topics relevant to nuclear science are not rare. Linjse et al. (1990) have argued that information derived from the media on the radioactivity following the Chernobyl accident was particularly important as a starting point for science education topics that relate to the life-world domain. Henriksen and Jorde (2001) reported that a visit to an exhibition on radiation-related environmental issues provided science learning outcome for the majority of the students; however, students who had strong alternative conceptions about the exhibition's issues found it difficult to interpret correctly new concepts introduced at the exhibition.

In this study, we have used articles from two Greek newspapers. The articles were not used intact but they were modified/adapted by one of the Greek authors of this paper (GT), to meet the needs of the study. In particular, the adaptation concerned addition and emphasis of necessary scientific concepts and the deletion of those parts that were outside the purposes of the study (when they dealt, for instance, with political issues). The adapted (slightly abridged) articles are in the "Appendix". A number of questions that were based on each article were constructed by the Greek authors, following the methodology of Shwartz et al. (2006). Four experienced Greek teacher-physicists checked the questions for content, appropriateness and clarity; following their comments, corrections and changes were made and the final form was reached.

Although many questions tested only relevant science knowledge, several also dealt with societal issues which, in our opinion, relate to, and attempt to promote students' civic scientific literacy (see below). One might rightly ask, whether students' answers would be different if they had not read the newspaper articles. Unfortunately, our data do not enable us to answer this question. However, as all the questions were related to information and topics discussed in the articles, we believe that the reading of the articles, and the coupling and association of the questionnaires with the articles should make evident to the students the importance and relevance of the concepts and topics of nuclear science to modern society locally, nationally, and internationally.

[3] See for example, Wellington (1991), Jenkins (1999), Halkia et al. (2001a, b).

3.1.1 Article 'A': ITER: The reactor that is going to change the world

One article discusses the new thermonuclear reactor for hydrogen fusion that is going to be constructed in the French town Cantaras by a consortium of collaborating nations (Varvoglis 2005). Examples of questions used and the corresponding relevant excerpts from the articles follow. (Emphasis has been added by the authors of this article, to focus students' attention on the terms and phrases that were relevant to the questions.)

- The energy that is released when 1 g of hydrogen atoms (1 mol of atomic hydrogen) undergoes the fusion reaction is equal to the energy that is released from the burning of about 23,000 liters of gasoline. *How could one explain in physics terms the huge production of energy that is released in nuclear reactions?* (HINT: The explanation is connected to a famous twentieth-century physicist.) / *Has the hydrogen nuclear fusion a relationship with sun, the star that supplies us with energy?*
- Since 1954, when the first testing of the **hydrogen bomb** was carried out, physicists have been trying to develop a **peaceful use** of this **new source of energy**, **hydrogen fusion**. *Do you know of another, non-peaceful use of nuclear energy?—You can provide relevant historical information.* However, that target proved much more difficult to achieve than the corresponding effort to harness **atomic energy** from the **decomposition (fission) of uranium**. *What do you know about the decomposition ('fission') of uranium?*

3.1.2 Article 'B': Depleted Uranium: A disastrous nuclear waste

The second article was a combination of two Greek newspaper articles (Bitsika 2001; Vagena 2001) about 'depleted uranium', the nuclear waste and its danger for health. Because of its great hardness, depleted uranium is extensively used in highly penetrating, and therefore highly destructive missiles. Examples of questions and the corresponding relevant excerpts from the article follow:

- The **radioactive mineral uranium** (U) that exists in **nature** consists mainly of **two isotopes**, **U-235** (^{235}U) and **U-238** (^{238}U). *What are isotopes and what are radioisotopes?*
- U-235 is used in **nuclear reactors** to produce **huge amounts of energy** by means of the **nuclear fission reaction**, while U-238 is not useful in that. *What is a nuclear reactor? Refer to the similarity and from one to three differences between the nuclear reaction that takes place in the explosion of a nuclear bomb and the nuclear reaction that takes place in a nuclear reactor.*
- When it explodes, splinters and radioactive material in the form of very fine dust disperse over a **large distance**, and, practically, they **remain there forever**, **polluting** the **soil** and the **water-carrying zone**. *What do we mean by the terms 'radioactive material' and 'nuclear radiation'? Why does* ^{238}U *pollute forever?*
- The **annual permitted radioactivity** for **nuclear workers** was 156 rem (a dose that also depends on the kind of radiation, and which is ten-times higher for **alpha particles** than for **gamma** or **X rays**). *What are 'alpha particles'? What is 'gamma radiation'? What is 'X radiation'?*

Both texts deal with uses directly related to life, society, the economy and politics. The scientific knowledge that is involved in the two articles (nuclear fusion reaction, nuclear fission, mass-energy relationship, magnetic field, isotopes, radioactive isotopes, types of radiation, radio-active decay, half-life time, etc.) are part of the physics curriculum for general education of the Greek 12th grade, but also of the chemistry curriculum for the 10th grade as the last unit in both curricula. However, the chapter on nuclear chemistry was at the end of the chemistry textbook for the Greek 10th grade and was never taught; on the other hand, the physics course for the Greek 12th grade, which covered nuclear physics, was no longer compulsory but an elective, which was not chosen by the large majority of students. For these reasons, we hypothesized that the relevant knowledge of upper-secondary Greek graduates would be weak. Note that in the currently under revision chemistry curriculum for the Geek 10th grade, the chapter on nuclear chemistry has been removed, while the destiny of the topics on nuclear physics in the new physics curriculum is still unknown.

In the case of Turkey, the relevant knowledge is part of the curriculum of the 11th grade (in the current chemistry curriculum) and the 12th grade (in the current physics curriculum) as the last unit in both curricula. On the other hand, since the Turkish curriculum was changed in recent years, the Turkish sample of this study had not studied nuclear physics in high school. They were only taught nuclear chemistry in the 10th grade. The hypothesis of weak relevant knowledge in the case of the Turkish graduates, like their Greek counterparts, is also raised here.

The articles, with their accompanying questions, were randomly distributed to the students. All students were informed about the research character of the study and participated voluntarily in it. Each student answered one questionnaire only. In the case of the Greek sample, the evaluation of the students' answers was carried out by one of the authors (SH) according to an evaluation scheme agreed between the two Greek authors, which distinguished answers into (1) *acceptable*, showing ability to think and understand; (2) *partially acceptable*, showing partial understanding/restricted ability of thinking; (3) *unacceptable*, showing fundamental error(s)/lack of understudying/irrelevant thinking. Both Greek authors evaluated a number of papers, until agreement between them was reached. In addition, reliability of the evaluation of the answers was checked by ten secondary education teachers (7 physicists and 3 chemists). To the ten teachers, another questionnaire was distributed in which 72 selected students' answers were included and the teachers were asked to evaluate them according to the above evaluation scale. The selection of some of the students' answers was made on the basis of the difficulty of their evaluation by the researcher. The agreement between the researcher and the ten teachers varied between 73.3 and 94.1 %, with an average value of 86.5 %.

The Turkish version of the instrument was translated from English into Turkish by the Turkish author (CN) of this study and by two Turkish doctorate students of chemistry education. A single text was then compiled by CN, and this version was used with eight first-year chemistry education students, who just graduated from secondary schools, like the Turkish sample of this study. After examining the students' answers and discussing with them, changes were made and the final version of instrument was prepared. To establish the content validity of the instrument for the Turkish case, both the current and the previous secondary school chemistry and physics curricula and textbooks were examined by the Turkish author of study. In addition, three chemistry and five physics teachers were involved in the validation.

To establish reliability of the evaluation of the Turkish students' papers, first, the Turkish author translated into English a number of student papers for each test (8 of ITER and 8 of DU). Secondly, these papers were scored independently by the Turkish and one Greek author (SH) according to the evaluation scheme used for the Greek students' papers. A 90 % agreement for the ITER test, and 84 % agreement for the DU test were noted. Any discrepancies were discussed among the authors until agreement was reached. Following that, the rest of Turkish papers were evaluated by the Turkish author.

3.2 The Greek Context

Upper secondary education ('lykeion') in Greece has three grades (10th, 11th, and 12th) where science is taught as separate subjects. In 'lykeion' we distinguish between subjects for general education, and advanced courses for specialized *streams* or *tracks* of studies. Physics is taught as general subject in all three grades, while chemistry only in the 10th and 11th grades, and biology in the 11th and 12th grades. All students follow the same courses up to the end of 10th grade. Starting at 11th grade, students have to follow one of three 'streams': The 'Positive' Stream (PS), the 'Technological' Stream (TS), and the 'Theoretical' Stream (ThS). The PS is for students who want to study science, engineering, agricultural studies, and related applied subjects, or health-related studies (medicine, dentistry, pharmacy, etc.); it has mathematics, physics, chemistry and biology as specialized courses. Except for health-related studies, the TS pursues similar studies to the PS. It also shares with the PS the specialized mathematics and physics courses, but does not include the study of chemistry or biology. Finally, the ThS is for students who want to study literature, law, humanities etc. and does not, include any specialized mathematics or science courses. A national curriculum with standard textbooks published by the state is followed strictly. To enter tertiary education, Greek students take entrance examinations, organized and administered by the Ministry of Education, which include the specialized courses for each stream.

3.3 The Greek Sample

The Greek subjects of this study were 85 first-year undergraduate Physics (PHY) students and 104 first-year undergraduate Primary Education (PriEd) students (age 18–19) from a Greek university. Their knowledge in nuclear physics derived only from their secondary education.

The choice of the PHY students for our study is obvious, by providing a point of reference for this study. The PriEd students differ from their fellow PHY students as follows: while all PHY students had followed mainly the TS and in small part the PS, the PriEd students were 36.5 % from the TS or the PS and 63.5 % from the ThS. Because physics is not important in the university entrance examinations of the ThS, it is natural that the students of this stream pay little attention to their physics courses. However, these students had achieved better grades in these examinations. As a result, it was expected that they would show less skill at technical issues (for example in writing about nuclear reactions) but more skill in giving complete explanations or interpretations.

The students took the nuclear physics test during the months of February and March of 2008 before the university physics course had dealt with nuclear physics. Therefore, knowledge on which the students based their answers was that received in their upper secondary chemistry courses.

3.4 The Turkish Context

In Turkey, secondary school (*lycée* or *high school*) comprises grades 9–12, ages 15–18. It encompasses different categories of educational institutions. In the 10th, 11th and 12th grades, chemistry and physics lessons are taught either as compulsory or elective courses according to the category of secondary school and *streams* or *tracks* chosen by students.

The Turkish samples of this study were taught according to the previous physics and chemistry curricula. Although the topic of nuclear science was placed in the previous high school chemistry curriculum of the 10th grade, nuclear science topics were not part of the previous high school physics curriculum. So we hypothesized that the relevant knowledge of secondary Turkish graduates would be weak. (Note that Turkey introduced nuclear science into both the physics and chemistry curricula for General high schools, Anatolian high schools, and Science high schools at 11th and 12th grades in 2011. However, both the unit on nuclear chemistry and that on nuclear physics are at the end of the chemistry and physics textbooks respectively.)

3.5 The Turkish Sample

The sample was drawn from four first-year departments at the two faculties of a public Turkish University (at the beginning of the academic year 2009, age 18–19). The samples were: (1) Physics (PHY) ($n = 37$); (2) Physics Education (PhyEd) ($n = 48$); (3) Science Education (SciEd) ($n = 85$); and (4) Primary Education (PriEd) ($n = 103$). Their knowledge in nuclear physics derived only from secondary education. With the exception of PriEd, the students had attended the *Science* stream and had taken the chemistry and physics lessons as separate and compulsory courses in the 10th, 11th and 12th grades. The PriEd students were mainly from the *Turkish language–Mathematics* stream (89 %) and partly from the *Science* stream (9 %). The students of the *Turkish language–Mathematics* stream did not have chemistry and physics lessons as compulsory courses. The PhyEd, SciEd, and PriEd students were higher achievers than the PHY students—"achievement" refers to achievement in the Turkish University Entrance Examination.

4 Results

4.1 General Findings

A large number of students abstained from providing answers to many questions. Table 1 shows the data for the two tests. (The letters I and D preceding the number of the question signify the ITER and the Depleted Uranium Questionnaire respectively.) As a rule, questions that were not answered by high proportions of students received small proportions of acceptable answers (compare the data of Table 1 with the data in subsequent tables). More than 50 % of Greek students did not respond to seven (out of 15) questions on the ITER test and to twelve (out of 23) questions on the DU test. On the other hand, only for one question (I-6c) on the ITER test, and for two questions (D-1a$'$ and D-2c) on the DU test, did the proportion of Turkish students who did not respond exceed 50 %. In general, Greek students abstained in larger proportions than the Turkish students in answering most of the questions. It is not easy to supply an explanation for that. It might be that cultural factors are in operation here. This is in contradiction to and supported by the fact that the Greek students provided more acceptable responses than the Turkish students in most of the questions.

Comparison of the proportion of no responses between the two samples of Greek students, leads to the finding that in many questions PriEd students had higher proportions than the PHY students (although there were a notable number of questions in which PHY

Table 1 Percentages of no responses for each item of the two tests

ITER test			DU test					
Question	GR	TR	Question	GR	TR	Question	GR	TR
I-1	18.1	4.5	D-1a	56.8	15.2	D-7	44.2	30.4
I-2	62.8	39.1	D-1a′	87.4	55.8	D-8a	70.5	35.5
I-3	58.5	42.1	D-1b	31.6	21.0	D-8b	63.2	36.2
I-4	39.4	11.3	D-2a	40.0	34.1	D-8c	53.7	44.9
I-5	17.0	13.5	D-2b	57.9	34.8	D-8d	63.2	27.5
I-6a	54.3	20.3	D-2b′	57.9	36.2	D-9	31.6	13.8
I-6b	62.8	36.1	D-2c	67.4	51.5	D-10	37.9	21.0
I-6c	59.6	62.0	D-2d	45.3	23.9	D-11	42.1	21.0
I-7	29.8	26.3	D-2e	68.4	37.7			
I-8a	28.7	16.5	D03	40.0	21.7			
I-8b	55.3	16.5	D-4a	55.8	26.1			
I-9	54.3	22.6	D-4b	57.9	41.3			
I-10a	37.2	21.0	D-4c	37.9	10.2			
I-10b	30.9	18.1	D-5	31.6	21.0			
I-11	34.0	16.6	D-6	20.0	11.6			

The letters I and D preceding the number of the question signify the ITER and the Depleted Uranium Questionnaire respectively

students had higher proportions). Recall that the PriEd students had received little teaching of nuclear physics in their physics courses. But even if these differences are taken into account, the PriEd sample had, as a rule, still higher proportions of no responses than the Turkish sample.

4.2 Categorization of the Questions

In our presentation of the results of the various questions in the two tests, we have categorized the questions into a number of categories as follows:

- Questions on knowledge provided in the texts
- Scientific questions about nuclear science
- Chemistry and physics knowledge questions not involving nuclear science
- General knowledge questions
- Questions about specialist knowledge discussed in the mass media, which is not usually part of the school curriculum
- Critical thinking questions.

This categorization resulted following discussions among the three authors. A number of Principal Component Analyses were carried out on the total as well as various parts of our data, but failed to provide consistent support for this or any other categorization of the questions. It appears that miscellaneous factors are in operation, but we are unable to detect a structure in the questions. As a result, the categorization of the questions that we follow in our presentation below should be treated only as a convenient organizational tool.

4.2.1 Questions on Knowledge Provided in the Texts

A small number of questions could be answered by using directly or combining information provided in the given newspaper texts. Table 2 has the results for these questions. As expected, students were, in modest proportions, successful with these questions, although the Greek students had better performance than their Turkish counterparts.

4.2.2 Scientific Questions about Nuclear Science

A number of questions in both tests required for their answer specialized knowledge from nuclear science. Although, as stated above, such knowledge is part of the curricula in both countries, this knowledge is not taught and/or is paid no attention in the teaching and the examinations. However, one or two questions in nuclear science are *sometimes* included in the Turkish university entrance examination. It is not then surprising to get poor results from both the Greek and Turkish students. Table 3 has the relevant data.

4.2.3 Chemistry and Physics Knowledge Questions Not Involving Nuclear Science

Some questions involved knowledge that is taught in the chemistry and physics course (some of which is prerequisite for understanding nuclear concepts), but does not involve directly nuclear science: ionization of hydrogen; origin of protons and electrons of plasma; production of hydrogen by electrolysis of water; isotopes; mass number. (For instance, "*Do you know the method of preparing hydrogen from water? Does it require energy and if so, of what form?*") We do not present the results here, but suffice it to say that performance was better than in the scientific questions about nuclear science. This supports the argument that knowledge of nuclear science is not well covered in either Greek or Turkish high schools.

Table 2 Questions on knowledge provided in the texts

		% Acceptable only		% Acceptable + partially acceptable		% Unacceptable[a]	
		GR	TR	GR	TR	GR	TR
I-1	Thermonuclear reactor	51.1	30.9	66.0	63.2	16.0	32.3
I-7	Production of magnetic field	40.4	36.1	51.0	43.6	19.1	30.1
I-9	Main property of plasma in fusion reactor	30.9	16.5	30.9	18.0	14.9	59.4
D-2a	Nuclear reactor	30.5	6.5	42.1	15.9	17.9	50.0
D-4c	U-238 pollutes for ever	30.5	21.7	40.0	34.7	22.1	55.1
D-9	Radioactivity affects human and animal health	36.8	7.2	55.7	31.1	12.6	55.1

[a] Excluding no responses

Table 3 Scientific questions about nuclear science

Questions		% Acceptable only		% Acceptable + partially acceptable		% Unacceptable[a]	
		GR	TR	GR	TR	GR	TR
I-2	Equation for hydrogen fusion reaction	4.3	0.7	11.7	6.0	25.5	54.9
I-3	$E = m\,c^2$	2.1	0.0	20.2	0.0	21.3	57.9
D-2c	$E = m\,c^2$	1.1	0.0	12.7	0.7	20.0	47.8
I-6a	Decomposition (fission) of uranium	5.3	0.0	13.8	6.0	31.9	73.7
D-1a′	Radioisotopes	4.2	13.8	7.4	16.7	5.3	27.5
D-2d	Nuclear fission reaction	14.7	0.0	28.4	10.9	26.3	65.2
D-2e	Other than fission nuclear reaction	17.9	2.2	17.9	21.7	13.7	40.6
D-3	Half life	7.4	5.8	17.9	18.1	42.1	60.2
D-8a	Alpha particles	8.4	2.9	14.7	21.0	14.7	43.5
D-8b	Gamma radiation	0.0	0.0	14.7	6.5	22.1	57.3
D-8c	X-rays	2.1	0.0	20.0	1.5	26.3	53.6
D-8d	Other type of radioactive radiation	2.1	31.9	4.2	39.9	32.6	32.6

[a] Excluding no responses

4.2.4 General Knowledge Questions

Five questions dealt with matters of general knowledge that are relevant to nuclear science, Except for question I-5, the percentage of acceptable answers was low. On the other hand, for three questions, the percentage of acceptable and partially acceptable answers was larger than 50 %. For the results see Table 4.

4.2.5 Questions Involving Specialist Knowledge about Nuclear Science

A number of questions involved specialist knowledge about nuclear physics, which is or has been discussed in the mass media, but usually is not part of the school curriculum. As a consequence, student performance in these questions was low (see Table 5).

Table 4 General knowledge questions

		% Acceptable only		% Acceptable + partially acceptable		% Unacceptable[a]	
		GR	TR	GR	TR	GR	TR
I-5	Actual non-peaceful use of nuclear energy	58.5	28.6	68.1	54.9	14.9	31.6
I-10b	Radioactive waste	16.0	13.5	57.5	28.5	11.7	53.4
D-2b	Similarities of nuclear bomb and nuclear reactor	15.8	3.6	30.5	20.3	11.6	44.9
D-2b’	Differences of nuclear bomb and nuclear reactor	23.2	0.0	33.7	4.4	8.4	59.4
D-5	Nuclear waste	20.0	4.4	52.6	23.9	15.8	55.1

[a] Excluding no responses

Table 5 Questions about specialist knowledge discussed in the mass media, which is not usually part of the school curriculum

		% Acceptable only		% Acceptable + partially acceptable		% Unacceptable[a]	
		GR	TR	GR	TR	GR	TR
I-4	Nuclear fusion in sun	13.8	3.0	23.4	10.5	37.2	78.2
I-6b	Enriched uranium	4.3	0.0	8.6	0.0	28.7	63.9
I-6c	Depleted uranium	5.3	0.0	9.6	0.0	30.9	38.0
D-4a	Radioactive material	5.3	0.7	21.1	21.7	23.2	52.2
D-4b	Nuclear radiation	3.2	2.9	23.2	7.2	18.9	51.5
D-7	Natural radioactivity	10.5	2.2	18.9	5.8	36.8	63.8
D-10	Medical diagnostic and therapeutic applications of nuclear physics	6.3	1.5	17.9	2.2	44.2	76.8

[a] Excluding no responses

4.2.6 Critical Thinking Questions

Just two questions could be answered by combining general or school knowledge or knowledge provided in the text. Critical thinking is a HOCS ability, so performance was generally not satisfactory (see Table 6).

4.3 Keywords and Unclear Concepts in the Texts

At the end of each questionnaire there were three questions of a different kind, which were taken from the questionnaires in the Shwartz, Ben-Zvi, and Hofstein paper (2006): *Make a list of keywords for this article. List concepts of which the meaning is not clear to you. Write down the central ideas of the article*. No restriction to the number of listed keywords as well as of unclear concepts was imposed. Regarding the last question, very few students wrote down the central ideas of the article. This should be attributed to dislike and possibly the difficulty for the students to provide an open answer, that is, to write in prose. For this reason, we do not discuss further this point.

The results for the two activities are in two tables. Table 7 provides a list of the most frequent keywords. Table 8 has the concepts that were not clear to the students. Only the

Table 6 Critical-thinking questions

		% Acceptable only		% Acceptable + partially acceptable		% Unacceptable[a]	
		GR	TR	GR	TR	GR	TR
I-10a	Uranium atomic reactors and atomic bomb	0.0	3.8	16.0	31.6	46.8	47.4
D-11	Radiation limits for general population and for nuclear workers	5.3	20.3	27.4	16.7	30.5	42.0

[a] Excluding no responses

keywords and the concepts that had a frequency of occurrence higher than 5 % for both or one of the two national samples are included. In both tables, the percentages of nil responses for Turkish students are lower than for their Greek counterparts similar to the results for the other questions.

From Table 7, it can be seen that both the Turkish and the Greek students provided in high or relatively high percentages important keywords for each activity. On the other hand, the frequencies of unclear concepts were most often lower in the case of the Turkish students and these must relate to differences in teaching of these concepts in the two national cases.

As expected, Greek students from the theoretical stream listed in higher proportions unclear concepts than the students of the positive and the technological streams. Also, regarding the Greek sample, two issues that should be paid attention to are: students who declared concepts unclear to them had significant participation in the rest of the questions, despite their unacceptable answers; on the other hand, students who did not state any unclear concept had more nil responses in the rest of the questions.

Table 7 Frequencies of appearance of keywords for the two activities

ITER			DU		
Keyword	% Appearance		Keyword	% Appearance	
	GR ($n = 94$)	TR ($n = 133$)		GR ($n = 95$)	TR ($n = 138$)
Thermonuclear reactor	53.2	48.1	Radiactivity	46.3	21.7
Fusion of hydrogen to helium/fusion	45.7	44.4	Depleted uranium	40.0	29.7
Plasma	33.0	23.3	Nuclear reactor	30.5	19.6
Decomposition (fission) of uranium	26.6	18.8	Effects on environnent/pollution/ nature/food chain	27.4	15.2
Radioactive waste	26.6	22.6	Radioactive uranium–uranium	25.3	23.2
Magnetic field	24.5	8.3	Fission	24.2	11.6
Atomic energy	21.3	12.0	Isotopes–radioisotopes	18.9	14.5
Peaceful use	17.0	1.5	Half life	17.9	0.7
Electric current	14.9	–	Radiation	21.1[a]	10.2[a]
Hydrogen bomb	11.7	13.5	Natural radioactivity	18.9	5.8
Hydrogen	11.7	15.8	Rem	12.6	2.9
Electrical power plant	9.6	12.0	Latent period	8.4	–
Invisible wall	6.4	8.3	Radioactive waste	7.4	11.6
Uranium	3.2	6.0	U-235, U-238	6.3	8.7
Helium	3.2	6.0	Alpha particles	[a]	7.0[a]
Nuclear energy	4.2	5.3	Beta particles	[a]	6.5[a]
No response	29.8	9.0	*X*-rays	[a]	6.5[a]
			Radioactive material	1.1	6.5
			No response	29.5	14.5

Keywords are arranged according to descending frequencies

[a] Some Greek students noted just 'radiation' and others wrote alpha, gamma and *X* radiation or alpha, beta and *X* radiation. But no one Greek student wrote only alpha radiation or only beta radiation etc. The opposite was the case with the Turkish students

Table 8 Frequencies of appearance of concepts that were not clear to the students for the two activities

ITER			*DU*		
Concept	% Appearance		Concept	% Appearance	
	GR ($n = 94$)	TR ($n = 133$)		GR ($n = 95$)	TR ($n = 138$)
Fusion/fusion of hydrogen to helium	31.9	24.1	Nuclear fission	29.5	16.7
Fission	26.6	10.5	Depleted uranium	21.1	2.9
Plasma	23.4	6.8	Isotopes–radioisotopes	20.0	2.9
Enriched and depleted uranium	22.3	5.3	Types of radiation	14.7	–
Thermonuclear reactor	21.3	27.1	Fissionable material	12.6	2.9
Reactor	3.2	7.5	Half life	12.6	–
ITER	3.2	6.0	Nuclear reactor	8.4	11.6
Ionized	18.1	1.5	Rem	7.4	10.1
Invisible wall	4.2	9.8	Gamma radiation	–	8.7
Uranium atomic reactor	–	9.0	Alpha particles	2.1	8.0
Tokamak model	5.3	8.3	X radiation	9.5[a]	5.1
Atomic energy	–	5.3	U-235, U-238	–	7.3
No response	40.4	19.6	No response	48.4	31.9

Note Concepts are arranged according to descending frequencies

[a] Most Greek students who noted X radiation, included also other types of radiation (alpha, beta, but not gamma)

4.4 Selective Results and Representative Students' Answers

4.4.1 ITER Reactor

I-1 *What is the meaning of the term 'thermonuclear reactor'*?

This question was not very demanding as the concept was clear in the given article about what a thermonuclear reactor is and why it is built. This justifies the fact that the question attracted the least 'nil responses': 18.1 versus 4.5 % for the Greek (Gr) and the Turkish (Tr) students. Acceptable and partially acceptable answers were provided by 66.0 % (Gr) and 63.2 % (Tr). Typical acceptable answers, including the correct fusion procedure and the correct energy transformation, were: "It is a kind of electric plant occurring by utilizing the fusion from hydrogen to helium". "It is a device in which fusion from hydrogen to helium occurs to get thermal energy from nuclear energy, which finally we can use to obtain electrical energy".

Examples of partially acceptable answers: "(A thermonuclear reactor) is the event of using the fusion from hydrogen to helium to provide a great amount of energy"; "It is a machine/device in which hydrogen molecules are transformed to a gaseous mixture of protons and electrons". In the latter answer, description ends in the plasma concept without any reference to energy production or the high temperature needed. Many students gave answers such as: "It is a device that will produce electrical energy from hydrogen's fusion to helium".

Examples of unacceptable answers: "It is a device that operates using thermal and nuclear energy"; "(It is) a reactor where fission of the nucleus of the uranium atom is carried out by using thermal energy"; or "A site where nuclear reactions take place, that is, the splitting of the nucleus of an element".

Many students missed the point that the article was about nuclear fusion, not fission. The case might also be that many students had the misconception that nuclear reactions have to do only with nuclear fission. Also, a number of students considered thermal energy as a cause and not as a result of the nuclear process. Few students focused on energy: "Thermonuclear means nuclear energy", or "Thermonuclear reactor is production of energy", or "(It is) a kind of energy source".

As expected, primary education students showed a greater ability for describing issues they had read in a text. A couple of students stated in their—acceptable—answers that "this device is extremely dangerous", probably having in mind fission reactors. Finally, it is worth noting that some answers included society-relevant comments such as: "Its construction is very important because it will end the monopoly of precious energy sources that some countries still have".

I-2 *Could you write the equation for the nuclear reaction that describes the fusion of hydrogen?*

Things got really disappointing here. Acceptable answers were provided by 4.3 % (Gr) and 0.7 (Tr) of the students. Very few students wrote down an equation. One Greek student commented: "I was not really good in chemistry", considering the term 'equation' only as chemistry related. In partially acceptable answers, students provided a fusion equation by using the information given in the text, but demonstrated misconceptions or wrote equations without coefficients. Only few students tried to use the suggestion that had been provided.

I-5 *Do you know of another, non-peaceful use of the nuclear energy?—you can provide relevant historical information.*

Very few students failed to respond here: 17.0 % (Gr), 13.5 % (Tr). Popular answers included: "Usage of nuclear energy can be dangerous for environment" and "Nuclear reactors are very harmful for environment". Large numbers of students made in one way or another mention of Hiroshima and Nagasaki. Very few students talked in addition about Chernobyl as a non-peaceful fact of nuclear energy in history: "Nuclear weapons and nuclear bomb, Hiroshima, Nagasaki, Chernobyl"; "Explosion of Chernobyl caused damage in human life". It is noteworthy that one student wrote—correctly—that the atomic bombs dropped on Hiroshima and Nagasaki were fission weapons. Considering the Greek students who had taken the Theoretical Stream, where history was among their primary subjects, it seems that atomic bombing or other non-peaceful uses of nuclear energy did not fall into the social or historical interests of many of these students.

I-6a *What do you know about the decomposition (fission) of uranium?*

Acceptable answers were provided by very few students: 5.3 % (Gr), 0 % (Tr). Few also were the partially acceptable answers, such as: "Uranium fission occurs when a neutron collides with the uranium nucleus, and in this way two daughter nuclei are created"; "Fission is a splitting reaction. The decomposition of uranium releases so much energy"; "^{238}U is a very unstable element, so it is very fissionable, giving isotopes and producing harmful radiation". Sample wrong answers: "To get energy by breaking off electron from uranium"; "Very fast moving protons are launched onto a uranium atom, and out of this collision large quantities of energy are released"; "Protons are emitting to break the nucleus"; "It must be very difficult. It doesn't happen easily, but only under certain circumstances".

I-10 All the countries participating in the Consortium were willing to host the thermonuclear reactor, because it is "clean" and safe, unlike the **uranium atomic reactors**, which are always in danger of **exploding** or producing **radioactive waste**.

I-10a *Does this explosion relate to what is referred to as explosion of an atomic bomb?*

Examples of unacceptable answers: "Yes, it relates. Notable examples are Hiroshima and Nagasaki"; "I would say that it is stronger than an atomic bomb"; "The atomic bomb leaves behind a lot of waste and kills many lives for many years after its explosion, the other does not". Examples of interesting but still very insufficient answers: "Yes, in both cases the contamination that is caused is huge because of the radioactive elements and the waste that is liberated"; "It relates because in both cases huge amounts of energy are produced"; "Not necessarily. Perhaps it relates more to the waste or the (nuclear radiation) leaks".

I-10b *What is the meaning of the term 'radioactive waste'?* (This question is similar to D-5).

In some of the few acceptable answers radioactive waste was connected exclusively with the explosion of the atomic bomb: "The useless products that are produced in nuclear fission"; "Waste that emits radiation". A partially acceptable answer given by a number of students: "After an explosion in a nuclear reactor, the area is contaminated with radiation". The common misconception confusing contamination from the waste (because of its toxic properties) with radiation (which can be weak) has also been reported in the Eijkelhof's studies (Eijkelhof et al. 1990; Eijkelhof and Millar 1988). There were also answers that contained substantial errors: "They are materials emitting ultraviolent radiation"; "Radioactive substances that are no longer useful in production of radioactivity".

I-10c According to advocates of nuclear energy projects, these have significant advantages over conventional fuels (these are carbon/coal and carbon's chemical compounds such as in oil). *Can you cite some of these advantages?*

The students here were asked to think about the arguments of the advocates of nuclear energy projects; however, the students' own perspective could interfere here, and as a result it was difficult to mark students' answers as acceptable or unacceptable. For this reason, this sub question was not included in our data. Examples of unacceptable and partially acceptable answers: "The use of nuclear energy does not leave behind free radicals in the atmosphere"; "They are not harmful to the environment and it is not easy for deposits to be exhausted as is the case with the oil"; "They are not dangerous and safe—Oil is accumulated in certain places of our planet, while hydrogen is more easily available and more economical"; "As we know, oil deposits are becoming less and there are other forms of energy that could be used". The third answer demonstrates ignorance or no consideration of alternative sustainable energy forms.

4.4.2 Depleted Uranium and Its Effect on Human Health

D-1a and D-1a′ *What are isotopes and what are radioisotopes?*

Despite the fact that 'isotope' is a much discussed concept in high school, Greek students provided only a small proportion of acceptable (24.2 %) or acceptable plus partially acceptable (29.5 %) answers. Turkish students did better: 51.5 and 57.3 %

respectively (note that ‘isotope’ is one of the key concepts in the Turkish chemistry curriculum). Radioisotopes proved much more difficult: only 7.4 % (Gr) and 16.7 % (Tr) students provided acceptable plus partially acceptable answers. The most common error committed was the confusion of ‘mass number’ with ‘atomic number’ or vice versa. Some students focused on the difference between isotopes and radioisotopes: “Isotopes are elements with the same atomic number, while radioisotopes have different atomic number”; “Isotopes are atoms of an element which have different mass numbers, while radioisotopes are atoms of an element which have the same mass number, but one of them emerged after a nuclear fission”. Several students thought that the number of electrons in an atom was important for isotopes: “Atoms of the element that have different numbers of electrons”.

D-2d *What is the nuclear fission reaction?*

Examples of partially acceptable answers: “The nucleus of radioactive elements with large atomic number splits (when is hit) by very fast moving free electrons”; “It is a kind of nucleus reactions used for obtaining great amount of energy. The atomic nucleus is exploded/split”. An interesting unacceptable answer was: “The atoms split into protons and electrons”. Note that the Greek and Turkish school textbooks are clear about this issue, mentioning that they are not fast moving electrons but low-kinetic-energy free neutrons. Other vague answers included: “The splitting of a chemical element.” Some answers revealed misconceptions: “It is the reaction in which an element splits to isotopes and radiation is emitted simultaneously”; “When the radioactive material is divided into its two isotopes”; “Fission reactions are (involve) separation/dissociation”; “Fission reactions are decay”; “It is a reaction in which bigger molecules are broken into smaller molecules”; or “Explosion of nucleus/atom”.

D-8a *What are alpha particles?*

Alpha particles are often mentioned in the Turkish physics high school curriculum and also are included in the nuclear chemistry unit. A considerable number of Turkish students (18.1 %) gave partially correct responses, with many of them mentioning that “the alpha particle is $^{4}_{2}\alpha$”. Examples of unacceptable answers: “It (alpha) is a radiation which occurs by means of interactions of protons”; “It is a radiation which comes from the sun”; or “It is the weakest radiation”. Note that alpha particles are mentioned in many instances of the Greek physics high school curriculum and not only in 12th grade. A Greek student answered “maybe they are particles occurring from alpha radiation”, while another noted “Less dangerous radioactive particles”. The Greek school textbook classifies alpha, beta and gamma radiations according to their penetrating capacity, so it is not strange to consider them as “non dangerous”. Some wrong descriptions included: “They must be ultra–violet radiation”, or they are “the particles with the shorter wavelength”.

D-8b *What is gamma radiation?*

None Greek or Turkish student gave an entirely acceptable answer, while partially acceptable answers were provided by 14.7 % (Gr) and 6.5 % (Tr) students. One Greek student wrote: “It is a high frequency radiation that is used in some electrical devices”; it seems that this student confused microwaves with gamma radiation. Two other Greek students noted: “It is a form of radiation that can penetrate living tissues and distort or destroy them”. A fourth student noted that “It is the radiation emitted during a gamma decay”, without describing what exactly it is or even mentioning the word ‘photon’. Some students gave unclear ("a radiation", "a kind of radiation") or unacceptable answers: "Extremely small particles that penetrate (human) tissues and cause harm"; "UV radiation"; "It looks like X-rays but it is less harmful. It does not go through everything". Not even one Greek or Turkish student mentioned "photon".

D-9 *Do you have any idea of how radioactivity affects human and animal health?*

Over one-third of Greek students did not respond or wrote 'I don't know'. From the rest students who expressed a view, some referred to DNA or genetic material: "It causes changes in the structure of DNA and in the physical functions of living organisms". Some mentioned mutation, some referred to cancer, and others to human cells. No-one mentioned ionizing radiation. The primary education Greek students had taken biology as one of their elective subjects (radiation is discussed in the 12th grade biology course). Most of these students referred to DNA mutations, various forms of cancer and genetic material decays. Turkish students did much worse in this question. Most of the students who provided acceptable answers referred to two kinds of radiation damage acting together, that is, genetic damage and direct damage to the body/its organs, or mutation and cancer: "Radiation can cause mutation of gene of biological organisms and cause cancer". Partially acceptable answers referred to various forms of cancer, for example: "Radioactivity has negative effects. This is harmful for human being. For example: to cause skin cancer".

D-10 *Do you know if nuclear physics (or nuclear chemistry) has medical diagnostic or therapeutic applications? If you do know such an application, please refer to it.*

Here again, we got poor answers: 17.9 % (Gr) and 2.2 % (Tr) gave acceptable plus partially acceptable answers. Many students mentioned X-rays as a medical diagnostic application. In addition, there were many answers like this one: "….in cases of cancer, it is treated with laser (beams) that target locally on the suffering tissue." Three Greek physics students talked about PET (Positron Emission Tomography), while three other Greek physics students gave complete explanations using scientific terms (one student described thyroid's treatment and radio-iodine therapy). Very few students referred to chemotherapy or to NMR. Many Turkish students also mentioned "X-rays or Röntgen radiation". Note that in the Turkish language 'radiation' (*radyasyon*) is used commonly with the meaning of 'radioactivity', and this leads to the misconception that "all radiation type is radioactive". Although the Turkish chemistry textbooks refer to medical diagnostic and therapeutic applications of nuclear chemistry, four students stated that "Nuclear science has not therapeutic applications due to harmful effect of radioactivity", while one student said that "It might have medical diagnostic, but is does not have therapeutic applications".

D-11. According to the USA Department of Energy, since 1930 the annually allowed limit for nuclear workers was gradually lowered reaching 15 rem by the 1950s, 5 rem between 1960 and 1990, and 2 rem today. For the general population (not the nuclear workers) this limit has finally been suggested at the 1/10, i.e. 0.2 rem. *Can you think why radiation workers are given higher dose exposure limits?*

No-one student gave an answer involving the fact that the general population involves a variety of people, including sensitive groups such as children and elderly people or people with poor health. A considerable proportion of students, 36.3 % (Gr) and 13.0 % (Tr), supplied answers that referred to a hypothesized property of the human organism to "get used to radiation" or to "adapt to it", or to "be more resistive to it" or to "have acquired a kind of immunity" as many students noted: "Because they are exposed every day to these conditions, so their organism has more immunity"; "Because the general populations' organism is more sensitive to radiation, while nuclear workers are somehow adapted"; "Because workers are used to radiation and they wear special gowns". In the few answers that were marked as acceptable, the difference was focused on the protection measures that nuclear workers are required to take, such as wearing special gowns.

5 Summary of Students' Misconceptions, Difficulties, and Deficiencies

This study showed clearly that many conceptual difficulties and misconceptions were found to be common among the Greek and the Turkish students. Students were confused about nuclear fusion and nuclear fission. Many students appeared to assume that nuclear reactions have to do only with nuclear fission. Also, a number of students considered thermal energy as a cause and not as a result of the nuclear processes. Very few students knew about the fission of uranium. For some students, in fission, atoms split into protons and electrons, and for some, bigger molecules break into smaller molecules. The concepts of isotopes and radioisotopes proved difficult, but knowledge of the latter was much weaker. Students confused 'mass number' with 'atomic number' or vice versa. Some students thought electrons play a role in isotopes.

Lack of knowledge and great confusion was encountered with the concepts of alpha particles and of gamma radiation. No Greek or Turkish student gave an entirely acceptable answer for gamma radiation. Some students confused gamma rays with other radiation, such as X-rays, but assumed gamma radiation as less harmful. Turkish students confused radioactive radiation with other types of radiation, so they thought that the harmful effect of X-rays was relating to its radioactive nature instead of its ionization power. This finding is similar to that of Prather (2005), whose students described ionizing radiation as having the same properties as radioactive materials. It is remarkable that Sesen and Ince (2010) scanned 200 websites to check whether information obtained from the internet was a source of misconception about radiation and radioactivity, and found that 24.3 % of the sites included the misconception "if an object is exposed to ionizing radiation, it becomes radioactive".

Students' knowledge about atomic bombing or other non-peaceful uses of nuclear energy or about nuclear accidents was rather weak. It appears that such knowledge does not fall into the social or historical interests of many students. In addition, the issue of how radioactivity affects human and animal health is a source of generalized knowledge. Some students referred to changes in the structure of DNA, in human cells and in the physical functions of living organisms; many mentioned cancer, e.g. skin cancer. Few students distinguished between genetic damage (mutation) and direct damage (cancer) to the body/its organs. Knowledge of biology helps here. No-one student mentioned ionizing radiation. The knowledge of the large majority of students was poor about the medical diagnostic and therapeutic applications of nuclear science. Many students mentioned X-rays as a medical diagnostic application of nuclear science. Some students accepted the diagnostic applications but were ignorant about the therapeutic ones.

Finally, it appears that students focused more or exclusively on the harmful effects of radioactivity rather than its useful aspects. It seems that even though students had been taught about the applications of nuclear chemistry (as was the case with the Turkish students), some of them could not identify beneficial uses of radioactivity. This finding reinforces that by Nakiboğlu and Tekin (2006) who reported that 29 % of the Turkish high school students of their sample explained that "radioisotopes are used only to obtain energy because they are very harmful for humans".

The overemphasis on the harmful effects of radioactivity in the news might be the cause. Atwood and Sheline (1989) called attention to this by stating how negative impressions of nuclear chemistry may be heightened by media treatments of topics such as dangerous Rn concentrations in houses, and difficulties with disposing of high-level nuclear waste.

6 Conclusions and Implications for Research and Instruction

As with most science concepts, the concepts and topics of nuclear science are conceptually challenging for the students (Nakiboğlu and Tekin 2006). Conceptual difficulties and alternative conceptions were reflected in the present study. It is known of course that students' knowledge and the formation of misconceptions are influenced by a range of factors, such as intuitive responses to phenomena (diSessa 1993; Taber and García Franco 2010). On the other hand, the knowledge of the basics of the concepts and related technological issues is an indispensable component of both *practical/functional* and *civic scientific literacy*.

The study referred to the case of just two countries, Greece and Turkey. The findings indicated that, in the case of Greece, acceptable or partially acceptable answers were provided on average by around 20 % of students, while large proportion (on the average, around 50 %) abstained from answering the questions. The corresponding figures in the case of Turkey were around 11 and 27 % of the sample. The findings are rather disappointing, but they should be seen in the light of the limited or no coverage of the relevant learning material in the Greek and the Turkish high school program. The fact that the topics of nuclear science, including the useful applications of nuclear science and the harmful effects of radioactivity, are usually placed in the last chapters of textbooks, results in not giving sufficient attention to them. It would be of interest to repeat/extend such a study to other countries, with a better coverage of nuclear science and with curricula that place more emphasis on the connection of science to STES education.

Regarding the curriculum and the instruction, it is imperative that a change is adopted of content and approach of teaching the concepts and topics of nuclear science in high school. Taking into account that the current Turkish physics and chemistry curricula and textbooks deal with nuclear science topics in more detail than the previous ones, further study deserves to be done in order to check if there is an improved picture of the Turkish students. In the case of the Greek high school curriculum, which is currently under revision, we have to wait to see if there will be a change in the relevant coverage.

At this point, some limitations of our study should be acknowledged. The Greek and Turkish participants represented convenience samples, which varied in their composition and we cannot claim that, from the statistical perspective, they were representative of the corresponding student populations. In addition, although the two samples displayed certain similarities, we cannot claim that they were equivalent. These limitations suggest that any attempt to make statistical comparisons about students' knowledge of nuclear science and its connection with civic scientific literacy would be inappropriate, and therefore such analyses were not undertaken.

Much of the large quantitative differences between the two national samples is likely to be attributable to differences in teaching and learning methodologies employed in Greece and Turkey. In particular, differences might arise due to the following factors: curricula (both in terms of organization of the subject matter, and in the extent of coverage within the programs of study); textbooks; teaching and testing methodologies; students' attitudes to science or school in general; and variation between the two languages with respect to the terms and concepts of nuclear science. Note that in this work, apart from looking at the curricula for the two countries with respect to nuclear science topics, no effort was made to compare either the books used or the attitudes of students towards these topics.

In the concluding paragraphs of the paper, the focus will be on the one hand, on the need to employ in schools modern educational pedagogy; and, on the other hand, on the implications of the present study for students' civic scientific literacy, with the role and relevance of context-based teaching, interdisciplinarity, and what modern school science should seek to do to encourage scientific literacy with respect to topical issues, being discussed.

Science education research has consistently proposed that modern school science should encourage: (a) active and constructivist teaching and learning; (b) meaningful and conceptual understanding; (c) development in students of practical abilities; (c) a spiral curriculum; (d) cultivation of higher-order cognitive skills (such as critical thinking, problem solving, evaluative thinking and decision making), (e) cooperative learning, and (e) connection of science with everyday life. In principle, the application of instructional methodologies that are in line with the above aims and requirements is primarily the responsibility of the teacher. However, considering the limited awareness on the part of secondary school teachers of findings and implications of educational research (Costa et al. 2000), both the school science curricula and the textbooks should aid the teacher in this task.

Special attention should be paid to context-based approaches to science teaching that are expected to be popular and relevant, and consequently promote scientific literacy. Also to enhance student interest in, and choice of careers that relate to science, engineering and technology (European Commission 2004). 'PARSEL (Popularity and Relevance of Science Education for scientific Literacy) (http://www.parsel.uni-kiel.de/cms/) is a recent development that, responding to the European Commission's (2004) call, provides open-access teaching modules in English, but also in a number of other European languages. A module that is relevant to nuclear physics, also involving ethical and political issues, is entitled "Would you have dropped the nuclear bomb?"

Very important in recent educational reforms in many countries is 'inter-disciplinarily' One aspect of inter-disciplinarily is the coupling of various school subjects, a coupling that demonstrates the interdependence as well as the interaction between disciplines. Another aspect of interdisciplinary is the connection of the school subjects with everyday life and society. The topic of nuclear science fits perfectly into such an interdisciplinary approach, combining knowledge of physics, chemistry, biology, mathematics, and even economics and social and political science.

Finally, coverage in schools of topics related to crucial and controversial issues, such as those associated with nuclear science, depends heavily on the social structures within a country. Social structures influence various systems, one of which is the educational system. Schools consist of students, teachers, rules and roles. Also there are traditions, customs, ideologies, kinship systems, languages (Lukes 1970, cited in Outhwaite 2001). According to Harré (2009):

> if one wants to change the institution one must change the rules and conventions that members make use of in their activities. Since apparent 'structures' are epiphenomena of the flux of practices, it is strictly impossible to change an institution by changing the structure. This can only be done by changing the practices. (p. 469)

Although reforms, seeking to promote modern instructional approaches, notably constructivist teaching, to education and to science education in particular, have been recently introduced in both Greece and Turkey, traditional formalist science teaching remains prevalent and dominant. Traditional science education tends not to include, or even encourage, the discussion of controversial topics of importance to society, economics, and politics, such as those related to nuclear science and technologies. University entrance examinations, which test mainly for rote reproduction of a fixed amount of knowledge and application of practiced algorithms, provide an important additional inhibitive factor to the implementation of modern pedagogies, in both Greece and Turkey. These encourage teachers, students and their families to follow narrow learning procedures that concentrate mostly, or solely, on what is to be tested in the examinations, allowing little room for STES education. It will not be easy to change our traditional educational system and introduce educational reforms without ignoring the conventions of the past. Educational reform should seek, not only to place emphasis on the introduction of modern pedagogies and discussion of topical scientific and technological issues, which are of interest and importance for society, but should also seek to have an accompanying effect on students' preparation for the transition from secondary to tertiary education.

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Appendix: The Newspaper Articles Used in the Study

NOTES

1. For economy of space, the articles have been slightly abridged.
2. In the actual questionnaires, in each text the lines were numbered, and in the questions the lines were noted in which the relevant text was located. Emphasis was added by the authors of this article, to focus students' attention on the terms and phrases that were relevant to the questions.

ARTICLE A, *ITER: The reactor that is going to change the world* [Adapted from Varvoglis (2005)]

Following long years of negotiations about the construction of the thermonuclear reactor in the French town of Cantarache, a consortium of countries has finally started to put the project into effect…. Its successful operation will be a milestone for our technological civilization entering a new era. …There is already a consortium of nations working in what seems to be on good track. This consortium aims at the construction of the first experimental **thermonuclear reactor,** which will prove the possibility of constructing **electric power plants** by using as energy source **the fusion of hydrogen to helium**. The energy released when 1 gram of hydrogen atoms (1 mol of atomic hydrogen) undergoes the fusion reaction is equal to the energy released from burning about 23.000 liters of gasoline. This is a very large amount of energy, covering Greece's energy needs for 1 h.

Since 1954, when the first testing of the **hydrogen bomb** was carried out, physicists had already been trying to develop a **peaceful use** of this **new source of energy**, **hydrogen fusion**. However, that target proved much more difficult to achieve than the corresponding effort to harness **atomic energy** from the **decomposition (fission) of uranium**. The reason is that the hydrogen fusion occurs at high temperatures (of million degrees centigrade), while even the most resistant materials available on the Earth melt at 3,000 or 4,000 degrees centigrade. So, how can a reactor be constructed which can resist such high temperatures?

Many ideas and techniques have been tried since 1954. One idea which proved the most successful was to use a **magnetic field** as a sort of the reactor's "**invisible wall**". At the high temperatures required for the fusion, the **hydrogen is ionized**, and the gas is then **a mixture of protons and electrons.** This mixture is referred to as **plasma**. According to one fundamental law of physics, the **plasma is "repelled" away from the regions where there is a strong magnetic field**. Therefore, all we need to "keep" the plasma in the thermonuclear reactor is a serious of magnets, placed in a manner that the resulting magnetic field will be weak in the reactor's center and strong near its side walls. …

All the countries participating in the Consortium were willing to host the thermonuclear reactor, because it is "clean" and safe, unlike the **uranium atomic reactors**, which are always in danger of **exploding** or producing **radioactive waste**. Ultimately, it seems that the ongoing increase in the oil prices has had a decisive effect on the negotiations, resulting in the decision to construct the thermonuclear reactor in the French town of Cantarache, as supported by the European Union.

The successful operation of the ITER reactor will constitute one of the most significant technological milestones of our civilization. It will mark the definite withdrawal of mankind from the most important sources of energy used to this day, that is, coal and oil. If one looks back at the few recent centuries in human history, one will realize that most major wars were waged in pursuit of possessing and managing of energy resources, which have always been located in small regions around the globe and have been of limited capacity. In contrast, **hydrogen exists in water, therefore we can obtain it from water.** In this way the energy problem of the residents of this planet can be regarded as solved for thousands of years to come.

ARTICLE B, *Depleted Uranium: A disastrous nuclear waste* [Adapted from Vagena (2001) and Bitsika (2001)]

During the 1980's, the Military Industry developed and started mass production of a new highly penetrating missile. The high penetrating material used in this missile derived from a nuclear waste called **depleted uranium** (or DU for short). The producers were proud for the havoc (disaster) caused to military tanks by this missile, that they nicknamed it "tank-killer".

Depleted uranium is the by-product that is left behind by the process of enriching the mineral of uranium, which is used as **the fissionable material** in nuclear plants. The **radioactive mineral uranium (U)** that exists in **nature** consists mainly of **two isotopes**, **U-235** (^{235}U) and **U-238** (^{238}U), as a rule in **proportions of 0.7 %** and **99.3 %**, respectively. U-235 is used in **nuclear reactors** to produce **huge amounts of energy** by means of the **nuclear fission reaction**, while U-238 is not useful in that (U-235 has a higher fission probability to undergo fission, while the U-238 has small probability). Therefore, it is essential that natural uranium is **enriched** by means of a special process that removes a large part of U-238 while leaving behind U-235. The U-238 that is obtained in this way is called **depleted uranium**. Having a half life of 4.5 billion years (!), U-238 in practice never decomposes. (U-235 has a half life of 704 million years.)

A 30 mm DU missile contains about 4.650 fragments of DU, weighing approximately 300 grams. When it explodes, splinters and radioactive material in the form of very fine dust disperse over a over a **large distance**, and, practically, they **remain there forever**, **polluting** the **soil** and the **water-carrying zone**. Extended use of DU missiles was reported for the first time during the Gulf War in 1991 and a few years later in the War in the Balkans.

Depleted uranium is still controversial about its **consequences** on **public health** and the **environment**, which are due to its radioactivity. The World Health Organization (WHO) refers to the dangers from depleted uranium, pointing out that it does not cause leukemia, but it can have toxic action on the human organism, affecting kidneys and lungs. In addition, deaths have been reported of soldiers who participated in the Iraqi warfare, which were attributed to what is known as the Gulf Syndrome. Concern has also been expressed about a problem that might be caused if depleted uranium enters the **food chain** through the **water-carrying zone** in the Balkan territories, where the bombs were thrown.

(Nuclear physicist) Dr. Athanasios Geranios claimed that the slightest exposure to radioactivity is serious. … The **maximum permitted limit** of **0.2 rem** coming from the dose we receive annually from **natural radioactivity** allows for only one chest X-ray per year! As a result, there is no margin for additional dose of radioactivity. Note that this not a case of a personal choice, but something enforced to us by others or it happens without our being aware of it. As Dr. Geranios explained, … there will be an approximate 10-year **latent period** for the likely appearance of symptoms of illness related to radioactivity. Following that is the so–called **plateau**, which may last even 30 years, and during this period there is probability for cancer…. Of great importance are the **age**, the **type of radiation,** and the **dose** received at the beginning of the period…

Finally, according to the USA Department of Energy, since 1930, the **annual permitted radioactivity** for **nuclear workers** was 156 rem (this dose also depends on the kind of radiation, and which is ten times higher for **alpha particles** than for **gamma or X rays**), while 600 rem is the **deadly dose**. However, this limit is gradually lowered, reaching 15 rem by the 1950s, further reduced to 5 rem in the period 1960–1990… For the **general population** (but not the nuclear workers) this value is currently set at the 1/10, that is, **0.2 rem**.

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