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ARTICLE

Misconceptions, Knowledge, and Attitudes Towards the Phenomenon of Radioactivity

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Abstract
The teaching of the phenomenon of radioactivity is considered a key ingredient in the path towards developing critical thinking skills in many secondary science education curricula. Despite being one of the basic concepts in general physics courses, the scientific teaching literature of the last 40 years reports a great deal of misconceptions and conceptual errors related to radioactivity that seemingly appear regardless of the educational level and context. This study reports the first cross-sectional diagnostic study in Spain to secondary education students and pre-service teachers. Data were collected in the year 2019 through a questionnaire adapted from a previously validated one to explore the main misconceptions, attitudes, and knowledge status on the topic on a sample of 191 secondary school students and 29 Physics-and-Chemistry trainee teachers in the Spanish region of Valencia. Open and closed questions were used to categorize the entity itself, its properties, and the main misconceptions related to radioactivity. The responses were analysed using conventional statistical methods. The results indicate an evolution from a widespread dissenting notion on the phenomenon, which is staunchly related to danger, hazard, and destruction in the lowest educational levels, towards a more rational, relative, and multidimensional perspective in the highest ones. On the other hand, the ideas, emotions, and attitudes of the inquired individuals are in good agreement with the main misconceptions reported in the literature.

1 Introduction

The public awareness of Science is an ambitious goal to be achieved by contemporary society. It implies informed, responsible, and active citizens in connection with the scientific and technological progress currently driving social change. Within this point of view, scientific literacy (Holbrook & Rannikmae, 2009; Coll & Taylor, 2009) is one of the key competences that students must develop during their compulsory education.

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Such a challenging task does not only imply the development of intellectual capabilities but also attitudinal, societal, and interdisciplinary skills (Holbrook & Rannikmae, 2009). Hence, teaching science and technology in their historical, cultural, ethical, economical, and political contexts — i.e., teaching the relationships between Science, Technology, Society and Environment (STSE) — is beneficial for the teaching–learning process, as students get a deeper and more consolidated scientific knowledge and develop a better attitude towards the study of science (Solbes & Vilches, 1997; Pedretti, 2003).

In this respect, Nuclear science (NS) represents one of the most significant paradigms of STSE education due to the social, historical, ethical, economical, and political implications of nuclear applications (Levy, 2017; Tsaparlis et al., 2013). Some hot topics in current international agendas include the combined exploitation of fission power plants with renewable energies as a short-term solution to climate change or violations of the Non-Proliferation Treaty. In Spain, the results of the 2019 local elections in the small village of Retortillo (Salamanca) shot up by a 35% the shares of the Australian mining company Berkeley, as the winning party supported the Berkeley's uranium mine project in town. Recently, the operating permission extension of the nuclear power plant of Cofrentes (Valencia) until 2030 has caused new conflicts between ecology organizations and political parties. In most cases, the corresponding political and social strategies are guided by the public opinion, implying that the citizenship should develop critical thinking skills to make informed and responsible decisions on topics related to NS applications. For these reasons, NS concepts are usually included in educational programs.

The present work is focused on a widespread NS concept, the phenomenon of radioactivity. Radioactivity — the spontaneous emission of radiation from atomic nuclei (Collins, 2021) — is not only crucial in the quest for the very essence of matter (Butler, 2019; Hardy & Towner, 2015; Kornakov, 2018), but is also at the foundation of many useful or beneficial everyday applications in medicine, energy, industry, archaeology, arts, and research. Yet it also entails potential risks for environment and humankind in the form of nuclear weapons, accidents, and ionizing radiation contamination. When asked, the broad audience tends to relate NS with a harmful use of radioactivity. It is hence worth exploring the reasons behind the unpopularity of this term before designing any educational action on NS. As a matter of fact, the social environment and the mass media are well known to stimulate the development of misconceptions — this is, ideas that do not fit in with currently accepted scientific theories — in the population. Based on this, radioactivity-related ideas are very likely to differ at varying socio-demographic conditions, but surprisingly, the available science teaching literature shows similar thoughts irrespective of the time and place of the reported studies.

The only systematic survey on radioactivity carried out in the Spanish educational context dates back to the 1980s (Posada & Prieto, 1989). In their study, Posada & Prieto (1989) inquired 334 secondary education students in Madrid (Spain), reaching the conclusion that their perceptions were far away from the scientifically accepted theories on radioactivity. Apart from the long time elapsed from the study of Posada and Prieto, it is worth noting that in Spain, the educational competences belong to the regional governments. There is a national curriculum that provides a general indication of the contents, criteria, and competences to develop in each level (BOE, 2015). But each individual autonomous region fixes the details of the curriculum, with nuances that might differ from one region to another. As a result, the implementation of new studies, better adapted to presently existing educational contexts in the country, becomes essential. To this aim, we have performed a cross-sectional study on the misconceptions, knowledge and attitudes towards radioactivity and its related concepts held by pupils and pre-service teachers in the educational reference frame of the Valencian Community (Spain).

2 Literature Review

Misconceptions have a complex and varied origin, such as the establishment of wrong analogies, the use of everyday words with a loose meaning, or the construction of erroneous reasonings. Furthermore, our anthropocentric view of the world and our limited sensory capabilities help biasing our perception of some processes and phenomena (Driver et al., 1985; Harlen, 2000, 2003). In the teaching–learning process of NS, the mass media and the teacher's interventions provide two of the most common means of misconceptions' transmission (Nakiboglu & Tekin, 2006). Such erroneous ideas are more likely to be superseded by the correct ones if they are adequately considered in the instructional programs (Nesher, 1987). To this aim, some authors have carefully analysed the misconceptions and learning difficulties of secondary-school students in different contexts and countries (H. M. C. Eijkelhof et al., 1990; Millar & Gill, 1996; Nakiboglu & Tekin, 2006; Neumann & Hopf, 2012; Posada & Prieto, 1989; Tsaparlis et al., 2013). Some of the most noteworthy studies are contextualized in the framework of nuclear catastrophes (H. Eijkelhof & Millar, 1988; Martins, 1992; Neumann & Hopf, 2013; Plotz & Hollenthoner, 2019), while others are limited to the cognitive confusion caused by the NS concepts themselves (Millar & Gill, 1996; Tsaparlis et al., 2013). On the other hand, Colclough et al. (2011) analysed the knowledge and attitudes of trainee teachers about nuclear radiation associated risks; other authors, as Powell et al. (1994) and Williams (1995), highlighted the need of introducing the historical, social, and political frame in the programmed NS training to properly integrate STSE topics of common interest such as nuclear energy or nuclear waste disposal. Finally, the relevance of the social and affective dimensions beyond the intellectual one was stressed by Alsop (2001) in a comparative study framed in areas affected by normal and high levels of radon gas.

These and other works report a series of misconceptions that are summarized in the following:

1. Radiation can accumulate in matter. According to H. M. C. Eijkelhof et al. (1990), after the Chernobyl accident, a broad audience believed that radiation had entered into the food chain through the vegetal matter, which would have been expelled again after being absorbed and accumulated there.
2. Radioactivity is harmful for living beings (Millar & Gill, 1996). As a result, there is a widespread fear to any type of radiation and in any situation.
3. Radiation is highly destructive and dangerous. As indicated elsewhere (Esteban Santos & Perez-Esteban, 2012; Linjse et al., 1990; Sesen & Ince, 2010), the main actors for this misconception to spread out are the Internet and other mass media.
4. Radioactivity has a different effect on living and inert matter. Klaassen, Eijkelhof, and Lijnse (1990) revealed that many students think living matter is more vulnerable to radioactivity than inert matter. Some of them use verbs such as 'attract' and 'absorb' to justify this thought, which is related to the analogy detected by H. M. C. Eijkelhof et al. (1990) between radioactivity and a viral or microbial disease.

5. Objects and living beings exposed to radiation become radioactive. It is to note, though, that such a misconception may be true when the radiation carries enough energy to excite the atomic nucleus or induce a nuclear reaction (Plotz, 2016).
6. Radioactivity is conserved. This idea of conservation refers to the fact that many students think that if a body becomes radioactive, it remains radioactive forever (Millar et al., 1990).
7. Radioactivity is artificial. In fact, only a reduced number of students are aware of the existence of natural sources of radioactivity (Neumann & Hopf, 2012). On the contrary, a vast majority thinks radioactivity can only be produced artificially in nuclear power plants (Boyes & Stanisstreet, 1994).
8. Atoms cannot change their nature (Nakiboglu & Tekin, 2006). This thought is clearly in opposition to the scientific fact of spontaneous alpha and beta decay.
9. Ionizing radiations are the cause of some CO_2 related environmental problems, such as greenhouse effect, pollution, or the hole of the ozone layer (Boyes & Stanisstreet, 1994; Neumann & Hopf, 2012).
10. All electrical devices emit harmful radiation. In their study, Neumann & Hopf (2012) noted that some students were usually asked by their parents to shut down the mobile phone and other electrical devices before going to sleep.
11. The terms 'radioactivity', 'radiation', and 'radioactive material' are often mixed up and ambiguously used. Kaczmarek et al. (1987) reported an amazing belief of second-year medicine students with no previous radiological training in New York University (USA). Almost 75% of them thought that objects in an X-ray room could become radioactive after a diagnose examination. Similarly, Prather (2005) noticed that students attributed the same properties to ionizing radiation and radioactive material. Other studies (Sesen & Ince, 2010) point to the interchangeable use of these terms in the mass media as the most likely error source.
12. The terms 'irradiation' and 'contamination' are indistinguishably used. This is most likely a consequence of the interchanged use of the words 'radiation' and 'radioactive material', as the first is related to irradiation and the second to contamination as stated by Millar & Gill (1996).
13. The terms 'isotope', 'radioisotope', 'atom', and 'chemical element' are often confused or vaguely differentiated (CPEP, 2019).
14. Nuclear fusion and fission reactions are usually confused. Indeed, many students think of fission as the only existing nuclear reaction (Tsaparlis et al., 2013).

Note that conceptual mistakes related to NS concepts such as the atomic mass, the atomic number, and the half-live can be found in the literature (Nakiboglu & Tekin, 2006; Prather, 2005). Nonetheless, these are identified either in non-science major physics students or after teaching interventions at undergraduate level. Thus, they fall out of the scope of this work.

3 Research Questions

The research questions are:

1. What is ontological and phenomenological understanding of radioactivity?

2. How does knowledge of radioactivity and its related ideas evolve with educational training?
3. Which misconceptions are held towards the phenomenon of radioactivity?
4. How do these misconceptions evolve with educational training?
5. Which emotions, attitudes, and interests evokes radioactivity?
6. How do the emotions, attitudes, and interests towards radioactivity evolve with educational training?

4 Methodology

The diagnostic tool used is an updated questionnaire adapted from one designed and validated by Martins (1992). The previous questionnaire is mainly focused on the sources and nature of knowledge about radioactivity, i.e., how do students understand the entity itself, its properties, and where this knowledge has been acquired. Meanwhile, the present one has been complemented with open-ended questions to obtain detailed information on the research questions listed in Section 3. In total, 191 secondary school students and 29 Physics-and-Chemistry trainee teachers have been inquired. In both cases, information on socio-demographic variables were collected. In the secondary school sample, these are 'level', 'group', 'age', and 'sex', while in the master sample they are 'career', 'age', and 'sex'. In total, a matrix with 220 cases has been generated.

4.1 Field Work

The study has been carried out in a secondary school and a public university, both located in the metropolitan area of the city of Valencia (Spain). The secondary school sample consists of 10 groups of students aged between 13 and 19 taking the 2nd, 3rd, and 4th courses of compulsory secondary education (ESO, in Spanish acronym) and the first optional course of secondary school (called 1st Bachillerato). According to the Physics-and-Chemistry Spanish and Valencian curricula (BOE, 2015; DOGV, 2019), NS concepts such as atomic nucleus and isotope are introduced for the first time in 2nd ESO, while the phenomenon of radioactivity is approached for the first time in compulsory education in the 3rd course of ESO. In this level, the concepts of alpha, beta, and gamma radiation are introduced. The social and ethical dimensions of NS are integrated through the study of some applications of radioactivity, such as nuclear energy and radioactive waste disposal. In the (optional) academic path of secondary education, NS is only resumed in the second course (called 2nd Bachillerato). Concomitantly, concepts with a certain connection to NS, such as the atom, the atomic structure, its composition, and the atomic interactions, are widely approached in all secondary levels.

The university sample is comprised by 29 trainee teachers attending a master on secondary school teaching on Physics and Chemistry, aged between 22 and 35. Most of them have a degree in Chemistry, although other career backgrounds such as Biochemistry, Biotechnology, Biology, Engineering, and Physics can be found. Around 40% of them have received advanced training on NS at undergraduate level, and nearly 30% has or is about to have a Ph.D in any of these science disciplines.

4.2 The Questionnaire

The questionnaire used here for data collection is provided as supplemental material. Items 1, 2, and 3 have been extracted from the questionnaire of Martins (1992), while Item 4 is new and consists of a series of open-ended questions. Item 1 is connected with the research questions (1) and (2) of Section 3 and is focused on the ontological nature of the phenomenon. To this aim, different entities, related to everyday objects, physical concepts, and processes, are listed in a table together with two possible answers: 'yes', if the surveyed student believes the entity is somewhat related to radioactivity, and 'no' in the opposite case. The list is exactly equal to that provided by Martins (1992), except for the entity 'particles', which has been added in the new version. Item 2 is connected to all research questions (see Section 3) and is focused on the properties attributed to radioactivity. A table listing pairs of adjectives with opposite meanings, each one marked as (a) or (b), is provided. Four answers allow inquired students to consider the extent to which radioactivity can be defined with the pair of adjectives: 'totally or possibly (a)', '(a) and (b)', 'nor (a) nor (b)', and 'totally or possibly (b)'. The list is very similar to that designed by Martins (1992), except for several pairs of adjectives that have been eliminated, mainly because the misconceptions or ideas behind them are treated in other questions. Item 3 provides a list of NS applications and issues to explore which are the most interesting to students, hence focusing on research questions (5) and (6). Finally, Item 4 consists of seven open-ended questions aimed at addressing all the research questions listed in Section 3, with a special emphasis on the main misconceptions reported in the literature. The categorization of the responses to Item 4 is shown in Table 1 and Fig. 5. The selection of the categories has been performed following discussion between the authors. In general, we find three types of categories: (1) related to characteristics or features related to the phenomenon (displayed in several ones), (2) answers related to illness or danger, and (3) unrelated to the phenomenon. The frequency of unanswered questions is also indicated in the table. The significance of each category is clarified in Section 5.4, where representative answers are given as examples for some cases.

5 Results and Discussion

The collected data have been treated statistically with the free analysis program R (R Core Team, 2014). In the following, we will discuss the results separately for every item of the questionnaire.

5.1 Item 1: On the Nature of Radioactivity

The first item explores the mental schemes built by students in relation to the idea of radioactivity. The aim is to classify how they connect this phenomenon to the physical concepts and processes shown in the first table of the supplemental material. The answers to Item 1 have been analysed using the hierarchical clustering technique (Rokach & Maimon, 2005). This procedure identifies separate groups of entities in order to provide a categorization of the considered elements. The dissimilitude between pairs of entities is evaluated using a metric that calculates the distance between them. Meanwhile, clusters are created from a linkage algorithm based on the selected metric. In our case, we have used the Euclidean metric and Ward's clustering

Table 1 Categorized types of responses for questions 4.1–4.4 and 4.6–4.7. The number of students and the percentages of answers enclosed in each category are also shown

Question 4.1 How many types of nuclear radiation do you know?		
Type of response	n. of students (N = 220)	Percentage (%)
Refers to nuclear radiation	47	21
Refers to nuclear applications	26	12
Refers to non-nuclear radiation	32	15
Refers to non-nuclear applications	7	3
Refers to radioactive material	17	8
Refers to scientific concepts	5	2
Refers to nuclear reactions	3	1
No answer	85	39
Question 4.2 Which one do you think is the most dangerous for human beings?		
Type of response	n. of students (N = 220)	Percentage (%)
Refers to nuclear radiation	41	19
Refers to nuclear applications	19	9
Refers to non-nuclear radiation	8	4
Refers to radioactive material	10	5
Refers to scientific concepts	19	9
Refers to nuclear reactions	3	1
No answer	106	48
Question 4.3 Why some nuclei are radioactive?		
Type of response	n. of students (N = 220)	Percentage (%)
Refers to cause-effect relationships	14	6
Uses analogies with other scientific concepts	56	26
Refers to the artificial origin of radioactivity	15	7
Uses concepts related to illness	6	3
Refers to nuclear concepts	32	15
No answer	73	33

Table 1 (continued)

Question 4.4 How can we protect ourselves from a radioactive substance?		
Type of response	n. of students (N = 220)	Percentage (%)
Refers to contact/contamination	92	42
Refers to exposure/irradiation	69	31
Uses terms related to emergency situations	19	9
Refers to non-nuclear radiation	5	2
No answer	46	21
Question 4.6 Do you think radioactivity affects inert and living matter equally?		
Type of response	n. of students (N = 220)	Percentage (%)
Thinks it affects more or only living matter	129	59
Thinks it has the same effects on both	62	28
Thinks it affects more inert matter	2	1
No answer	27	12
Question 4.7 Can radioactivity turn objects radioactive?		
Type of response	n. of students (N = 220)	Percentage (%)
Refers to irradiation	96	44
Refers to contamination	45	21
Refers to accumulation	7	3
Uses concepts related to illness	25	11
No answer	37	17

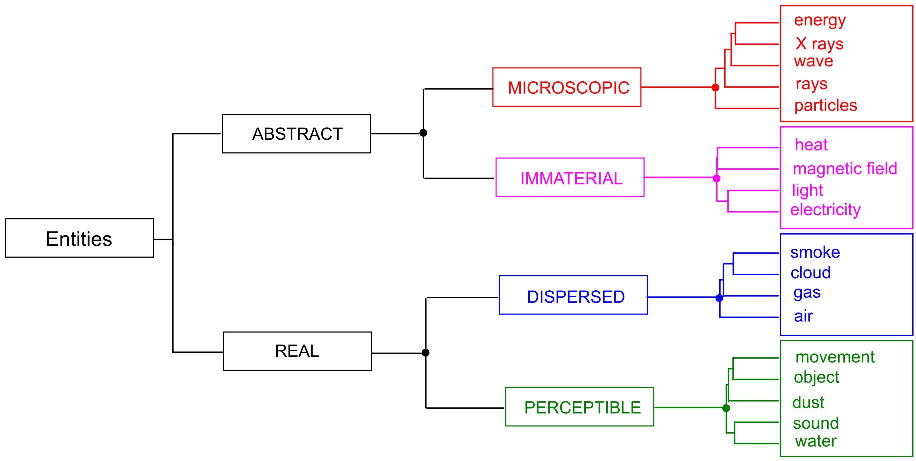

Fig. 1 Dendrogram showing the hierarchical cluster analysis results of Item 1 for the secondary school sample. Details are discussed in the text

algorithm (Ward, 1963). Results for the secondary school sample are shown in Fig. 1. Two main clusters or ontological categories can be clearly distinguished. The first comprises well-known concepts that are accessible to our senses and are present in our daily life, whereas the second includes intangible or immaterial entities, inaccessible to human senses, and, hence, less familiar to individuals. For this reason, the first category has been called 'real' and the second one 'abstract'. In turn, the category 'real' is subdivided in two additional clusters, 'perceptible' and 'dispersed'. Concepts such as water, object, dust, sound, and movement are comprised within the sub-category 'perceptible' due to their accessibility to human senses. Meanwhile, air, gas, cloud, and smoke are grouped in the sub-category 'dispersed' for their dissipated and/or scattered nature. The category 'abstract' is also formed by two sub-categories, 'immaterial' and 'microscopic'. While the first refers to physical concepts related to thermodynamics and electromagnetism (electricity, light, magnetic field, and heat), the second includes entities related with atomic, nuclear, and particle physics (particles, rays, waves, X-rays, and energy). The latter sub-category defines the most complex cognitive group due to the high level of abstraction required to understand the concepts.

It is interesting to examine the degree of correlation established between the concept of radioactivity and the four ontological categories identified in the hierarchical clustering analysis, as well as the influence of formal education in the construction of the concept's mental picture. With this aim, we have performed a categorical analysis of the answers to Item 1 for each of the academic levels described in Section 4.1, including the trainee teachers. An illustration is given in Fig. 2, where the entities are ordered in increasing cognitive complexity according to their category. The response distributions, normalized to the total number of students per level, are shown per academic course (see legend). The frequency of positive answers is indicated in the left axis, while that of negative answers is shown in the right one. At first sight, one can appreciate a gradual increasing trend of positive answers with the cognitive complexity of the categories. The observed evolution is in line with the progression from simple to

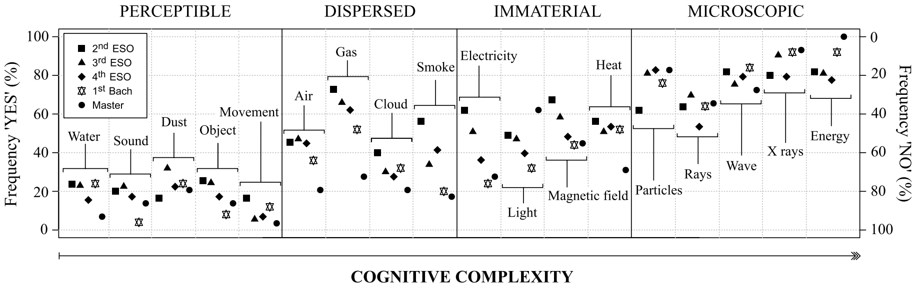

Fig. 2 Response distributions per academic level (see legend) for Item 1. The frequencies of positive answers are indicated in the left axis and those of negative answers in the right axis. The entities are displayed as a function of the ontological categories identified in the cluster analysis: 'perceptible', 'dispersed', 'immaterial', and 'microscopic'. Frequencies are normalized to the total number of students per academic level

complex, close to remote, familiar to strange, and definite to abstract that connects the discussed concepts. Hence, the surveyed individuals seem to use selection criteria such as the accessibility to human senses, the immateriality, the complexity, and the level of abstraction to make their choices. Within this perspective, radioactivity is assigned to the last ontological group, as it is appreciated as highly abstract, complex, remote, and completely inaccessible to senses.

For each entity listed in Item 1, the dissimilarity of the response distribution among different educational levels has been evaluated with a Fisher test. The only entities that show statistically significant differences are 'gas', 'smoke', and 'electricity'. These are concepts assigned to the intermediate categories 'dispersed' and 'immaterial'. Interestingly, these cognitive groups are halfway through the most tangible and abstract categories. On the contrary, the categories 'perceptible' and 'microscopic' raise a broader agreement among the different educational levels. They represent the least and most linked with the idea of radioactivity, respectively. Unsurprisingly, the group 'microscopic' is integrated by concepts of atomic, nuclear, and particle physics.

5.2 Item 2: On the Properties of Radioactivity

The second item explores which properties are more commonly attributed to radioactivity and how do these attributions evolve with the instructional level. Similarly to Item 1, a categorical analysis of the responses for each pair of adjectives has been performed. In order to discuss the associated misconceptions, the pairs of adjectives have been grouped in five general qualities: microscopic nature, uniqueness, duration, activity, and emotion/functionality. The classification is shown in Fig. 3, where the response distributions for the lowest (2nd ESO) and highest (Master) educational levels are shown as an illustration. For the sake of clarity, only two options out of the four available in the questionnaire (see supplemental material) are displayed. These are indicated in the x axis of the top and bottom panels, respectively, and correspond to either the most voted ones or those showing the biggest discrepancies among educational levels. As before, the frequencies are normalized to the total number of students in each level.

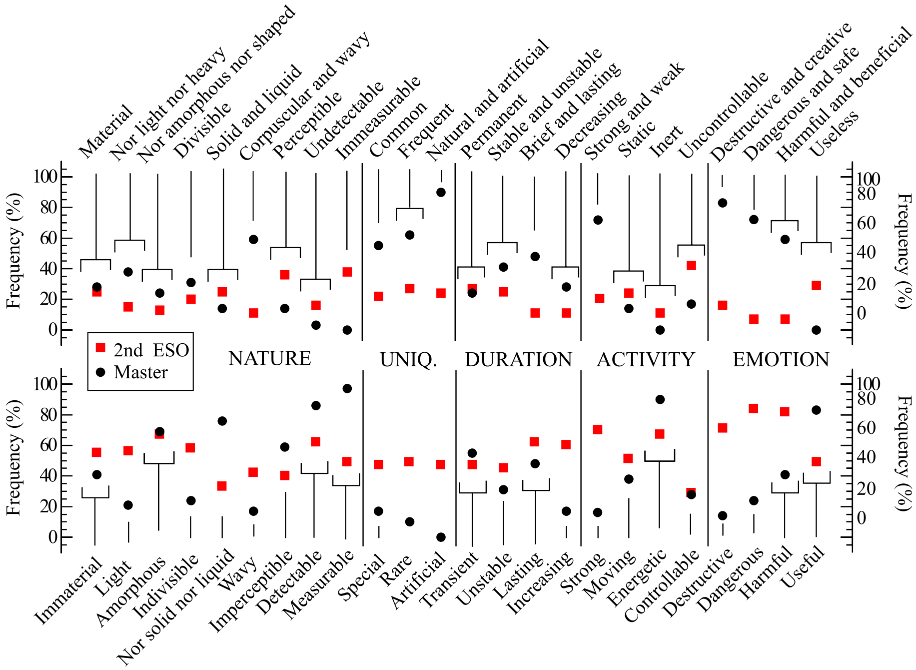

Fig. 3 Sample of answer distributions for the pairs of adjectives listed in Item 2. Frequencies are given for 2nd ESO (red squares) and the master group (black dots). Labels in the top and bottom panels refer to the option marked. See text for details

5.2.1 Microscopic Nature

This group of adjectives is labelled as 'NATURE' in Fig. 3. The main aim here is to inspect the ideas about the structural nature of the particles involved in the process of radioactivity. In turn, these allow one to better understand the causes behind the confusion caused by the terms 'radiation' and 'radioactive material'. In the case of the pair 'material-immaterial', about 50% of the surveyed students select the option 'immaterial', in accordance with the results of the cluster analysis of Item 1 (see Section 5.1). However, radiation can be both material and immaterial as it can consist of quantum particles with mass, such as alpha or beta particles, or without mass, such as photons. It is to note that the mental picture of immateriality persists in the higher educational levels; in particular, there is no increase of the option 'material and immaterial' for the trainee teachers, even if a significant number of them have received advanced undergraduate training on NS. There is even a clearer consensus on the perception of radioactivity as an amorphous entity, most likely due to its microscopic and abstract nature.

The adjectives 'solid' and 'liquid' can only describe a macroscopic material entity. For this pair of adjectives, the number of inquired students that select the option 'nor solid nor liquid' concomitantly increases at increasing educational level. Meanwhile, around 40% of students in compulsory secondary education believe that radioactivity is 'perceptible' even if radioactivity is a microscopic phenomenon completely inaccessible to human senses.

The confusion caused by the microscopic composition of matter can be clearly appreciated in the response distributions of the pairs 'divisible-indivisible' and 'corpuscular-wavy'. They show the most varied responses in this group, bringing to light the lack of familiarity with the aspects of Modern Physics (Fischler & Lichtfeldt, 1992; Gil & Solbes, 1993; Tuzon & Solbes, 2016). In both cases, the correct answer ['(a) and (b)'] holds a small percentage for the two pairs of adjectives in secondary education. This pattern is somehow expected, as the Valencian curriculum for these educational levels does not foresee formal instruction on quantum physics aspects such as the wave-particle duality. On the other hand, the response distributions of the master students are quite surprising. For the pair 'divisible-indivisible', a scarce 20% opts for the answer 'divisible and indivisible'. This percentage raises to 60% in the pair 'corpuscular-wavy', yet nearly 40% of the trainee teachers select the answers 'corpuscular' or 'wavy', evincing a retrieval of the classical picture of Physics to construct the mental concept of radioactivity. This suggests that the macroscopic representation of the microscopic world persists through formal education up to the highest instructional levels. The idea of materiality is revisited again in the pair 'light-heavy'. The preferred option of secondary school students is 'light', possibly referring to radiation, while the frequency of the adjective 'heavy', relating to radioactive material, is kept below 20% for all levels. On the other hand, the percentage of subjects selecting 'nor light nor heavy', in association with immateriality, is rather low except for the master course. Finally, the responses to the pairs of adjectives 'detectable-undetectable' and 'measurable-immeasurable' show an increasing frequency of options 'detectable' and'measurable' with the educational level; this is, most of students correctly state that radioactivity can be detected and measured.

5.2.2 Uniqueness

Another important issue about the mental picture of radioactivity is its uniqueness. This attribution is explored in Item 2 with three pairs of adjectives, 'common-special', 'frequent-rare', and 'natural-artificial'. In the three cases, there is a clear difference between the compulsory secondary school students and the trainee teachers, being the most significant one the pair 'natural-artificial' (see label 'UNIQ.' in Fig. 3). While the former mainly consider radioactivity as an 'special', 'rare', and 'artificial' entity, the later prefer to define it as 'common', 'frequent', and 'natural and artificial'. Thus, the perception in compulsory secondary education seems closely linked to the misconception that radioactivity has an artificial-only origin (Boyes & Stanisstreet, 1994). Meanwhile, the master group is perfectly aware of the existence of natural sources such as the cosmic rays or the Earth. The gradual increase of the correct options with the educational level is a clear indication that formal instruction does amend this misconception. According to these data, the conceptual bridge towards the natural picture of radioactivity seems to be built in the optional secondary levels.

5.2.3 Duration

The idea of radioactivity as a constant, perpetual entity is a well-known misconception in science education research (Millar et al., 1990). The knowledge of the nuclear waste disposal problem or the long time needed to decontaminate areas affected by nuclear accidents might be at the heart of this idea. It is to note, though, that the duration of radioactivity depends on the half-life, a property that is unique to each radionuclide and that can range from a few microseconds to billions of years (CPEP, 2019). In addition, the radioactive decay law establishes that the original sample of radionuclides changes into a less energetic, more stable nucleus exponentially with time. In the present survey, secondary school students prefer to describe radioactivity as a 'lasting' and 'increasing' entity. At the same time, they opt for the adjectives 'transient' and 'unstable'. This clash of ideas (that might be partially contradictory) is manifested through the generally highly fragmented response frequencies. Surprisingly, beyond 60% of the trainee teachers opt for the answers 'stable' or 'stable and unstable', a percentage that raises to nearly 100% for the options 'lasting' and 'brief and lasting'. Even if they represent the group with the highest level of scientific literacy — and hence should be the more coherent of all — these results seem in contradiction with those obtained for the pair 'transient-permanent', for which beyond 50% of them selected the option 'transient'.

5.2.4 Activity

In the case of the pair 'strong–weak', a vast majority of inquired students in secondary school believe that radioactivity is a 'strong' process (see label 'ACTIVITY' in Fig. 3). This perception changes abruptly for the master students, who consider it can be 'strong and weak'. The consensus to define radioactivity as an 'energetic' entity is also large, reaching nearly 100% in the higher levels. This answer is in complete agreement with — and indeed confirms — the results obtained for the cluster analysis of Item 1 (Section 5.1). There, the entity 'energy' was located in the ontological group 'microscopic', considered by students as the one conceptually closer to radioactivity. The pairs 'static-moving' and 'controllable-uncontrollable' generate more confusion in secondary school students, leading to a higher fragmentation of the response distributions. In the first case, around half select the option 'moving', indicating that the main trend is establishing mental schemes in relation to radiation rather than to radioactive material. It is to note that the responses to this pair preserve a certain coherence with the pair 'light-heavy'. For instance, the preferred options of students are 'light' and 'moving', clearly referring to radiation. For the pair 'controllable-uncontrollable', we see a variety of views that partially clears up for the master group. In this case, nearly 60% thinks radioactivity can be 'controllable and uncontrollable'.

5.2.5 Emotion and Functionality

The latter group of adjectives is marked as 'EMOTION' in Fig. 3. As can be seen in the figure, there is a widespread belief among secondary school students that radioactivity is 'destructive', 'dangerous', and 'harmful'; clearly showing a connection with negative emotions and feelings. Meanwhile, the options 'destructive and creative','dangerous and safe', and 'harmful and beneficial' are the preferred ones for the master group. This changing trend shows the effect of formal education on the emotional misconceptions about radioactivity. The trainee teachers appear to be more aware of the complexity of the phenomenon; this can be destructive or creative, dangerous or safe, or harmful or beneficial depending on several factors, such as the absorbed dose or the time of exposure. Surprisingly, a growing majority in all educational levels still consider radioactivity 'useful'. This result seems to disagree with the other emotional pairs of adjectives. In order to mitigate these incoherences, it is worth properly integrating the STSE relationships of NS in instructional programs (Alsop, 2001; Tsaparlis et al., 2013).

5.3 Item 3: On the Interests on NS Applications

Item 3 poses the multiple-choice question ‘Would you like to know more about any of the following aspects of radioactivity?’. There are nine possible answers: ‘scientific explanations’, ‘interaction of radiation with matter’, ‘medical applications’, ‘energy applications’, ‘nuclear accidents’, ‘radiation safety and control’, ‘food conservation and sterilization’, ‘industry applications’, and ‘others’. Of these, individuals can select as many as they want. The results for the eight first answers are shown in the left panel of Fig. 4, where the frequencies of response for each academic level are given. At first sight, one can see that the preferred topics are ‘nuclear accidents’ and ‘radiation-matter interaction’, with about 60% of students showing their interest in the corresponding topics. This suggests that those aspects inspiring more curiosity in students, overall, in secondary education, are the cause-effect relationships of radioactivity, in particular, its harmful effects on the human beings and the environment. Meanwhile, the categories ‘food sterilization’, ‘industry applications’, and ‘energy applications’ are the least popular, with around 40% of students wishing to know more about them. Even if there are no statistically significant differences among levels, a qualitative analysis of Fig. 4 reveals that master students generally show more interest for the applications and scientific explanations of radioactivity. This progression appears to be logical since the higher the level of scientific literacy, the better the appreciation and enthusiasm towards science-related issues (Díaz et al., 2003; Solbes & Vilches, 1997).

The number of selected topics per student has also been examined. The results are shown in the right panels of Fig. 4, where the normal (top) and accumulated (bottom) frequencies are displayed as a function of the number of aspects that each student has chosen. At first sight, one can see that only around 2% declares no interest in any topic. Meanwhile, the figure reveals that well beyond 70% selects more than 2 topics. We can conclude, then, that the willingness of students to learn STSE aspects based on radioactivity is excellent.

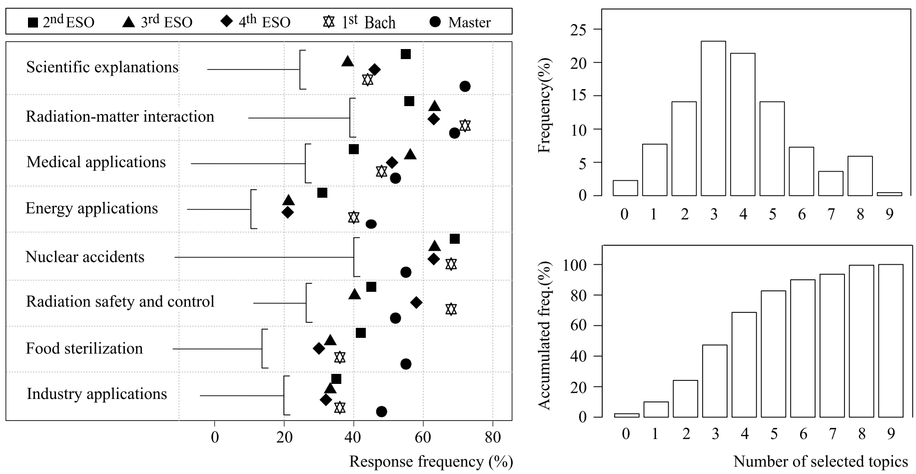

Fig. 4 Selection frequencies for each answer given in Item 3 (Would you like to know more about any of the following aspects of radioactivity?). (Left) Frequencies per topic selected and academic level (see legend in the top panel). (Right, top) Frequencies of the number of topics selected per student, normalized to the total number of inquired students. (Right, bottom) Accumulated distributions of the frequencies shown in the right top panel

5.4 Item 4: On the Misconceptions About Radioactivity

This item corresponds to the open questions of the questionnaire (see supplemental material). The categorization of the responses for the questions 4.1–4.4 and 4.6–4.7 is provided in Table 1, while the categories extracted for question 4.5 are shown in Fig. 5. In the following we will discuss the significance of the categories and comment on some representative answers.

Questions Q4.1 (‘How many types of nuclear radiation do you know?’) and Q4.2 (‘Which one do you think is the most dangerous for human beings?’) try to approach the confusion generated by the terms ‘radioactivity’, ‘radiation’, and ‘radioactive material’. In absolute agreement with the scientific literature (H. M. C. Eijkelhof et al., 1990; Kaczmarek et al., 1987; Martins, 1992; Millar et al., 1990; Neumann & Hopf, 2012; Plotz, 2016; Prather, 2005), this ambiguity is also appreciated in the individuals surveyed here. Fifteen percent of them think that other types of radiation, such as microwave radiation, solar rays, ultraviolet rays, X-rays, or even the sound have a nuclear origin. Consequently, they attribute applications based on these types of radiation to radioactivity. Among others, they cite the computer, the mobile, the tablet, the TV, the oven, the microwave, radiographies, ecographies, etc. They also identify some protection measures for non-ionizing radiation as protection measures for nuclear radiation. In some cases, these are recommendations without scientific base that have been spread by the media. In summary, they tend to connect the ideas related to waves with radioactivity. As a result, they mix up the cause-effect relationships of radioactivity and believe that some nuclei are radioactive because they emit waves.

Another group of students (8%) alludes to radioactive substances such as uranium, plutonium, or nuclear residues when they enumerate types of nuclear radiation, i.e. they confuse ‘radioactive material’ with ‘radiation’. As well, toxic substances such as mercury or applications of radioactivity such as nuclear power plants are cited in the answers.

Making the attempt to explain a microscopic phenomenon without the adequate academic training is a difficult task. The goal of question Q4.3 (‘Why some nuclei are radioactive?’) is exploring the mechanisms used by students to describe a phenomenon as complex and abstract as radioactivity from their current mental picture of the world. Twenty-six percent of them use well-known macroscopic physical, chemical, or biological phenomena and properties to search for an explanation. Among the answers, we find familiar concepts already learned at school that are equally abstract and microscopic, such as the electrons, the electricity or the fission, and fusion reactions. Six percent of the students refer to waves and radiation, showing up the confusion generated by the cause-effect relationships of radioactivity. Meanwhile, other students (7%) point to an artificial origin of radioactivity, citing either bombs or nuclear reactions or even explicitly stating the belief that radioactivity can only be produced

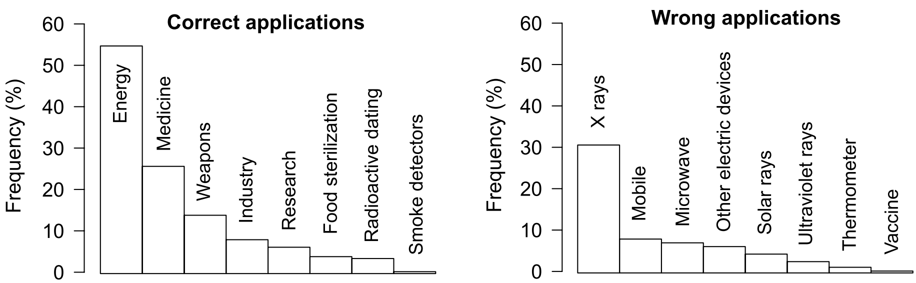

Fig. 5 Applications of radioactivity cited in the answers to question Q4.5 of Item 4. Correct applications are shown in the left panel, while wrong applications in the right one. In both cases, frequencies are normalized to the total number of inquired students

in nuclear reactors. These answers already exhibit some misconceptions; for instance, that radioactivity, in general, is dangerous and harmful, needs a propagation medium, can only be produced in fission and fusion reactions, has the same properties than electricity, or acts like a virus or bacteria (H. M. C. Eijkelhof et al., 1990). Finally, 15% of students allude indirectly to the nuclear forces, citing protons, particles, or the mass number. Two representative answers are ‘they are unstable’ and ‘they have an irregular combination of neutrons and protons’. Of these, only one individual alludes to the synthesis of nuclei to provide an explanation (‘it depends on the circumstances under it was created’).

Question Q4.4 (‘How can we protect ourselves from a radioactive substance?’) mainly addresses the vagueness of the terms ‘irradiation’ and ‘contamination’. As a result, a considerable number of students (42%) believe that they can protect themselves from radiation damages avoiding contact with the radioactive substance. Most of them (30%) do not consider the exposure to nuclear radiation nor the dose received. This is, they speak about radioactivity as if it were a toxic product or pathogen. It is to note that even if these students allude to radiation suits, their twofold purpose — to avoid contamination from radioactive material and protect mainly from radiation — is not clear to them. On the other hand, an equivalent number of learners (30%) refers to exposure or irradiation in their answers. Moreover, a 9% imagine a nuclear emergency crisis when confronted with this question, as if they only could be affected by radioactivity in these situations (‘hide in a bunker’, ‘abandon the city’, etc.). The catastrophic view of radioactivity, related to hazard and destruction, is the predominant misconception observed here. Other emerging ideas are related to non-nuclear radiation (‘use sun cream’) or the association with a microbial illness (‘put the contaminated objects in quarantine’).

The aim of question Q4.5 (‘How many applications of radioactivity do you know? List them.’) is exploring how well students have integrated the STSE relationships of NS in their mental schemes of radioactivity. Figure 5 summarizes the results for this question. The left panel lists response frequencies for correct applications, while the right one indicates frequencies for wrong applications. Among the correct ones, we notice the production of electric energy, several applications of medicine, the development of nuclear weapons, industry applications, research, food conservation, and sterilization and radioisotope dating. Only one master student cites smoke detectors of ^{241}Am. In the right panel, six out of eight applications are based on electromagnetic radiations in frequency ranges lower than nuclear radiation. These are X-rays, mobiles, microwaves, other electric devices, solar rays, and ultraviolet rays. The other two applications are thermometers and vaccines. These provide further evidence of previously cited misconceptions and conceptual errors, such as the ambiguity caused by the terms ‘radiation’, ‘radioactivity’, and ‘radioactive material’ or the connection established with toxic substances and viral or microbial diseases.

In the figure, one can see that more than 50% of students cite the production of nuclear energy. This high frequency is in line with the contents of NS foreseen in the Spanish and Valencian curricula of Physics and Chemistry (see Section 4.1). Surprisingly, the second application most frequently cited are X-rays, with about 30% recurrence. This conceptual error can be motivated by different factors. For instance, the cognitive difficulty associated to the abstraction of the microscopic world, which contributes to mistakes in the atomic and nuclear domains. The closeness with some medical applications of X-rays, such as the radiographies, might also be at the heart of this error. Or even some textbooks, which introduce UV and X-ray ionizing radiations in the NS chapter without specifying their generally lower energy and non-nuclear origin. As a result, it is not clear to students that only very energetic radiation can excite nuclei or induce nuclear reactions in their interaction with matter. Even though, the frequency of inquired students that do not list any erroneous application (54%) almost doubles that of students that do not list any correct one (33%).

In order to build up the mental schemes that lead to a meaningful learning of radioactivity, a conceptual leap from the macroscopic to the microscopic world is required. A clear indication of such a fulfilment is given when the student is capable of identifying and differentiating chemical and nuclear processes. To this aim, question Q4.6 ('Do you think radioactivity affects living and inert matter equally?') is posed. An overwhelming 59% of students consider the effects of radioactivity in living matter (Alsop, 2001; Klaassen et al., 1990). This, in some cases, leads to the erroneous conclusion that the structure of inert matter is not altered by radioactivity. Consistently, a biological terminology is usually used in the answers, with references to genetic mutations and analogies with viral and microbial diseases. Among the responses, two more groups are found, those who think that radioactivity affects similarly to inert and living matter (28%) and those who believe that it affects more inert matter (only 1%). The variety of arguments is wide. Some representative examples are 'the duration of radiation is different. In an object it can last years, but it kills living beings over time', 'radioactivity changes the composition of human beings and causes their death. Meanwhile, inert matter does not change its morphology', 'Radioactivity affects more living beings because it can react more easily with living matter than with lifeless objects', or 'Radioactivity does not affect inert matter, but it can remain in it and infect living matter'.

Question Q4.7 ('Can radioactivity turn objects radioactive?') mainly addresses two misconceptions. The first is the confusion caused by the terms 'irradiation' and 'contamination' (Millar & Gill, 1996). The second appears reiteratively in radioactivity teaching research and is related to the idea that objects become radioactive when they are irradiated (Nakiboglu & Tekin, 2006; Prather, 2005; Sesen & Ince, 2010). Actually, such an idea has to be put into context, since non-radioactive matter can only become radioactive by irradiation with very energetic radiation or by contamination with radioactive material. As a matter of fact, only Plotz (2016) clarifies this idea is a misconception for the whole electromagnetic spectrum excepting gamma radiation. In fact, it should be emphasized that the idea that radioactivity turns objects radioactive is true for most of the nuclear and cosmic radiation (including alpha rays, beta rays, protons, neutrons, etc.) because it is energetic enough to excite other nuclei or induce nuclear reactions that result in the production of unstable nuclei. We shall comment four response patterns here. The first only refers to irradiation ('The properties of an object or organism can be altered in order to fulfil the conditions to be called radioactive'). The second cites contamination ('atoms of radioactive objects must be transferred to other objects'). The third conceives the idea of radiation as 'something' that can be conserved and accumulated in matter ('radioactive particles enter and remain in matter and that is how it turns radioactive'). Finally, the fourth associates radioactivity with illness ('if [radioactivity] is used in the human body, it can cause cancer or diseases'). Frequencies for each response pattern are shown in Table 1.

One shall make a connection between the responses referring to contact with radioactive material (contamination) and the underlying difficulty to implement a microscopic nuclear model that explains nuclear reactions, most likely because radioactivity is an imperceptible, intangible, and abstract phenomenon that individuals cannot directly experiment. This, in turn, boosts the development of further misconceptions, such as that radioactivity can be accumulated in matter, already introduced by H. M. C. Eijkelhof et al. (1990).

6 General Remarks

The present study provides an excellent ontological frame to understand the nature and properties of radioactivity and its related ideas using a questionnaire as diagnostic tool. It is possible then to inspect how the ideas about radioactivity develop and evolve along the different educational stages and determine when, how, and why the alternative ideas appear in both the cognitive and affective domains. From the categorical analysis of Items 1 and 2, one can conclude that radioactivity is perceived as an extremely complex phenomenon, far off experience, unfamiliar, and highly abstract. In addition, radioactivity is mostly understood as a microscopic active entity, very strong and energetic, but light. It is also perceived as lasting, amorphous, and immaterial, but detectable and measurable. At the same time, radioactivity is recognized as extraordinarily dangerous, destructive, and harmful. Paradoxically, it is generally considered useful. These contradictory appreciations are very likely due to the post-formal nature of the entity, which leads to build complex, relative, antithetical, and multifaceted mental pictures of it. The data analysis has also revealed a progression in the understanding of radioactivity with formal education. On the one hand, the cluster analysis of Item 1 has shown a tendency to include radioactivity in the intermediate ontological categories 'dispersed' and 'immaterial' in compulsory secondary education. On the other hand, the higher levels place radioactivity with more certainty in the category 'microscopic', indicating that the differences among ontological groups are better appreciated at increasing educational training. We have also observed discrepancies in the properties attributed to radioactivity as a function of the educational level. Here, trainee teachers are more aware of the relative and multidimensional character of radioactivity and show a more cohesive and unbiased view of the phenomenon. Accordingly, while secondary school students perceive it as strong, lasting, special, artificial, rare, wavy, and increasing, the master group prefers to define it as both strong and weak, artificial and natural, wavy and corpuscular, brief and lasting, or increasing and decreasing depending on the context. Yet the most significant differences are found in the emotional dimension. While secondary education students classify radioactivity as highly destructive, damaging, and dangerous, the trainee teachers realize that it can be either destructive or creative, harmful or beneficial, and dangerous or safe depending on the situation. The observed change in the affective perspective might have its origin in the more extended scientific base of the master students. For instance, they generally know that radioactivity is far more common and frequent than believed by the broad audience or that its duration is an intrinsic property of each radionuclide. This improved understanding of the scientific facts related to radioactivity allows them to make more fair-minded judgements.

In general, the misconceptions found are very similar to those already cited in the literature and are held by individuals from all populations studied. The most frequently observed here is the ambiguous use of the terms 'radioactivity', 'radiation', and 'radioactive material'. This misconception boosts the appearance of further alternative ideas, such as that the ozone layer can protect us from radioactivity, the electrical devices are radioactive, or the confusion caused by the terms 'irradiation' and 'contamination'. These two terms are related to 'radiation' and 'radioactive material', respectively, as indicated by Millar & Gill (1996). Regarding the association with contamination (Boyes & Stanisstreet, 1994; Neumann & Hopf, 2012), students frequently relate radioactivity to environmental problems of differing origin such as the greenhouse effect, the hole in ozone layer, or the global warming. As a curiosity, some students cite 'toxic emissions from industrial plants', 'cow farts', and 'plastics and cans' as applications of radioactivity.

The conceptual leap associated to the abstraction of the microscopic world also stimulates a number of misconceptions. One widely spread is the confusion between the basic unit of nuclear matter, i.e. the nucleus, and the basic units of Chemistry and Biology, i.e. the atom and the cell (Nakiboglu & Tekin, 2006; Posada & Prieto, 1989). Some authors attribute this mistake to the confusion caused by the term 'radiation' (Kaczmarek et al., 1987), since both the atom and the nucleus are sources of electromagnetic radiation. In the present study, a significant percentage of students cite X-rays as a type of nuclear radiation, and radiographies as an application of radioactivity (see Fig. 5). In line, some of them justify the nature of radioactivity through chemical processes ([nuclei are radioactive due to] 'the number of electrons', 'the atomic structure', 'the chemical composition', or 'the stability of electrons'). As a consequence, there are difficulties to distinguish the concepts of atom, nucleus, isotope, and radioisotope (Nakiboglu & Tekin, 2006). As well, some find hard to believe that all chemical elements can become radioactive. Although in a lesser extent, the association with biological processes also emerges in some explanations ('radioactivity passes on from generation to generation through genes', 'dead cells do not absorb radiation').

The use of analogies with more familiar entities has also been extensively observed here. This strategy is commonly and unconsciously used by individuals to build up a cognitive bridge towards more complex and abstract concepts. In the case of radioactivity, the most noticed one is the analogy of the microbial disease (H. M. C. Eijkelhof et al., 1990). Indeed, the use of a medical vocabulary to refer to radioactivity is quite usual in the responses to the open-ended questions. Terms such as 'infection', 'transmission', 'illness', 'cancer', 'tumour', 'toxicity', 'vaccines', and 'virus' frequently appear. Consistently, it is believed that once radiation enters into one body, it 'remains' there until the body dies, making the comparison with a virus or bacteria. Others believe radiation is a tangible entity that can be 'attracted' by atomic nuclei and 'remain' in there, as if they were speaking of a toxic agent.

Apart from the chemical and biological processes mentioned before, students also establish analogies with physical phenomena already learned at school, such as the sound or the electricity. They normally use macroscopic properties, such as the pressure, the mass, or the volume, to explain radioactivity (it is to note some of these properties are appropriate if dealing with alpha and beta radiation). They also use known microscopic concepts such as the fission and fusion reactions, although in a lesser extent. It is hard to find references with similar misconceptions in the scientific literature. Perhaps the closest one is the belief that radioactivity is produced in nuclear reactors (Boyes & Stanisstreet, 1994), as fission reactions are implicitly used there to build a coherent explanation of the phenomenon. Similarly, some students argue in the open questions that radioactivity is originated by nuclear fuel.

The danger associated to a large time exposure to nuclear radiations or the time needed for radioactivity to disappear is also often brought up by students. These ideas are intimately related to concepts still unknown in compulsory secondary education, such as the half-life, the radioactive dose, or the radioactive decay rate. Some students believe that a prolonged or intense exposure to radiation turns bodies radioactive, no matter what the type of radiation is. Others insist in the persistence of radioactivity through the microbial disease analogy. In this case, it is perceived as a material and tangible entity that can be accumulated and transferred to other bodies. As such, radioactivity is believed to remain in matter unless it comes out or it is somehow extracted. For some students, this misconception has evolved into a technological version in which bodies can 'accumulate' radioactivity, as if they were batteries than can be charged and discharged. This analogy does not seem to have been detected before in the scientific literature, most likely because this is one of the first systematic enquiries on radioactivity to digital natives. The idea that atoms do not change their nature, or that elements are immutable, also appears linked to the notion of durability.

In the present study, the only nuclear reactions mentioned by the secondary school sample are the fusion and fission reactions, precisely the only two foreseen in the Valencian curriculum of Physics and Chemistry. This suggests an unawareness of the existence of other types of nuclear reactions in nature and, at the same time, explains why most of the secondary students attribute an artificial origin to radioactivity.

Finally, it should be noted that the attitudes and emotions towards the phenomenon of radioactivity are approached in some items of the questionnaire, inspecting which applications do students know and which is their perception about their utility, advantages, and disadvantages. As a result, secondary school students identify radioactivity with danger, damage, illness, contamination, and destruction, showing a biased perspective. Despite recognizing some beneficial applications such as medicine, they generally exhibit an instinctive fear to radioactivity, most likely due to the catastrophic view given by Internet and the mass media, which usually bring death into focus.

7 Conclusion

We have carried out the first cross-sectional study about misconceptions, knowledge, and attitudes towards radioactivity of secondary students and pre-service teachers in the educational reference frame of the Valencian Community (Spain). The analysis tool employed is a questionnaire adapted from a previously validated one that includes both, closed and open questions aimed at exploring the ontological and phenomenological understanding of radioactivity, its related misconceptions, and the interests and emotions that radioactivity evokes in students. As well, we have investigated how their ideas and attitudes evolve with educational training.

As a result, the work has verified most of the misconceptions reported in the scientific literature. Given the new intervention context, some up-to-date nuances have been observed and discussed. On the other hand, we have identified deficiencies in the mental schemes built by students on the nature and properties of radioactivity. This aspect seems fundamental to develop the emotional facet of the concept, which shows a clear evolution from a radical catastrophic view in the compulsory levels to a more moderated, critical thinking-based perspective in the master group. Regarding the attitudinal dimension, we have verified a strong interest towards the applications of NS, with an overwhelming 98% of students wishing to learn new aspects. As shown in Fig. 4, nuclear accidents and effects of ionizing radiations in living and inert matter raise the highest interests in secondary education, while more technical issues, such as the scientific explanations of radioactivity or its applications, are better appreciated at increasing instructional level. Importantly, the present study prepares the ground to develop specific teaching strategies to approach the deficiencies found here. Such procedures must lead to a meaningful learning of the NS concepts in order to promote the critical thinking skills necessary to discuss and make decisions about the most controversial STSE aspects of nuclear science.

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Data Availability The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Code Availability The code used in this study has been generated with the programs R and root.

Declarations

Conflicts of Interest The authors declare that they have no conflict of interest.

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