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Senior pre-service chemistry teachers' perceptions, alternative conceptions and knowledge structure regarding radiation and radioactivity

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This study investigates the perceptions, alternative conceptions, and knowledge structures of senior pre-service chemistry teachers regarding radiation and radioactivity prior to their enrollment in a nuclear chemistry course. A phenomenographic design was employed to reveal the qualitatively different ways in which these concepts are perceived and conceptualized. The phenomenographic analysis was conducted in three stages to identify the key issues within participants' perceptions and to organize the qualitative variation in these perceptions into hierarchically related categories. These categories were then secondarily interpreted to identify alternative conceptions and to map the underlying knowledge structures that illustrate how fundamental nuclear chemistry concepts are structurally interconnected within participants' mental frameworks. At the end of the study, SPSCTs' perceptions of radiation were grouped into five main issues: (1) ray, (2) emission of ray, (3) wave, (4) energy, and (5) emission of energy; while their perceptions of radioactivity were grouped into six main issues: (1) emission of radiation, (2) decomposition, (3) radiation, (4) energy, (5) reaction, and (6) matter. Energy emerged as the only common issue across both outcome spaces, indicating that senior pre-service chemistry teachers fundamentally associate both phenomena with energy. At the same time, radioactivity was primarily conceptualized as a process grounded in nuclear instability and material transformation, yet only partially distinguished from the physical phenomena of radiation. The findings further indicate persistent alternative conceptions among senior pre-service chemistry teachers, including the interchangeable use of radiation and radioactivity, the belief that all forms of radiation are harmful, and the alternative conception that nuclear reactions are a type of chemical reaction. These results underscore the need for targeted instructional strategies in teacher education programs to address structurally embedded conceptual confusions before formal nuclear chemistry instruction begins.

Introduction

People frequently encounter the terms "radiation" and "radioactivity" in their daily lives. Although these concepts are often mentioned together, they are not synonymous. Radiation is the propagation or transfer of energy through space or matter, either in the form of electromagnetic waves (photons) or through matter-based particles carrying kinetic energy, such as alpha and beta particles, protons, and neutrons. These forms of radiation can be classified into ionizing and non-ionizing types. In contrast, "radioactivity" refers to the process by which unstable nuclei become more stable by emitting alpha, beta, or gamma radiation (Boyes and Stanisstreet, 1994); thus, radioactivity involves the release of nuclear radiation. As stated by the United States Nuclear Regulatory Commission (NRC), "all types of nuclear radiation are also ionizing radiation; however, not all ionizing radiation is nuclear in origin (for example, X-rays are ionizing radiation but not nuclear radiation, since they do not originate from atomic nuclei)." In other words, ionizing radiation originating from nuclear processes (*i.e.*, nuclear radiation) constitutes a subset of ionizing radiation, and radioactivity involves the release of such nuclear radiation (NRC, n.d.). Despite these distinctions, society in general, and even high school and university students, often struggle to differentiate between these types and tend to confuse their meanings (Nakiboğlu and Ölmez, 2021, 2022a).

As explained above, radiation is an umbrella term encompassing both ionizing and non-ionizing forms; nevertheless, many studies have shown that students and adults use the terms "radioactivity" and "radiation" interchangeably. The interchangeable use of these context-dependent concepts prevents

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individuals from correctly interpreting certain events they encounter in everyday life. From an educational perspective, this indicates that the concepts of radiation and radioactivity should be explicitly addressed in both physics and chemistry teaching at the secondary school level. Nuclear chemistry and nuclear physics can together be defined as "nuclear science," which represents a fundamental field of study for both chemists and physicists and has significantly enhanced our understanding of the fundamental nature of matter as well as contributed to medicine, electronics, geology, archaeology, and industry (Atwood and Sheline, 1989). Topics related to nuclear science are included at various levels in upper secondary chemistry and physics courses; therefore, it is important that both chemistry and physics teachers develop a sound and accurate understanding of these concepts in order to design learning environments that support students' meaningful construction of these concepts.

On the other hand, since chemistry education students will eventually become chemistry teachers, they will need to teach these topics correctly to their own students. In order to support students' understanding of concepts related to nuclear energy, radioactivity, and radiation, pre-service teachers need to develop coherent and scientifically grounded conceptual frameworks. For this reason, they need to encounter course content related to nuclear chemistry during their training. Prior to formal instruction, they may hold a range of pre-existing conceptions, including alternative conceptions, which shape how new information is interpreted. The terms "radiation" and "radioactivity" are two of the central concepts in the nuclear science and represent prerequisite knowledge that must be addressed before starting a nuclear chemistry course.

Although, in this context, pre-service teachers' ability to teach these concepts "correctly" and "effectively" may appear to be closely related to discussions of pedagogical content knowledge (PCK), which focus on how content knowledge is transformed within instructional contexts (Shulman, 1986; Park and Oliver, 2008), the focus of the present study, independent of these frameworks and at a level preceding pedagogical transformation processes, is on examining how the concepts of radiation and radioactivity are conceptualized, differentiated, and structured through cognitive relations prior to instruction.

Accordingly, the present study aims to examine how senior pre-service chemistry teachers (SPSCTs) conceptualize and differentiate the concepts of radiation and radioactivity prior to instructional engagement, and to map the knowledge structures (KSs) underlying these conceptualizations through a comparative phenomenographic analysis.

Challenges in understanding radiation and radioactivity

Radiation and radioactivity are among the fundamental concepts that have long been taught in physics and chemistry education. Despite their central role in science curricula, research over the past four decades has consistently documented that students experience persistent and systematic difficulties in distinguishing between radiation and radioactivity.

Early studies documented that students often conflated radiation with radioactive substances, treating radiation as a material entity that can accumulate in objects or living organisms (Eijkelhof *et al.*, 1990; Lijnse *et al.*, 1990). Subsequent research expanded these findings by showing that such confusions are reinforced by everyday language, media representations, and risk-oriented contexts, leading students to associate all forms of radiation with danger and contamination (Boyes and Stanisstreet, 1994; Alsop, 2001; Prather and Harrington, 2001; Cooper *et al.*, 2003). More recent studies have further demonstrated that these alternative conceptions persist across educational levels and national contexts, including among pre-service teachers, and remain resistant to traditional instruction across educational levels and contexts (*e.g.*, Neumann and Hopf, 2012; Hull and Hopf, 2020; Nakiboğlu and Ölmez, 2021).

It has been noted that this problem is observed not only among secondary school students but also among university students in different fields (*e.g.*, pre-service teachers, medical students, physics majors, radiography students, technology-oriented undergraduates) before starting courses related to nuclear science, and that it even persists after taking such courses conducted through traditional instruction (Prather and Harrington, 2001; Hagi and Khafaji, 2011; Kohnle *et al.*, 2011; Bakaç and Taşoğlu, 2016; Maharjan, 2017; Rahmatullah *et al.*, 2018; Fakhar *et al.*, 2019; Yeşiloğlu, 2019; Pilakouta and Sinatkas, 2020; Ioannis and Konstantinos, 2021; Özdemir and Yarar, 2021).

Although the terms "radioactivity" and "radiation" have distinct and precise meanings, research has shown that children and students tend to use these two concepts interchangeably. This conceptual confusion is not limited to students but is also widely observed among the general public. Studies examining alternative conceptions about radiation and radioactivity among both students and the public began relatively late in science education research compared to other topics, with the first systematic findings emerging in the 1980s. Eijkelhof *et al.* (1990) summarized these early findings, emphasizing that students systematically confused the concepts of "radiation" and "radioactivity." They also noted that radiation was often perceived as a phenomenon that accumulates in living organisms, objects, and enclosed spaces. For example, following the Chernobyl nuclear disaster, it was widely believed that radiation concentrated in plant matter and was transmitted to humans through consumption. Moreover, any situation involving radiation was strongly associated with danger. The belief that all forms of radiation are dangerous or harmful has also been identified in many subsequent studies (Prather and Harrington, 2001; Nakiboğlu and Tekin, 2006; Neumann and Hopf, 2012; Tsaparlis *et al.*, 2013; Neumann, 2014; Karaca *et al.*, 2016; Cardoso *et al.*, 2020; Özdemir and Yarar, 2021).

Riesch and Westphal (1975), in their study with 15-year-old students in Germany, demonstrated that when explaining the propagation of radiation, students predominantly relied on "current" and "diffusion" models, while distancing themselves from the scientifically accurate ''particle'' and ''wave'' models. More importantly, the students confused the transport of radioactive material with the propagation of radiation, with concepts such as ''radioactive contamination'' reinforcing this misconception. Research has shown that the inability to distinguish between radiation and radioactivity constitutes a significant conceptual barrier to understanding the difference between contamination and irradiation (Hafele and Johnson, 2012).

Another recurring problem concerns the synonymous use of radiation and radioactive materials. In a study conducted in the Netherlands, Eijkelhof and Wierstra (1986) found that 17-year-old students used the concepts of ''radioactive matter'' and ''radiation'' interchangeably when evaluating the risks of ionizing radiation (cited in Eijkelhof *et al.*, 1990). Among these students, beliefs such as ''radiation accumulates in the body'' or ''irradiated food becomes radioactive'' were commonly observed. Toward the end of the 1980s, Lijnse *et al.* (1990), in a study with 16-year-old students in the context of the Chernobyl disaster, revealed that students held serious alternative conceptions related to radiation, radioactivity, radiation dose, and radioactive contamination. This and similar problems have been observed today and even among pre-service teachers. Prokop and Nawrodt (2024) found that German pre-service teachers were able to distinguish only partially and inadequately between radioactive matter and ionizing radiation. Similarly, Tasoglu *et al.* (2015) investigated Turkish prospective physics teachers' knowledge of and attitudes toward radiation and radioactivity and reported that most of these participants lacked sufficient knowledge of ionizing radiation and failed to differentiate between contamination and irradiation.

Millar (1994) extended Eijkelhof's work on conceptual confusion by examining the issue in a more systematic manner, with the aim of determining the extent to which students used the terms radioactive matter, radiation, and radioactivity synonymously, and exploring how this confusion varied across different contexts. His findings revealed that 16-year-old students in the United Kingdom frequently employed the expressions ''contains radioactive material,'' ''contains radiation,'' and ''is radioactive'' interchangeably. Among these, the phrase ''contains radiation'' emerged as particularly widespread and commonly used. However, students' interpretations of these terms were often imprecise and highly context-dependent, with major misconceptions especially evident in relation to the processes of radiation absorption and re-emission. What sets Millar's work apart from earlier studies is its systematic approach to investigating these conceptual confusions and its detailed analysis of how students applied the terms across various contexts (*e.g.*, food irradiation, medical applications). The study therefore demonstrates that the problem is not merely one of linguistic imprecision but reflects deeper conceptual gaps in students' understanding of the basic models of radioactive processes. These findings highlight the importance of curricula and instructional materials explicitly differentiating between radiation, radioactivity, and radioactive matter. Furthermore, Millar (1994) linked this phenomenon to the influence of the media. Phrases such as ''a cloud of radiation'' or ''water/milk containing radiation'' illustrate how journalistic discourse may unintentionally promote the perception of radiation as a tangible substance. While such terminology might sometimes be used as loose shorthand, it also reflects a deeper misconception that materials absorbing radiation can later re-emit it. This conflation, reinforced by media narratives, ultimately reflects a failure to distinguish between electromagnetic radiation (*e.g.*, X-rays, gamma rays) and particulate emissions (*e.g.*, alpha and beta particles).

Subsequent research has increasingly focused on students' perceptions of ionizing and non-ionizing radiation, as well as their beliefs about electromagnetic radiation emitted by electronic devices (Rego and Peralta, 2006; Kontomaris and Malamou, 2018; Kontomaris *et al.*, 2019). Rego and Peralta (2006), for example, found that although the majority of Portuguese students at the middle school, high school, and university levels had heard of the concept of ''radiation,'' a substantial proportion were unable to differentiate between ionizing and non-ionizing radiation. Many students further equated electromagnetic waves, particularly visible light, an integral part of daily life, with radioactive radiation. A similar pattern was reported by Nakiboğlu and Ölmez (2022b), who revealed that 60% of students in their study believed that radiation from mobile phones was radioactive, citing reasons such as the involvement of electricity, the presence of a battery, and general health concerns. Moreover, students were aware that radiation was emitted from mobile phones, but they lacked sufficient knowledge to recognize it as electromagnetic field (EMF) radiation. Comparable findings have been documented in other contexts: Mubeen *et al.* (2008) reported that Pakistani medical students held numerous alternative conceptions and faulty risk perceptions regarding the sources, risks, and protective measures associated with ionizing and non-ionizing radiation. These included beliefs that microwave ovens emit dangerous radiation and that MRI machines produce ionizing radiation. Likewise, Hagi and Khafaji (2011) reached nearly identical results with medical students in Saudi Arabia.

When examining the reasons why students confuse ionizing and non-ionizing radiation, studies consistently point to deficiencies in their understanding of atomic structure and ionization. Prather (2005) showed that undergraduates often relied on fragmented and inconsistent models of atomic structure and radioactive decay, including misconceptions such as attributing nuclear instability to proton–proton repulsion or explaining decay in terms of electron excitation. Similarly, Nakiboğlu and Tekin (2006) observed that many high school students explained nuclear stability in terms of atomic-level concepts such as the atomic number/mass number ratio or valence electrons. These findings highlight that conceptual gaps about atomic structure directly impede students' understanding of radiation processes. A related difficulty lies in the comprehension of ionization itself. Students who fail to construct a coherent mental model of what ionization entails, the fundamental properties of radiation, and the ionization process often either perceive radiation as a ''substance'' or conflate ionization with radiation emission. Hafele and Johnson (2012), working with non-science undergraduates, emphasized that such conceptual shortcomings play a major role in preventing students from distinguishing between ionizing and non-ionizing radiation.

In recent years, the focus of research has shifted toward examining how both students and pre-service teachers understand electromagnetic radiation (EMR) and radioactivity (Gavrilas and Kotsis, 2023; Gavrilas and Kotsis, 2024; Plotz and Hollenthoner, 2019). Despite the rapid proliferation of devices emitting electromagnetic waves, particularly cell phones and wireless technologies, studies in this field have revealed that pre-service teachers and the general public hold significant misconceptions and insufficient knowledge. For example, Gavrilas and Kotsis (2023) investigated pre-service teachers' knowledge of electromagnetic radiation and its applications in wireless technologies. Their findings indicated that teachers' knowledge of EMR was generally inadequate, with significant differences explained by the content of the courses they had taken, their scientific interests during high school, and gender. Extending this line of work, Gavrilas and Kotsis (2024) conducted a comprehensive review that revealed how misconceptions about electromagnetic radiation shape public perception and health-related anxieties. They emphasized that many individuals still associate EMR from cell phones and Wi-Fi routers with serious health risks (*e.g.*, cancer and neurological disorders). Such beliefs not only reinforce conceptual misunderstandings but also heighten health anxieties through the nocebo effect. The nocebo effect refers to the experience of real symptoms, such as headaches or dizziness, caused by negative expectations toward a harmless phenomenon, even when exposure levels are within safe limits or entirely absent.

Parallel to this line of EMR research, recent studies have also shown that pre-service teachers struggle to differentiate between radiation, radioactivity, and radioactive matter. Prokop and Nawrodt (2024) found that, similar to students, pre-service teachers often confused radioactive matter with ionizing radiation and used the concepts of fission and decay synonymously. Moreover, they were observed to reintroduce misconceptions they had previously denied (*e.g.*, the idea that ionizing radiation can "activate" materials). An important finding of this study was that the concept of "energy" emerged as a central coordination framework in shaping pre-service teachers' understandings of radioactivity.

Overall, these findings highlight both the persistence of alternative conceptions among SPSCTs and their limited ability to clearly distinguish between fundamental concepts (*e.g.*, radiation *vs.* radioactivity, ionizing *vs.* non-ionizing radiation). Given that these shortcomings directly affect future teachers' ability to convey accurate scientific knowledge to students, it is essential for teacher education programs and curricula to explicitly address and remediate these conceptual confusions.

In this context, a longstanding issue consistently reported in the literature on radiation and radioactivity is the persistent conflation of these two concepts by students and pre-service teachers. Previous studies have documented various manifestations of this conceptual confusion, establishing a substantial body of evidence particularly with respect to distinctions between contamination and irradiation, perceptions of harmfulness, the nature of radiation sources, and associations with electromagnetic radiation. Nevertheless, the majority of these studies have addressed this confusion primarily through the question of "which alternative conceptions exist," while remaining limited in systematically demonstrating the explanatory pathways, sub-conceptual relations, and hierarchical differentiations through which such confusion is generated.

Rather than approaching the conceptual confusion surrounding radiation and radioactivity at the level of a descriptive list of alternative conceptions, the present study aims to render the structural dimension of this confusion visible. To this end, separate phenomenographic outcome spaces were constructed for each concept and examined comparatively. This approach enabled the analysis of conceptual confusion not merely in terms of binary distinctions such as "correct/incorrect" or "present/absent," but with respect to the specific sub-conceptual nodes and explanatory trajectories along which it becomes concentrated. In particular, the findings reveal that sub-conceptual connections such as wave–ray–energy relations, nuclear-source emphasis, discourses of harmfulness, and the articulation of technological and chemical contexts play a critical role in the production of this confusion.

A further significant contribution of the study lies in its adoption of an analytical approach that extends beyond the generation of phenomenographic perception categories to enable the production of multiple analytical outputs from a single data set. In this context, the derived outcome spaces were used not only to describe variation in perceptions, but also as an analytical basis for identifying alternative conceptions and for mapping the KSs that illustrate how these conceptions are organized at the group level. In contrast to established approaches such as concept maps (*e.g.*, Nakiboğlu and Ertem, 2010; Anzovino and Bretz, 2016) or conceptual landscapes (*e.g.*, Zabel and Gropengiesser, 2011), which are primarily designed to trace individual learners' conceptual pathways and often rely on explicitly labeled relational links, the KS representations employed in the present study serve a different analytical function. Rather than following individual learning trajectories, these representations were derived from phenomenographic outcome spaces and were used to make visible collective cognitive patterns and conceptually problematic nodes at the group level. In this sense, the proposed representations do not aim to replace existing mapping techniques, but to complement them by offering an aggregate, variation-oriented perspective aligned with the phenomenographic focus on qualitatively different ways of experiencing a phenomenon.

From this perspective, the study offers an integrated analytical framework that elucidates how SPSCTs differentiate between radiation and radioactivity prior to nuclear chemistry instruction, under which conditions they equate these two concepts, and through which hierarchical organizations these meaning-making processes are constructed.

Rationale

As highlighted in the reviewed literature, students across different age groups and pre-service teachers at the university level enter classes on radiation and radioactivity with perceptions and conceptual frameworks that diverge from the scientifically accepted understanding of these concepts. Therefore, identifying how students perceive these concepts and mapping their KSs prior to instruction is crucial for the effective learning and teaching of nuclear chemistry course. In this regard, the central idea of the present study is to examine the perceptions of SPSCTs regarding radiation and radioactivity before they begin a nuclear chemistry course. This approach will make it possible to identify inappropriate perceptions and alternative conceptions at the outset thereby enabling the design of instructional strategies to address and overcome these difficulties.

By making pre-instructional KSs visible, the present study provides a foundation for the design of instructional interventions that explicitly target critical conceptual nodes and relations underlying students' and pre-service teachers' difficulties with radiation and radioactivity. Such an approach is expected to support the construction of scientifically accurate KSs, facilitate the deconstruction of persistent alternative conceptions, and ultimately enhance the effectiveness of teacher preparation programs in nuclear chemistry education.

The theoretical framework of the study

This study examines students' perceptions of the concept of radiation, their alternative conceptions, and how their KSs develop within a constructivist approach, addressing the dimensions of perception, alternative conception, and cognitive structure in a holistic manner. Although these dimensions are theoretically grounded in different foundations, they complement each other in the learning process.

Constructivism, in which learning is understood as a process of knowledge construction in the learner's mind (von Glasersfeld, 1989, 1991), was used as the theoretical framework for this study. This approach requires the appropriate structuring of the relationships between concepts established in the learners' minds during instruction. Rather than treating learning as a transmissive process, it emphasizes the active construction and reorganization of relationships between concepts in learners' minds through engagement with instructional contexts. Thus, meaningful learning emerges through learners' own cognitive activity rather than as a direct result of teaching.

The knowledge structure defines how the pieces of knowledge an individual possesses are related to each other and how they are organized. This structure seeks to explain how learned knowledge is organized in the mind, how it is connected, and how it is integrated with new information. The depth of students' understanding of a particular subject is therefore based on these KSs.

Within this framework, perception plays a key role. Perception refers to the process through which individuals interpret and make sense of stimuli from their environment, actively shaped by prior knowledge, context, and cognitive processes. According to Gibson's ecological theory of perception (Gibson, 1979), perception is not a passive reception of sensory input but an active, action-oriented process that arises from the dynamic interaction between the individual and the environment. In addition, sociocultural constructivist perspectives (Vygotsky, 1978) emphasize that cognition, and consequently perception, is mediated by social and cultural interactions. Language, communication, and cultural tools serve as central mechanisms in the development of perception and learning.

Alternative conceptions also constitute an important dimension in this study. As emphasized in the literature, the terms misconception and alternative conception are sometimes used interchangeably (Nakiboğlu, 2006). However, Taber (2000) highlights that misconceptions are often associated with temporary misunderstandings that emerge within instructional contexts, frequently due to poor communication or unclear explanations, and can usually be addressed through relatively limited conceptual clarification.

In contrast, alternative conceptions represent more resistant and deeply rooted ideas that conflict with scientific explanations and cannot be resolved by simple corrective feedback. Since the present study focuses on students' persistent and structured ideas about radiation and radioactivity, the term alternative conception is adopted here to better reflect the complex and enduring nature of these conceptual challenges. While KSs are shaped through learners' ongoing interactions with instructional contexts, they are also strongly influenced by students' prior knowledge, experiences, and existing cognitive frameworks, which contribute to the development of different perceptions of a given concept. Thus, considering the SPSCTs' previous perceptions and KSs regarding scientific concepts, the constructivist approach is thought to provide a powerful framework to explain how new information is perceived, how alternative conceptions are formed, and how relationships between concepts are organized.

From this perspective, perception becomes a fundamental component of learning, situated at the intersection of individual cognition and sociocultural interaction. For example, a student may initially experience radiation as an invisible danger (perception), which may later be interpreted as an alternative conception when this experiential meaning is examined in relation to scientific consistency, such as the belief that all radiation causes cancer, or when the learner fails to relate basic concepts such as the distinction between ionizing and non-ionizing radiation (KS).

In the present study, the distinction between perception and alternative conception is not treated as a merely terminological choice, but as an analytical lens for structuring phenomenographic outcome spaces and for identifying scientifically problematic nodes within students' KSs (Marton, 1981; Taber, 2000). While phenomenographic outcome spaces provide a robust means of describing qualitative variation in students' meaning-making, they do not, in themselves, specify which conceptual elements function as persistent sources of scientific inconsistency, nor do they explain why such problematic understandings tend to endure. Accordingly, the second analytical stage adopted in this study introduces an additional explanatory layer by examining how certain perceptions operate as recurrent, meaning-organizing nodes within students' collective knowledge structures. This distinction allows the analysis to extend beyond descriptive accounts of variation and to identify structurally persistent conceptual nodes that are analytically relevant for interpretation and for considerations related to instructional design. These analytically identified conceptual nodes are not treated as inherent properties of the data, but as analytically constructed interpretations grounded in systematic comparison, theoretical criteria, and iterative engagement with the empirical material.

Phenomenography. To explore students' perceptions of radiation and radioactivity, this study employed phenomenography as its analytical framework. Phenomenography is a qualitative research approach that focuses on identifying and describing the qualitatively different ways in which a phenomenon is experienced and understood by a group of learners (Marton, 1981). Within the theoretical framework of the present study, phenomenography is adopted primarily as an analytical and conceptual lens for examining variation in meaning-making, rather than as a prescriptive methodological procedure. Accordingly, the focus is placed on how variation in SPSCTs' pre-instructional meanings of radiation and radioactivity is constituted and structured, rather than on procedural aspects of data generation alone.

In science education, perception is conceptualized not merely as sensory interpretation but as an active meaning-making process, particularly when learners engage with abstract and intangible concepts such as radiation and radioactivity. Because these phenomena are invisible, odorless, and not directly accessible to sensory experience, students' perceptions are often mediated by indirect sources, including media representations, cultural narratives, and intuitive reasoning (Boyes and Stanisstreet, 1994; Neumann and Hopf, 2012). Such mediation plays a critical role in shaping learners' initial conceptual organizations, which may persist and later function as alternative conceptions.

Previous studies have consistently shown that one of the most persistent conceptual difficulties in this domain is the conflation of radiation and radioactivity, with students frequently using the two terms interchangeably (Boyes and Stanisstreet, 1994; Neumann and Hopf, 2012). This conflation gives rise to alternative conceptions such as believing that irradiated food becomes radioactive or that all forms of radiation are inherently harmful. From a theoretical standpoint, these findings underscore the need for an approach capable of capturing not only incorrect ideas, but also the underlying structure and variation of learners' meanings, making a variation-oriented framework particularly appropriate.

Phenomenography has been successfully employed in chemistry education research to investigate qualitative diversity in learners' conceptualizations (Liu, 2001; Stefani and Tsaparlis, 2009; Nakiboğlu and Ölmez, 2021). For instance, Nakiboğlu and Ölmez (2021) demonstrated its effectiveness in identifying categories of 12th-grade students' understandings of radiation and radioactivity, while Nakiboğlu and Nakiboğlu (2019) applied phenomenography to analyze SPSCTs' perceptions of precipitation. Comparable applications in other science education contexts further support phenomenography's theoretical strength in revealing structured variation in meaning (Pang, 2003; Åkerlind, 2005).

On this basis, phenomenography was selected as the theoretical framework of the present study because it provides a coherent means of examining variation in SPSCTs' pre-instructional perceptions and supports the comparative logic required to analyse radiation and radioactivity concurrently. Through this lens, radiation and radioactivity are conceptualized not as unitary or fixed entities, but as multifaceted phenomena whose meanings are shaped by experience, intuition, and sociocultural context. Although a substantial body of research has documented students' alternative conceptions related to these concepts, phenomenographic studies that comparatively examine both radiation and radioactivity within a single analytical design remain limited. Guided by this theoretical positioning, the following research questions were formulated:

RQ1. How do the SPSCTs perceive the concepts of radiation and radioactivity before taking the nuclear chemistry course?

RQ2. What similarities or differences emerge when comparing the hierarchical outcome spaces of radiation and radioactivity?

RQ3. Which of these perceptions reflect alternative conceptions or scientifically inaccurate ideas regarding radiation and radioactivity?

RQ4. How are the concepts of radiation and radioactivity, along with their related issues and other sub-concepts, organized within the KSs of SPSCTs as revealed through phenomenographic analysis?

Methods

Context of the study

This research was carried out within the Chemistry Teacher Education Program of a public university in Türkiye. The four-year chemistry teacher education program aims to prepare prospective chemistry teachers for secondary education and offers both compulsory and elective courses in chemistry and science education. One of these elective courses is the Nuclear Chemistry course. The course covers the theoretical foundations of nuclear chemistry, including topics such as nuclear stability, types of radiation, half-life and rate laws in nuclear reactions, radioactive decay series, fission and fusion processes, and practical applications of nuclear chemistry in everyday life and technology. The primary goal of the course is to equip the SPSCTs with the knowledge and skills to teach nuclear chemistry effectively and to engage their future high school students in informed discussions on socio-scientific issues related to radiation, radioactivity, and nuclear technologies.

In this study, the perceptions, alternative conceptions, and KSs of the SPSCTs regarding radiation and radioactivity were examined at the beginning of the course. Prior knowledge of these concepts originates not only from previous chemistry courses but also from various sources such as everyday life, media, cultural narratives, and personal experiences. Therefore, identifying how the SPSCTs perceive radiation and radioactivity before starting the nuclear chemistry course was considered a critical step for anticipating potential conceptual difficulties during the course and for developing appropriate instructional strategies.

Research design

This study was conducted within a qualitative research paradigm and employed a phenomenographic design. At this point, it should be noted that this study does not aim to claim objectivity in the positivist sense; rather, trustworthiness is established within an interpretive qualitative paradigm through analytic transparency, reflexive consistency, and theoretically grounded categorization.

Phenomenography is a holistic approach that encompasses both the research methodology and the analysis process, with the primary aim of revealing the qualitatively different ways in which individuals perceive, experience, and conceptualize a given phenomenon, in this case, radiation and radioactivity (Marton, 1981). Rather than focusing on individual differences, phenomenography seeks to identify a limited set of categories that describe the collective variation in perceptions and meanings within a group (Tóth and Ludányi, 2007). This approach is particularly well suited for making visible the conceptual diversity and alternative conceptions of students, allowing for an in-depth understanding of how these concepts are constructed, interrelated, and differentiated in the minds of SPSCTs.

Participants

The participants of the study consisted of 79 SPSCTs enrolled in the final year of the chemistry teacher education program, including 54 females and 25 males aged between 21 and 23 years. All participants had successfully completed the core chemistry curriculum, General, Analytical, Inorganic, Physical, and Organic Chemistry courses, providing a common academic background relevant to nuclear chemistry. Participants were selected through *convenience sampling*, a purposive method that enables researchers to work with an easily accessible and willing group (Patton, 2002). While this approach provides practical advantages, it also limits the transferability of results and carries a risk of sampling bias (Maxwell, 2013; Creswell and Poth, 2016). To minimize these limitations, the procedure was applied transparently: all SPSCTs present during the data collection sessions were invited, and only those who volunteered were included. All SPSCTs were preparing for professional practice as high school chemistry teachers. Participation was entirely voluntary, responses could be submitted anonymously, and ethical approval for the study was obtained from the Balikesir University Science and Engineering Ethics Committee.

Data collection and analysis

The data for this study were collected through an open-ended instrument designed to elicit participants' definitions and explanations of the concepts of radiation and radioactivity. The instrument consisted of 15 open-ended questions developed by the researcher to explore participants' perceptions and prior knowledge before the nuclear chemistry course.

This instrument was originally created as part of a multi-stage project aimed at examining SPSCTs' pre-instructional prior knowledge and conceptual readiness for a nuclear chemistry course, and served as a pre-knowledge concept test. The instrument included questions addressing different prerequisite domains (*e.g.*, nuclide, nucleon, mass number, atomic number, atomic nucleus stability, nuclear reaction); however, the present study focuses only on the responses to the two open-ended questions that directly probed the concepts of radiation and radioactivity.

Unlike multiple-choice items, open-ended questions require participants to articulate their own reasoning, thereby providing rich and qualitative data suitable for phenomenographic analysis. To capture the full range of variation and to allow participants' original ideas to emerge without interviewer influence, written responses were used as the primary data source (Marton, 1981). This method enabled the simultaneous collection of data from a large number of participants, ensured that each student's ideas were recorded in their own words, and made it possible to reveal the broad conceptual diversity required for phenomenographic categorization. Accordingly, the two selected definition prompts were appropriate for identifying phenomenographic categories of perception, revealing alternative conceptions, and mapping the KSs underlying SPSCTs' understandings of radiation and radioactivity.

In this study, phenomenographic analysis was employed as the primary method to identify SPSCTs' perceptions of radiation and radioactivity; at the same time, this analysis provided a secondary analytical basis for revealing alternative conceptions and mapping KSs. In order to operationalize the analytical distinction between perception and alternative conception, a two-stage analytical procedure was adopted.

In the first stage, all written responses were analysed phenomenographically with the sole aim of revealing the qualitatively different ways in which participants experienced and conceptualized the phenomena of radiation and radioactivity. At this stage, statements were categorized exclusively on the basis of experiential meaning, without considering their scientific correctness or incorrectness. These categories constituted hierarchically organized outcome spaces, representing variation in perception. The hierarchical ordering of categories was determined according to phenomenographic principles of increasing inclusiveness and explanatory scope: categories positioned at higher levels captured more comprehensive and structurally integrated ways of experiencing the phenomenon, whereas lower-level categories reflected more specific, restricted, or context-bound interpretations. In this sense, hierarchical relations in the phenomenographic outcome spaces are not treated as empirical properties inherent in students' cognition, but as analytically constructed interpretations developed to represent increasing inclusiveness and explanatory scope in ways of experiencing the phenomenon. The focus at this stage was descriptive rather than evaluative. Further procedural detail is provided in the section that follows, where the phenomenographic analysis is described step by step.

In the second stage, the phenomenographically derived categories were re-examined in light of the alternative conceptions literature, using criteria such as scientific inconsistency, conceptual overgeneralization, and resistance to correction through simple instructional interventions (Taber, 2000). Perceptions that conflicted with scientific explanations, reflected internally coherent yet scientifically inaccurate reasoning, and could not be resolved through limited clarification were interpreted as alternative conceptions.

This two-stage analytical procedure preserved the descriptive integrity of the outcome spaces while enabling the systematic identification of scientifically problematic conceptual nodes within the resulting KSs.

Accordingly, the same empirical material was examined at both a descriptive (perception-level) and an explanatory (conception- and structure-level) depth. Because the same hierarchical logic of inclusiveness and structural differentiation was applied across all issues (*e.g.*, ray, wave, energy, decomposition), the resulting outcome spaces were analytically comparable despite addressing different conceptual domains.

For example, a participant's statement that "*radiation is an invisible danger*" was interpreted as a perception in the first analytical stage, because it reflects how radiation is experienced and conceptualized by the learner through themes of invisibility and threat. At this stage, the scientific accuracy of the statement was not yet evaluated. At the level of the phenomenographic outcome space, this statement remains one variation among others in how radiation is perceived and does not, by itself, indicate a structurally problematic understanding. However, in the second analytical stage, the same statement was interpreted as an alternative conception, as it treats all types of radiation as inherently harmful, disregards the distinction between ionizing and non-ionizing radiation, and involves a scientifically inconsistent overgeneralization. At this stage, the statement is no longer considered in isolation, but is examined in terms of how it functions as an organizing node that shapes and constrains related ideas within the knowledge structure. Thus, the distinction between perception and alternative conception is not based on the wording or surface content of the statement itself, but on its analytical role within the broader pattern of meaning-making and knowledge organization revealed across the dataset. This example illustrates how the perception–alternative conception distinction was analytically implemented rather than applied as a fixed labelling scheme.

Following the phenomenographic categorization, the identified issues and categories were used to construct group-level KSs, illustrating how SPSCTs organized radiation- and radioactivity-related concepts and their interrelations. These representations visualize hierarchical and relational patterns among concepts such as ray, wave, energy, and nucleus, without evaluating the scientific accuracy of each individual connection. The purpose of these representations was not to trace individual learning trajectories, but to make visible collective cognitive patterns and structurally problematic conceptual linkages derived from the phenomenographic outcome spaces. Beyond serving as a methodological extension of phenomenographic analysis, these knowledge structure representations provide an empirically grounded means of revealing how students' perceptions and alternative conceptions are organized at a structural level within collective knowledge frameworks. By making visible not only which conceptions are present but also how they are hierarchically arranged and interconnected, the KS representations allow the identification of structurally persistent conceptual configurations that may remain obscured when outcome spaces are considered in isolation. From a chemistry education research perspective, this added structural visibility supports a deeper understanding of why certain alternative conceptions endure, how different conceptual domains (*e.g.*, radiation and radioactivity) are differentially organized, and where instructional interventions may need to target not isolated ideas but interconnected conceptual nodes. In this sense, the KS representations extend the contribution of the study beyond a method-internal rationale by linking phenomenographic findings to broader theoretical and pedagogical questions concerning conceptual organization, stability, and change in chemistry learning.

The phenomenographic analysis followed the three main phases described by Marton (1981, 2005) and Alsop and Tompsett (2004): Phase 1: *selection and relevance*: all written responses were read several times to gain familiarity with the data and to identify the key issues related to radiation and radioactivity. Selection was then carried out according to relevance criteria derived from preliminary pilot study (Nakiboğlu, 2018) and study with 12th grade students (Ölmez and Nakiboğlu, 2021). Phase 2: *isolation and variation*: each key issue was analysed in isolation from the others to capture the widest possible qualitative variation across the entire set of responses, allowing the identification of even subtle differences in how participants experienced the phenomenon. Phase 3: *structuring and outcome space*: in the final phase, the identified issues were organized into hierarchically structured descriptive categories, forming an outcome space. Alsop and Tompsett (2004, p. 244) define the outcome space as "*a hierarchically structured, multi-dimensional super-set of descriptions, where each subcomponent is a multifaceted issue or aspect bounded by a finite range of values*". To make the hierarchical structure of the outcome spaces analytically explicit and visually interpretable, schematic representations were constructed during the structuring phase. In these schematic representations (Fig. 1–11), arrows were used to indicate the hierarchical relations among levels of outcome. In these representations, arrows were deliberately used to depict how phenomenographic categories are hierarchically related to one another based on increasing inclusiveness and explanatory scope. Importantly, these arrows do not represent causal relationships, learning sequences, or developmental progression over time; rather, they serve as analytic indicators of structural relations within the outcome space, consistent with phenomenographic principles (Marton, 1981, 2005; Åkerlind, 2005).

Table 1 Example of the analytic transformation from raw student responses to phenomenographic levels for the ''wave'' issue

Raw student statement	Identified issue	Assigned level	Analytic rationale
Radiation is an electromagnetic wave.	Wave	3c – Electromagnetic wave	The statement defines radiation solely through its electromagnetic nature and does not include any reference to a source (*e.g.*, atom or atomic nucleus), process (radioactivity), effect (harmfulness), or context (technological or chemical). For this reason, it is grouped under the issue wave and coded at Level 3c, which represents a perception focused on the physical nature of the wave without contextual expansion (see Table 5 in the Findings section). This level marks the termination point of the electromagnetic-wave-oriented conceptual line within the outcome space. From this point onward, new conceptual orientations emerge, beginning with Level 3d, where radiation is linked to a nuclear source and associated energy, and subsequently branching into interpretations emphasizing harmfulness (levels 3e–3g) or energy transfer (level 3h). Despite these divergent orientations, all branches reconverge at the most abstract level (3i), where radiation is reduced to a general designation as wave.

To concretely illustrate how raw written student responses were transformed into hierarchically structured phenomenographic categories, Table 1 presents an example of the analytic coding process drawn from the ''wave'' issue in the radiation outcome space.

While presenting the phenomenographic categories, SPSCTs' perceptions were reported without judging them as correct or incorrect. After each issue was fully analysed, a subsequent comparative step was undertaken to determine which perceptions represented alternative conceptions or scientifically inaccurate ideas, and the results of this secondary analysis were addressed in the second research question.

Following the phenomenographic analysis, the group's KSs were mapped using the issues and codes derived from the analysis. This mapping illustrates how SPSCTs organized the concepts of radiation/radioactivity and its related sub-concepts (*e.g.*, ray, wave, energy) and how these concepts were interconnected within their knowledge frameworks. In these KS representations, arrows were used to indicate the presence, direction, and relational orientation of conceptual links between issues and sub-concepts, showing how one concept was associated with, derived from, or conceptually connected to another within the group's collective knowledge organization. The links among categories such as ''ray,'' ''wave,'' and ''energy'' reveal the hierarchical and relational patterns in participants' thinking. This representation does not evaluate the scientific accuracy of each connection but visualizes the overall organization of knowledge, providing a foundation for interpreting where and how alternative conceptions may arise within the group. All graphical representations were created using Microsoft Word drawing tools.

Comparison of outcome spaces. The comparison of phenomenographic outcome spaces for radiation and radioactivity is not intended to evaluate students' ideas in normative terms, but to examine how closely related concepts are differentially structured within learners' collective knowledge frameworks. The identification of ''problematic'' conceptual nodes does not imply an empirical property of the data itself; rather, it represents an analytically constructed interpretation grounded in systematic comparison across outcome spaces and in reference to established scientific explanations. In this sense, conceptual problematicity is treated as an interpretive analytical outcome rather than as a judgment about individual learners' understanding.

After constructing the hierarchical outcome spaces for SPSCTs' perceptions of radiation and radioactivity, the resulting graphical representations were used for a systematic cross-concept comparison. Two main criteria guided this comparison: (1) category similarities and divergences: identification of common issues emerging in both radiation and radioactivity as well as those unique to only one concept, and (2) hierarchical structural differences: examination of the depth and branching of connections extending from the central concept to subcategories in order to reveal how extensively each phenomenon is differentiated.

To illustrate how these comparative criteria were applied in practice, the issue of energy, which emerged in both the radiation and radioactivity outcome spaces, can be considered as a concrete example. In the radiation outcome space, energy appears as a perceptual focus that branches into qualitatively different orientations, such as radiation conceptualized as energy in wave-based descriptions (4a) and as energy associated with emission (4b) or technological applications (4f). These branches reflect increasing inclusiveness by extending the meaning of radiation beyond a single physical characterization. In contrast, in the radioactivity outcome space, energy is hierarchically embedded within process-oriented interpretations that emphasize nuclear change, instability, and material transformation (4a, 4b), and it does not branch toward non-nuclear or applied contexts. Thus, although energy constitutes a common issue in both outcome spaces (category similarity), its hierarchical position, branching structure, and organizing role differ across the two concepts (hierarchical structural difference). This example demonstrates how hierarchical levels across different conceptual domains were compared based on shared phenomenographic principles of inclusiveness and explanatory scope, rather than on assumptions of identical conceptual content.

In conducting this comparison, hierarchical levels across different conceptual domains were treated as comparable only insofar as they were constructed according to the same phenomenographic principles of increasing inclusiveness and explanatory scope. Categories occupying similar hierarchical positions were therefore not assumed to represent identical conceptual content; rather, they were compared in terms of how comprehensively they integrated multiple issues, how broadly they organized related sub-concepts, and how structurally differentiated their branches were within each outcome space. This criterion-based approach makes the comparative logic explicit and allows the reader to trace how similarities and differences across radiation and radioactivity were analytically established.

Reliability and validity. In the present study, the analysis followed a theory-informed phenomenographic approach. While the key issues (*e.g.*, ray, wave, energy) were derived from previous phenomenographic research and therefore framed deductively at the issue level, the construction of categories and hierarchical outcome spaces was grounded inductively in participants' empirical responses. This approach is consistent with phenomenographic methodology, which allows analytic focus to be guided by prior theoretical work, provided that qualitative variation and category construction remain data-driven (Marton, 1981; Marton and Booth, 1997; Åkerlind, 2005; Green and Bowden, 2009).

It is noted that within a qualitative and interpretive research paradigm, concepts such as reliability and validity are addressed not as indicators of objectivity, but as criteria of trustworthiness grounded in analytic transparency and coherence.

In this study, phenomenographic categories and the hierarchical relations among them are treated as inherently interpretive and relational analytic constructions. For this reason, inter-coder reliability coefficients such as Cohen's Kappa or Krippendorff's Alpha were not calculated. These coefficients are based on assumptions of independent, nominal coding decisions, whereas phenomenographic outcome spaces involve hierarchically and relationally structured categories that are analytically interdependent. Accordingly, analytic trustworthiness was supported through complementary qualitative strategies rather than through statistical reliability indices.

With respect to reliability, stability (temporal consistency) was adopted as the primary criterion. Stability refers to the extent to which the same data can be coded consistently across time and is a commonly used indicator of reliability in qualitative analysis (Gay and Airasion, 2000). To examine stability, the entire dataset was re-analysed by the researcher at three different time points, with at least one month between each analytic cycle. This interval was deliberately chosen to minimize memory effects and to test the continuity of coding decisions. A comparison of the first two rounds of analysis revealed approximately 90% agreement; the third round was then conducted to examine the remaining minor discrepancies in detail and to finalize the coding scheme. This process demonstrated that the established phenomenographic categories were stable over time.

Rather than relying on researcher experience as a guarantee of objectivity, analytic credibility was supported through the use of an explicit, theory-informed category framework and systematic procedural checks. In qualitative research, particularly in phenomenography, analytic adequacy is strengthened not by claims of expertise, but by making interpretive decisions traceable, constrained, and open to scrutiny (Marton and Booth, 1997; Åkerlind, 2005).

In addition, preliminary analyses conducted during the pilot phase of this project (Nakiboğlu, 2024), together with a previous phenomenographic study by Nakiboğlu and Ölmez (2021), in which two researchers independently coded data from 12th-grade students and established inter-coder agreement, provided both a methodological and empirical foundation for the present analysis. Accordingly, the present study did not involve unrestricted inductive code generation, but applied a theoretically informed phenomenographic issue framework, while allowing categories and outcome space structures to emerge inductively from the data. General qualitative analysis frameworks were used to support procedural transparency and analytic rigor, rather than to define the phenomenographic logic of category construction (Hsieh and Shannon, 2005).

To further enhance analytic credibility and address concerns associated with single-researcher coding, an external verification step was incorporated. Ten percent of the dataset was independently analysed by a second researcher with formal training in phenomenographic methodology. The comparison yielded an agreement rate of approximately 95%, confirming the coherence and stability of the coding decisions. In this external verification process, the second researcher examined not only category assignments, but also the coherence and stability of the hierarchical relations among categories, thereby directly supporting the trustworthiness of the hierarchical structuring within the phenomenographic outcome spaces. This selective external auditing approach is recommended in qualitative methodology as an alternative to full double coding when large datasets and interpretive frameworks are involved (Patton, 2002).

As a further analytic safeguard, the finalized phenomenographic category structure and hierarchical relations were subjected to peer debriefing with an experienced researcher familiar with phenomenographic analysis. This step functioned as an analytic audit aimed at challenging assumptions and confirming interpretive coherence, rather than as a statistical reliability check (Lincoln and Guba, 1985).

With respect to validity, particular attention was given to the principle of closeness of categories, which requires that each category be clearly delimited and empirically grounded so as to faithfully represent the variation in participants' meanings (Marton and Booth, 1997; Åkerlind, 2005). Accordingly, all categories were iteratively reviewed and refined through continuous reference back to the original student responses, ensuring that they captured the full range of meanings expressed by the SPSCTs. These procedures enhanced the transparency and coherence of the analysis and supported the trustworthiness of the phenomenographic categories.

The researcher's long-standing teaching and research experience in nuclear chemistry informed sensitivity to disciplinary meanings during analysis; however, analytic credibility was grounded primarily in systematic procedures, iterative data checking, and explicit category definitions rather than in claims of researcher authority.

Regarding the development of the open-ended instrument, the data collection tool used in this study was not developed *ad hoc* for the present manuscript. Rather, it was developed by the researcher within a broader, multi-stage research project (Nakiboğlu, 2024) that examined SPSCTs' knowledge, alternative conceptions, and conceptual development in nuclear chemistry across different phases of instruction, including pre-instructional, instructional, and post-instructional components. Within this larger project, the present instrument was specifically designed to capture pre-instructional meanings related to radiation and radioactivity. As part of that project, the instrument was administered to a group with characteristics similar to the target population as a pilot implementation. During the pilot, the clarity of the questions, their non-leading nature, and their adequacy in eliciting the target concepts (radiation and radioactivity) were evaluated, and the questions were reviewed in light of the feedback obtained. This pilot implementation constituted a key step in supporting the face validity of the instrument.

Findings

Issues identified from SPSCTs' definitions of radiation and radioactivity (RQ1)

To address this research focus, the issues identified from SPSCTs' definitions of radiation and radioactivity are presented separately below. At this stage of the analysis, the findings are reported at the level of perception, that is, in terms of the qualitatively different ways in which SPSCTs experienced and conceptualized the phenomena, without yet evaluating the scientific adequacy of these meanings.

Issues identified from SPSCTs' definitions of radiation. In relation to RQ1, in response to the prompt asking the SPSCTs to define radiation, the phenomenographic analysis identified five main issues: (1) ray; (2) emission of ray; (3) wave; (4) energy; and (5) emission of energy. These issues represent distinct perceptual foci through which SPSCTs made sense of radiation, and thus constitute the descriptive basis of the phenomenographic outcome space. Additional issues were identified; however, only those that displayed sufficient internal variation and hierarchical differentiation were retained for outcome-space construction. The frequency distribution for all issues is presented in Table 2.

Table 2 Frequency distribution of issues for radiation (N = 79)

List of issues	f
Ray	32
Emission of ray	16
Wave	10
Energy	6
Emission of energy	5
Scattering	2
Force	1
Frequency	1
Split	1
No answer/nonsense	7
Total	81[a]

[a] Two of the SPSCTs wrote two separate statements that went into two different issues, and therefore two issues were included.

As seen in Table 2, 32 of the 79 SPSCTs perceive radiation as ''ray.'' The frequency distribution of the levels (1a–1o) for Issue 1 is presented in Table 3. Fig. 1 shows the hierarchical organization of these levels. At this point, the analysis remains at the perception level and aims to describe how the notion of ''ray'' is experienced and differentiated by SPSCTs, without yet judging the scientific adequacy of these meanings.

Fig. 1 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radiation as ''ray.'' At the most inclusive level, radiation is framed broadly within the electromagnetic wave domain, without being restricted to a specific source, type, or attribute. From this upper level, three main perceptual branches emerge, representing distinct meaning-making orientations rather than successive levels of scientific correctness. These branches illustrate how SPSCTs hierarchically organized their perceptions of radiation as ''ray'' across different depths within the outcome space.

In Fig. 1, 1a is positioned at the most general and inclusive level because it is not narrowed down to a specific example (*e.g.*, alpha–beta–gamma), a specific attribute (*e.g.*, harmful, invisible), or a specific source (*e.g.*, radioactive material, unstable atom), but instead, the concept of ''ray'' is directly considered within the framework of electromagnetic waves. This level thus represents a broad perceptual orientation rather than a scientifically evaluated definition.

From the multiple sub-branches and hierarchies in Fig. 1, it is seen that the SPSCTs' perceptions of radiation as ''ray'' are distributed across different depths. These branches illustrate qualitatively different ways of meaning-making rather than successive levels of scientific correctness. The first branch is the EM-focused branch, extending from 1a through 1b, 1c, 1f, 1h, and 1n. In this hierarchy, it is observed that the concept of ''ray'' progressively narrows within the electromagnetic framework, focusing on its types (alpha, beta and gamma rays; invisible rays; harmful rays), and finally ending with 1o (ray). Although several levels in this branch include scientifically problematic generalizations (*e.g.*, equating all rays with harmfulness), these interpretations are reported here as perceptual variations and are analytically re-examined in a later stage. The second path is the harm and source-focused branch extending from 1a to 1d. Beginning with 1d (electromagnetic harmful rays), it continues with 1e, 1g, 1l, 1m, and 1n, progressing in a direction that also indicates the source of the ray, such as 1g (harmful rays consisting of radio waves) and 1m (harmful rays for living things), and once again narrowing and ending with 1n (harmful ray) and 1o (ray). This branch reflects a perceptual organization in which harmfulness and source attribution are foregrounded, forming a critical basis for identifying alternative conceptions in the subsequent analytical stage. The third line is the radioactive-rays-focused branch, progressing

Table 3 Frequency distribution of levels of issue 1

List of levels		*f*
1a	Rays in the form of electromagnetic waves	1
1b	Electromagnetic ray	1
1c	Alpha, beta and gamma rays.	2
1d	Electromagnetic harmful rays	1
1e	It is a type of ray that is known to be harmful and that occurs as a result of activation.	1
1f	Invisible rays	1
1g	Harmful rays consisting of radio waves.	1
1h	Ray type	2
1i	They are invisible rays that are emitted as a result of the energy production of a radioactive material.	2
1j	Rays emitted by radioactive sources.	3
1k	They are harmful rays emitted by an unstable atom by continuously radiating.	1
1l	Harmful rays emitted by a substance	4
1m	Harmful rays for living things	6
1n	Harmful ray	5
1o	Ray	1

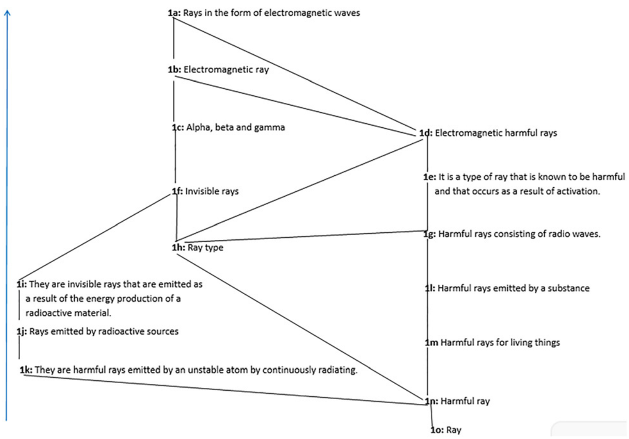

Fig. 1 A graphical representation of the hierarchy of levels of outcome for issue 1.

as 1i → 1j → 1k. In this line, the progression begins with the statement ''They are invisible rays that are emitted as a result of the energy production of a radioactive material'' (1i), continues with ''Rays emitted by radioactive sources'' (1j), and proceeds with ''They are harmful rays emitted by an unstable atom by continuously radiating'' (1k). From here, as in the other branches, it narrows and ends with 1n (harmful ray) and 1o (ray). This trajectory is particularly important analytically, as it demonstrates how perceptual associations between radiation, radioactivity, and harmfulness become structurally intertwined within the outcome space.

According to Table 2, 16 of the 79 SPSCTs conceptualize radiation as ''emission of ray.'' The frequency distribution of the levels within this issue is given in Table 4 (2a–2j). Fig. 2 shows the hierarchical organization of these levels. As with the previous issue, these categories are first presented as perceptual variations, forming the descriptive foundation for subsequent identification of alternative conceptions and knowledge-structure patterns.

Fig. 2 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radiation as the ''emission of ray.'' At the most inclusive level, emission is framed as a general process attributed to atoms or matter, without restriction to a specific mechanism, source, or evaluative criterion. From this upper level, three main perceptual orientations emerge, reflecting distinct meaning-making foci rather than levels of scientific correctness. Together, these orientations illustrate how the notion of ''emission'' is hierarchically structured within the outcome space.

Fig. 2 displays the hierarchical organization of the levels for this issue; the top level, 2a (emission of rays by an atom or matter.), is the most general expression and branches downward into three distinct foci. At this stage, these branches are interpreted as qualitatively different perceptual orientations toward the idea of ''emission,'' rather than as evaluative or correctness-based distinctions. The first of these is the radioactivity focus

Table 4 Frequency distribution of levels of issue 2

List of levels		*f*
2a	Emission of rays by an atom or matter.	2
2b	Emissions released as a result of changes occurring in the nucleus of an atom.	1
2c	Radiation emitted by radioactive substances	3
2d	The emission of harmful rays from equipment such as telephones, television, and X-ray through the medium.	2
2e	Emission of rays of electromagnetic waves.	1
2f	Emission of ultraviolet rays as a result of fragmentation or reaction.	1
2g	Emission of harmful rays through our body.	1
2h	Emission of harmful rays.	3
2i	High energy ray scattering.	1
2j	Emission of ray	2

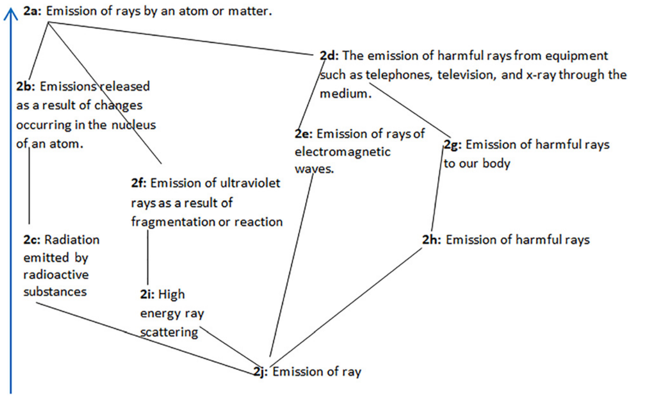

Fig. 2 A graphical representation of the hierarchy of levels of outcome for issue 2.

(2a → 2b → 2c), where 2b (emissions released as a result of changes occurring in the nucleus) ties the focus to nuclear processes; 2c (radiation emitted by radioactive substances) narrows this frame to the level of radioactive material and shows that the "emission of ray" conception contracts along the radioactivity axis. This branch is analytically important because it illustrates how emission is perceptually anchored to nuclear change, a linkage that later becomes central in identifying conceptions conflating radiation with radioactivity. The second branch, the spectrum/energy–process line (2f → 2i), begins with 2f (emission of ultraviolet rays as a result of fragmentation/reaction), a concrete starting point that targets a specific production mechanism and spectral band; this is followed by 2i (high-energy ray scattering), which—within the group-level pattern of perception inside the same issue—indicates a generalization of the focus from "which ray/which band and how is it produced?" to "the nature of propagation/scattering and a relative emphasis on energy" (here, "high energy" is coded as a relative label in participant language, without making a judgment about physical correctness). The third branch is the Dual-focus line (2d → 2e; 2d → 2g → 2h). The uppermost node, 2d (emission of harmful rays from equipment such as telephones, televisions, and X-ray devices), simultaneously rests on both the EM-wave nature and harmfulness attribution; hence it sits higher in the hierarchy and bifurcates: 2e (emission of EM-wave rays) continues the physical-nature line, whereas 2g → 2h (emission of harmful rays) continues the harm-oriented line. This bifurcation demonstrates how a single perceptual starting point can give rise to divergent conceptual orientations, a pattern that becomes analytically relevant when tracing structurally persistent alternative conceptions in later stages. All these lines converge at the lower level in 2j ("Emission of ray"). Thus, the outcome space in Fig. 2 reveals that the "emission of ray" conception is progressively narrowed along three orientations. Together, these orientations constitute the descriptive perceptual landscape from which alternative conceptions are subsequently identified through secondary analysis.

According to Table 2, 10 of the 79 SPSCTs perceive radiation as "wave." The frequency distribution of the levels for issue 3 (3a–3i) is given in Table 5. Fig. 3 reveals the hierarchical organization of the levels for this issue. As in the preceding issues, the categories presented here are first treated as perceptual variations, forming the analytical basis for later distinction between descriptive perception and scientifically problematic conceptualization.

Fig. 3 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radiation as "wave." At the most inclusive level, radiation is framed broadly within the electromagnetic spectrum, integrating themes of wave nature, spectral range, visibility, and harmfulness without being tied to a single source or process. From this upper level, two main perceptual orientations emerge, each reflecting distinct ways of organizing meaning rather than evaluative or correctness-based distinctions. Together, these orientations illustrate how wave-based perceptions of radiation are hierarchically structured within the outcome space.

When Fig. 3 is examined, 3a is the most general, inclusive level because, with the emphasis on "the whole of light/ray waves," it references a broad part of the EM spectrum (including UV/IR) and cannot be tied to a specific source/process, while at the same time bringing together the discourses of wave/spectral band and harm–visibility threshold. At this level, the statement is interpreted as a perceptual framing that integrates multiple experiential themes (wave, spectrum, visibility, harm) without yet constituting a stabilized explanatory claim. In the figure, starting from the top level 3a, two main lines and the intermediate steps connected to them are seen. Fig. 3 shows that the first line precedes in the direction 3b → 3c → 3i. This line starts with the emphasis on source and EM with the statement "electromagnetic waves that reach us from atoms

Table 5 Frequency distribution of levels of issue 3

List of levels		*f*
3a	UV, ultraviolet, and infrared, which can harm nature and human health, are the whole of light or ray waves whose spectrum is above a specific value, which is difficult to see with the eye.	1
3b	They are electromagnetic waves that reach us from atoms that emit rays.	1
3c	Electromagnetic wave	1
3d	They are waves emitted by the energy of the nucleus of the atom.	
3e	A harmful type of high-energy wave produced by radioactive reactions.	1
3f	These are harmful waves that are based on technological devices.	1
3g	Harmful waves emerge as a result of the reactions of chemical substances.	2
3h	Waves or particles that carry energy	1
3i	Wave	1

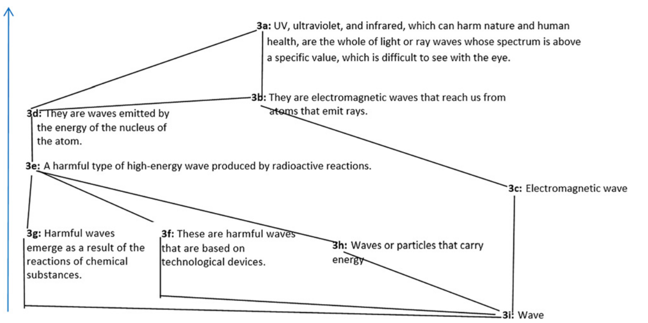

Fig. 3 A graphical representation of the hierarchy of levels of outcome for issue 3.

that emit rays'' (3b), then, with ''electromagnetic wave'' (3c), drops the source and makes a generalization to the EM-wave class, and finally, at the level ''wave'' (3i), abstracts to the general wave designation without even specifying the EM nature. Thus, along the axis of the physical nature of the wave, this branch exhibits a stepwise generalization from specific to general. Analytically, this branch illustrates how learners' perceptions may progressively lose contextual anchors (source, process) while retaining a generalized physical descriptor, a pattern that later becomes relevant when evaluating conceptual completeness and scientific coherence. It is seen that the second line starts with the upper information provided by 3a and 3b and proceeds through 3d and 3e. The reason for inclusiveness is that, when moving from 3a explained above to 3b, the emphases on source (atom) and EM are present. Based on the upper framework of both 3a and 3b, the line heads toward the level ''waves emitted by the energy of the nucleus of the atom'' (3d), bringing the focus to a nuclear energy source, and the orientation makes the perception of harm together with radioactivity explicit with the statement ''a harmful type of high-energy wave produced by radioactive reactions'' (3e). At this point, perception begins to consolidate into a more explanatory orientation in which nuclear source, energy, and harmfulness are hierarchically integrated; this orientation becomes analytically critical in identifying structurally persistent alternative conceptions in subsequent analyses.

From this point, the line splits into three sub-foci: the statement ''harmful waves emerge as a result of chemical reactions'' (3g) points to the perception of chemical source and harm; ''these are harmful waves that are based on technological devices'' (3f) points to the perception of technological source and harm; and ''waves or particles that carry energy'' (3h) reveals the perception of the energy and carrier nature of propagation independently of harm. This branching demonstrates how a single perceptual orientation can diversify into multiple source-based explanations, reflecting variation in learners' attempts to reconcile energy, source, and effect within their existing KSs. These three sub-foci converge at the lower level ''wave'' (3i), where they are encompassed under the general wave heading, independent of source and attribute. This convergence indicates that, despite divergent explanatory paths, participants ultimately collapse these meanings into a generalized wave concept at the perceptual level, providing a critical reference point for later distinguishing descriptive perception from scientifically problematic generalization.

According to Table 1, 6 of the 79 SPSCTs SPSCT perceive radiation as ''energy''. The frequency distribution of the levels for issue 4 (4a–4f) is given in Table 6. Fig. 4 reveals the hierarchical organization of the levels for this issue.

Fig. 4 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radiation as ''energy.'' At the most inclusive level, radiation is framed as a generalized form of energy encompassing waves and particles, without restriction to a specific source, process, or context. From this upper level, multiple perceptual pathways emerge, reflecting distinct orientations toward radioactivity, chemical and atomic processes, and applied technological contexts rather than evaluative or correctness-based distinctions.

At the top level, 4a (energy in the form of electromagnetic waves and particles) is positioned as the most general and inclusive level. This is because it frames energy in terms of both waves and particles without narrowing it to a specific source, process, or context. At this level, ''energy'' functions as a broad perceptual descriptor rather than as a stabilized explanatory construct, reflecting how participants initially conceptualize radiation through a generalized energy lens. From this general entry point, two main paths can be observed. The first path, 4a → 4b → 4c, reflects an orientation toward radioactivity and harm. Beginning with 4b (it is the energy emitted into an area created by radioactive radiation), the perception narrows to an environmental frame of radiation. This is further specified at 4c (harmful energy is released by radioactive materials), where energy is explicitly tied to radioactive substances and the perception of harm. Analytically, this progression shows that a general perception of energy increasingly intensifies toward a causal explanatory pattern that hierarchically integrates energy, radioactive source, and harmful effect, and that this configuration subsequently turns into a structurally persistent alternative conception.

Table 6 Frequency distribution of levels of issue 4

List of levels		f
4a	Energy in the form of electromagnetic waves and particles	1
4b	It is the energy emitted into an area created by radioactive radiation.	1
4c	Harmful energy is released by radioactive materials.	1
4d	A chemical energy possessed by a substance.	1
4e	Energy resulting from electron movements.	1
4f	The energy is released when using medical imaging devices.	1

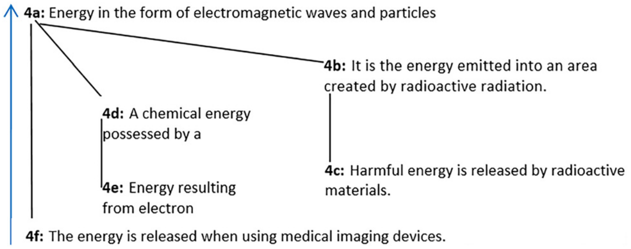

Fig. 4 A graphical representation of the hierarchy of levels of outcome for issue 4.

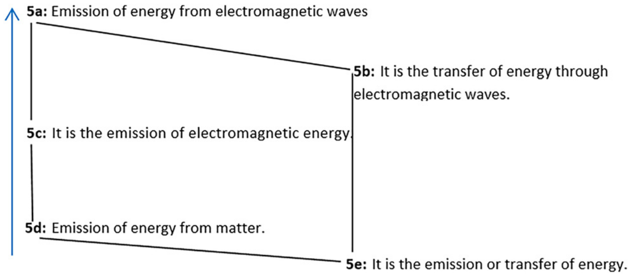

Fig. 5 A graphical representation of the hierarchy of levels of outcome for issue 4.

The second path, branching from 4a → 4d → 4e, shifts the focus to other forms of energy. Here, 4d (a chemical energy possessed by a substance) positions energy within a chemical framework, while 4e (energy resulting from electron movements) emphasizes electron-level processes. This line shows how SPSCTs extend the meaning of radiation-related energy beyond radioactivity toward broader notions of chemical and atomic energy. This branch demonstrates how learners extend the perceptual category of ''radiation as energy'' beyond nuclear contexts, integrating it into pre-existing chemical and atomic explanatory schemas. Finally, the third path, 4a → 4f, 4f (the energy is released when using medical imaging devices) stands as a more context-specific attribution, linking radiation-derived energy to its practical application in medical technology. This context-bound perception highlights the role of everyday and socio-technical experiences in shaping how radiation-related energy is conceptualized, providing an important reference point for understanding how applied contexts feed into broader KSs.

According to Table 1, 5 of the 79 SPSCTs PSCT perceive radiation as ''Emission of energy''. The frequency distribution of the levels for issue 5 (5a–4e) is given in Table 7. Fig. 5 reveals the hierarchical organization of the levels for this issue.

Fig. 5 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radiation as the ''emission of energy.'' At the most inclusive level, radiation is framed as a broad process of energy emission within the electromagnetic domain, without restriction to a specific mechanism, source, or contextual application. From this upper level, two main perceptual orientations emerge, reflecting process-focused and source-focused meaning-making rather than evaluative or correctness-based distinctions. Together, these orientations illustrate how emission-of-energy perceptions are hierarchically structured within the outcome space.

Table 7 Frequency distribution of levels of issue 5

List of levels		f
5a	Emission of energy from electromagnetic waves	1
5b	It is the transfer of energy through electromagnetic waves.	1
5c	It is the emission of electromagnetic energy.	1
5d	Emission of energy from matter	1
5e	It is the emission or transfer of energy.	1

Fig. 5 shows that at the top level, 5a (emission of energy from electromagnetic waves) is positioned as the most general and inclusive level. This indicates that SPSCTs perceive radiation as the emission of energy in the framework of electromagnetic waves, but do not narrow it to a specific mechanism or context. At this level, the notion of ''emission of energy'' operates as a broad perceptual framing, capturing how participants initially make sense of radiation in process-oriented terms without invoking causal or domain-specific explanations. From this entry point, the issue is divided into two main branches. According to Fig. 5, the first branch is in the direction of 5a → 5b, which leads to the perception of radiation as the transfer of energy through electromagnetic waves. At 5b (it is the transfer of energy through electromagnetic waves), the focus is on the process of energy transfer, and continuing from here, it ends with 5e (it is the emission or transfer of energy), where this understanding is generalized and reaches a broad definition of radiation that includes both the emission and transfer of energy without specifying its source or type. Analytically, this branch reflects a perceptual generalization in which radiation is reduced to a functional description of energy movemen. The second branch, 5a → 5c → 5d, reflects a more general physical perception such as the source or type of energy emission. At 5c (it is the emission of electromagnetic energy), radiation is expressed as the transfer of energy through electromagnetic waves, making it slightly more specific. After this, when moving to 5d (emission of energy from matter), it is seen that the perception of radiation goes beyond electromagnetic processes and is understood as matter itself being the source of energy and releasing it outward. This progression illustrates how learners' perceptual accounts begin to merge different explanatory domains (electromagnetic processes and material sources), a feature that becomes analytically significant when identifying structurally persistent alternative conceptions at the second stage of analysis. Again, this line ends with 5e (it is the emission or transfer of energy). The convergence of both branches at this generalized level highlights how diverse perceptual pathways ultimately collapse into a single, underspecified conceptual endpoint, which plays a key role in shaping the structure of the resulting knowledge maps.

Issues identified from SPSCTs' definitions of radioactivity. In response to the prompt asking the SPSCTs to define radioactivity, the phenomenographic analysis identified six main

Table 8 Frequency distribution of issues for radioactivity (N = 79)

List of issues	f
Emission of radiation	14
Decomposition	9
Radiation	8
Energy	8
Reaction	4
Matter	3
Subjects related to radioactivity	3
Harmful ray	3
Subjects related to wave	2
Attraction field	1
Activity	1
Situation	1
Mechanism	1
Frequency	1
No answer/nonsense	22
Total	81[a]

[a] Two of the SPSCTs wrote two separate statements that went into two different issues, and therefore two issues were included.

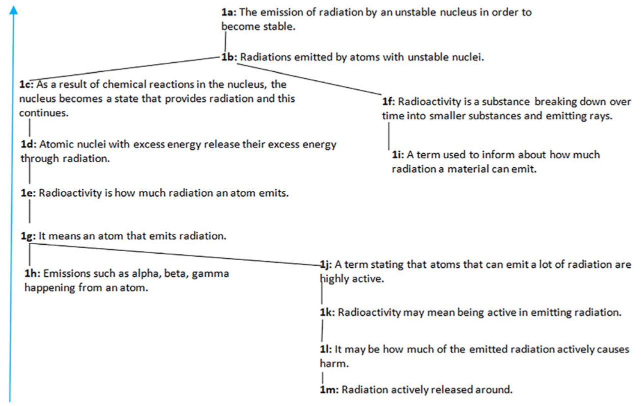

Fig. 6 A graphical representation of the hierarchy of levels of outcome for issue 1.

issues: (1) emission of radiation; (2) decomposition; (3) radiation; (4) energy; (5) reaction; and (6) matter. Beyond these categories, additional categories were also identified, but these issues did not possess sufficient hierarchical levels to support an outcome-space diagram. The frequency distribution for all issues is presented in Table 8.

According to Table 8, 14 of the 79 SPSCTs perceive radioactivity as ''Emission of Radiation''. The frequency distribution of the levels for issue 1 (1a–1m) is given in Table 9. Fig. 6 reveals the hierarchical organization of the levels for this issue.

Fig. 6 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radioactivity as the ''emission of radiation.'' At the most inclusive level, radioactivity is framed as a process associated with nuclear instability and radiation emission, without restriction to specific types, quantities, or evaluative criteria. From this upper level, multiple perceptual pathways emerge, reflecting distinct orientations toward nuclear processes, material properties, activity, and harmfulness rather than levels of scientific correctness.

At the top level, 1a (the emission of radiation by an unstable nucleus in order to become stable) is located. This level is positioned as the most inclusive because it defines radioactivity not through a specific type, harm, or quantity, but directly through the process of an unstable nucleus becoming stable. Thus, it functions as an overarching framework that can encompass all other focuses. At this level, radioactivity is framed as a process-based perception aligned with scientific descriptions.

When Fig. 6 is examined, it is observed that the emission of radiation issue diverges into three main paths. From Fig. 6, the first path starts from (1a → 1b) and continues as 1c → 1d → 1e → 1g → 1h. The statements in this branch show that the SPSCTS perceive radioactivity within the framework of nuclear changes and energy release. In 1b, the focus shifts to the radiation emitted by unstable nuclei; in 1c, it is incorrectly explained with the expression ''chemical reactions in the nucleus.'' This transition marks a critical point where an initially coherent perceptual framing begins to incorporate scientifically incompatible explanatory elements, which later becomes analytically salient in the identification of alternative conceptions. In 1d, this line narrows with a more energetic explanation in the form of ''nuclei with excess energy release their excess energy through radiation.'' When moving to 1e, it is seen that the SPSCTs' perception shifts to the idea that radioactivity is a quantity-oriented phenomenon and is considered

Table 9 Frequency distribution of levels of issue 1

List of levels		f
1a	The emission of radiation by an unstable nucleus in order to become stable.	1
1b	Radiations emitted by atoms with unstable nuclei.	1
1c	As a result of chemical reactions in the nucleus, the nucleus becomes a state that provides radiation and this continues.	1
1d	Atomic nuclei with excess energy release their excess energy through radiation.	1
1e	Radioactivity is how much radiation an atom emits.	1
1f	Radioactivity is a substance breaking down over time into smaller substances and emitting rays.	1
1g	It means an atom that emits radiation.	1
1h	Emissions such as alpha, beta, gamma happening from an atom.	1
1i	A term used to inform about how much radiation a material can emit.	1
1j	A term stating that atoms that can emit a lot of radiation are highly active.	1
1k	Radioactivity may mean being active in emitting radiation.	1
1l	It may be how much of the emitted radiation actively causes harm.	1
1m	Radiation actively released around.	2

as a measurement term such as "how much radiation an atom emits." Here, the perception evolves from a process-based understanding to a quantitative reinterpretation, indicating a reorganization of meaning that collapses conceptual distinctions between process, property, and measurement. The line continuing from 1e to 1g interprets radioactivity in terms of the atom and emission types. In 1g, radioactivity is defined as "an atom that emits radiation," while in 1h, this definition is reduced to specific types such as alpha, beta, and gamma. This narrowing illustrates how participants shift from describing radioactivity as a phenomenon to reifying it as an attribute or label of entities, a pattern that becomes analytically significant when mapping KSs.

From Fig. 6, the second path is seen to branch from 1b and continues as 1f → 1i. The reason why this branch is taken separately is that a transition is made from atom or atomic nucleus to matter. It is seen that the SPSCTs' perception is that radioactivity is a phenomenon dependent on matter, process-oriented, and containing measurement. In 1f, "a substance breaking down over time and emitting rays" is presented as a process-oriented explanation, while in 1i, "how much radiation a material can emit" is reframed as a measurement term. Analytically, this branch highlights how perceptual reasoning relocates radioactivity from a nuclear-level phenomenon to a material-level property, thereby obscuring its underlying physical basis.

In Fig. 6, there is also a main sub-path, starting from 1g and following 1j → 1k → 1l → 1m. Here, it is seen that the SPSCTS interpret radioactivity through activeness and associate it with the perception of harm. In 1j, the perception of activity comes to the fore with the idea that atoms emitting a lot of radiation are "more active." This line continues in 1k with the expression "radioactivity may mean being active in emitting radiation." In 1l, the emphasis is on how much of the emitted radiation actively causes harm, while in 1m, generalization is made with the expression "radiation actively released around". This branch makes visible how affective and risk-oriented perceptions become structurally embedded within the outcome space, allowing the later analytical distinction between descriptive perceptions and persistent alternative conceptions to be traced systematically.

According to Table 8, 9 of the 79 SPSCTs perceive radioactivity as "Decomposition". The frequency distribution of the levels for issue 2 (2a–2g) is given in Table 10. Fig. 7 reveals the hierarchical organization of the levels for this issue.

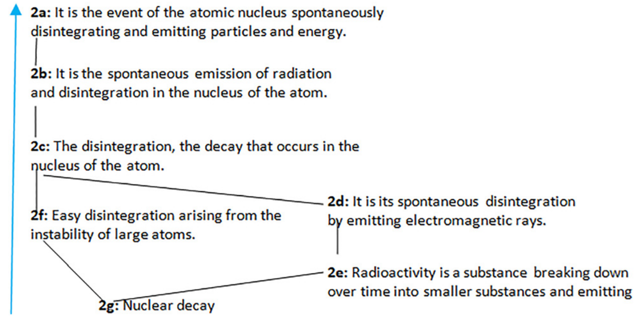

Fig. 7 A graphical representation of the hierarchy of levels of outcome for issue 2.

Fig. 7 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radioactivity as "decomposition." At the most inclusive level, radioactivity is framed as a spontaneous nuclear disintegration process accompanied by the emission of particles and energy, without restriction to a single explanatory dimension. From this upper level, multiple perceptual pathways emerge, reflecting distinct orientations toward nuclear processes, material-level transformations, and nominal or technical labeling rather than evaluative or correctness-based distinctions. Together, these pathways illustrate how decomposition-based perceptions of radioactivity are hierarchically structured within the outcome space.

From Fig. 7, it is seen that at the top level is 2a (it is the event of the atomic nucleus spontaneously disintegrating and emitting particles and energy.). At this most inclusive level, The SPSCTs perceive radioactivity as the spontaneous disintegration of the nucleus together with the emission of particles and energy. Thus, it is understood that this top level provides a broad framework that can encompass the dimensions of process, result, and source. At this stage, the statement is treated analytically as a perception, as it reflects a coherent way of experiencing and conceptualizing radioactivity, without yet evaluating the scientific completeness or boundaries of the explanation.

When Fig. 7 is examined, it is seen that it divides into two paths. Both paths initially follow 2a → 2b → 2c. This line starts with a general perception focused on the nucleus and covering the situation of spontaneity, then narrows to the emphasis on radiation and disintegration within the nucleus (2b), and then further narrows to structural disintegration only (2c). This progression illustrates how an initially process-oriented

Table 10 Frequency distribution of levels of issue 2

List of levels		*f*
2a	It is the event of the atomic nucleus spontaneously disintegrating and emitting particles and energy.	1
2b	It is the spontaneous emission of radiation and disintegration in the nucleus of the atom.	1
2c	The disintegration, the decay that occurs in the nucleus of the atom.	1
2d	It is its spontaneous disintegration by emitting electromagnetic rays.	1
2e	Radioactivity is a substance breaking down over time into smaller substances and emitting rays.	1
2f	Easy disintegration arising from the instability of large atoms.	1
2g	Nuclear decay.	3

perception becomes increasingly reductionist, foregrounding disintegration while backgrounding other defining constraints of radioactivity. Afterwards, the perception of the SPSCTs following the path 2f → 2g narrows from the general process perception in 2a to the emphasis on instability/atomic size (2f: easy disintegration arising from the instability of large atoms), and then concludes with 2g (nuclear decay), summarizing the process under a single technical term. Analytically, this route is significant because it shows a shift from experiential description to nominal labeling, where the phenomenon is compressed into a technical term without an explicit articulation of underlying mechanisms. Looking at the path following 2d → 2e, with 2e (radioactivity is a substance breaking down over time into smaller substances and emitting rays), we see that the SPSCTs' perception shifts from the nucleus to a matter-level/time dimension framework. Thus, the line exhibits a narrowing and reframing progressing in the direction of nuclear process → EM emphasis → matter/time. This reframing is analytically important, as it marks a conceptual relocation of radioactivity from a nuclear-level phenomenon to a macroscopic material process, which later becomes critical in distinguishing descriptive perceptions from structurally persistent alternative conceptions. Finally, it ends with 2g, that is, the transition to the brief technical definition. Taken together, the outcome space for the ''decomposition'' issue demonstrates how qualitatively different perceptions organize radioactivity either as a nuclear process, a material transformation, or a nominally defined event, thereby providing a structured basis for subsequent identification of alternative conceptions within the KSs.

According to Table 8, 8 of the 79 SPSCTs perceive radioactivity as ''Radiation''. The frequency distribution of the levels for issue 3 (3a–3h) is given in Table 11. Fig. 8 reveals the hierarchical organization of the levels for this issue.

Fig. 8 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radioactivity as ''radiation.'' At the most inclusive level, radioactivity is framed through the decay of unstable atoms and the radiation emitted during this process, integrating process, source, and outcome dimensions. From this upper level, multiple perceptual pathways emerge, reflecting distinct orientations in which radioactivity is merged with radiation, reconstructed through its effects or activities, or reinterpreted as an environmental or source-based property rather than as a distinct nuclear phenomenon. Together, these pathways illustrate how radiation-centered perceptions of radioactivity are hierarchically structured within the outcome space.

From Fig. 8, it is seen that at the top level is 3a (radiation emitted as a result of decay (disintegration) from the instability of atoms). This level is positioned as the most inclusive because it explains radioactivity directly through the decay process caused by the instability of the atomic nucleus and the radiation emitted during this process. Thus, it provides a broad framework that encompasses process (decay), source (unstable atom), and outcome (radiation) dimensions together. At this upper level, the definition reflects a process-oriented perception that remains close to the scientifically accepted framing of radioactivity; therefore, it functions as an inclusive perceptual category rather than an evaluative judgment about conceptual correctness.

When Fig. 8 is examined, it is seen that the hierarchical path starting in the direction of 3a → 3b → 3c is then divided into two. 3b (it is a term similar to radiation.) and 3c (it shows similarity to radiation. They are the effects of radiation.) first indicate that the SPSCTs perceive radioactivity as a phenomenon similar to radiation. In addition, radioactivity is seen as the effect of radiation and is associated with the results of radiation. At this stage, the analysis captures a perceptual shift in which radioactivity is no longer treated as a distinct nuclear process, but is instead experientially merged with radiation itself. After 3c, it is seen that the path proceeds in two directions. One of them, 3d → 3e, shows that the perception of the results or effects of radiation shifts from general to specific. At 3d (the whole of the results caused by radiation), the focus narrows to all the results. This branch illustrates how an initial perception of similarity evolves into an outcome-oriented framing, where radioactivity is interpreted primarily through its perceived consequences rather than its underlying mechanism. 3h (an environment or source that continuously contains radiation) branches off from this line and associates the phenomenon with an environment or source where radiation is continuously present. This expression shifts the phenomenon to an environmental/source-based perception. Here, radioactivity is no longer conceptualized as a process occurring in unstable nuclei, but as a static property of an environment or source, indicating a structural reorganization of the phenomenon at the perception level.

The other branch proceeds as 3e → 3f → 3g. At 3e (if I start from radiation, it is the rays being able to move actively), the emphasis is placed on the movement/active dimension of

Table 11 Frequency distribution of levels of issue 3

List of levels		*f*
3a	Radiation emitted as a result of decay (disintegration) from the instability of atoms.	1
3b	It is a term similar to radiation.	1
3c	It shows similarity to radiation. They are the effects of radiation.	1
3d	The whole of the results caused by radiation.	1
3e	If I start from radiation, it is the rays being able to move actively.	1
3f	The situations in which radiation is activated.	1
3g	Radiation activities.	1
3h	An environment or source that continuously contains radiation.	1

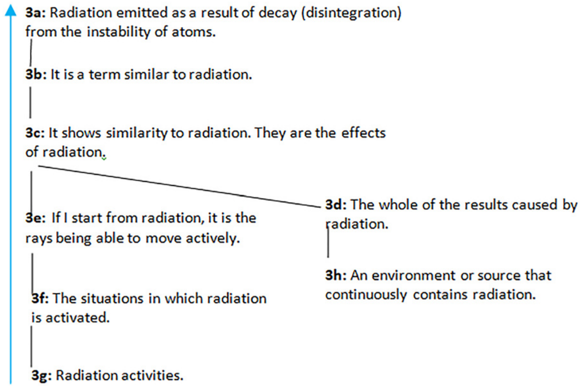

Fig. 8 A graphical representation of the hierarchy of levels of outcome for issue 3.

radiation. This orientation continues with 3f (the situations in which radiation is activated) and 3g (radiation activities), showing that radioactivity is perceived within a processual/activity dimension. Analytically, this branch is critical because it reveals how radioactivity is reconstructed as an extension of radiation's activity rather than as a distinct nuclear property. This perceptual reconfiguration later becomes a basis for identifying alternative conceptions when evaluated against scientific explanations.

According to Table 8, 8 of the 79 SPSCTs perceive radioactivity as ''Energy''. The frequency distribution of the levels for issue 4 (4a–4e) is given in Table 12. Fig. 9 reveals the hierarchical organization of the levels for this issue.

Fig. 9 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radioactivity as ''energy.'' At the most inclusive level, radioactivity is framed as an energetic outcome of nuclear processes, integrating source, process, and effect without explicit differentiation between nuclear reactions and radioactive decay. From this upper level, multiple perceptual pathways emerge, reflecting distinct orientations in which radioactivity is progressively reinterpreted as nuclear energy, chemical or harmful energy, or a generalized and abstract energy concept rather than as a specific nuclear phenomenon. Together, these pathways illustrate how energy-centered perceptions of radioactivity are hierarchically structured within the outcome space.

At the top level, 4a (light, energy that emerges in the splitting of the nucleus) is positioned as the most inclusive. This level explains radioactivity directly in relation to the process of nuclear fission and refers simultaneously to the process (splitting of the nucleus), the source (nuclear process), and the outcome (light/energy). In this way, it provides the broadest framework that can encompass the other levels. At this level, radioactivity is perceived as an energetic outcome of a nuclear process, reflecting an experiential integration of source, process, and effect rather than an explicit differentiation between nuclear reactions and radioactive decay.

When Fig. 9 is examined, it is seen that the hierarchy is divided into two main paths, both starting from 4a and leading to 4b. Level 4b (the energy occurring in the nucleus of the atom) places the focus on the nucleus itself and defines energy within the atomic nucleus context. This transition indicates a perceptual narrowing in which radioactivity is reinterpreted primarily as ''nuclear energy,'' marking a shift from process-oriented meaning toward a substance- or location-oriented framing. The first path proceeds from 4b through 4c → 4d → 4e. Along this line, the perception shifts in 4c (the chemical and harmful energy that a substance has) toward the chemical and harmful aspect of energy, then narrows in 4d (it is a type of energy) to a more general definition, and finally reaches 4e (energy), where energy is framed at its broadest and most abstract level, independent of source or type. Analytically, this path is significant because it shows how an initially nuclear-based perception progressively dissolves into a decontextualized and abstract energy notion, thereby obscuring the specific characteristics of radioactivity as a nuclear phenomenon. The second path moves directly from 4b to 4d → 4e. Here, students' perception bypasses the chemical/harmful dimension and proceeds directly to the idea of energy as a ''type,'' before again reaching the most general and abstract conception at 4e (energy). This shortcut highlights a perceptual compression process in which radioactivity is reduced to a generic energy category without intermediate conceptual distinctions, a pattern that later contributes to the emergence of alternative conceptions when evaluated against scientific explanations.

According to Table 8, 4 of the 79 SPSCTs perceive radioactivity as ''Reaction''. The frequency distribution of the levels for issue 5 (5a–5d) is given in Table 13. Fig. 10 reveals the hierarchical organization of the levels for this issue.

Fig. 10 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radioactivity as ''reaction.'' At the most inclusive level, radioactivity

Table 12 Frequency distribution of levels of issue 4

List of levels		f
4a	Light, energy that emerges in the splitting of the nucleus.	1
4b	The energy occurring in the nucleus of the atom.	1
4c	The chemical and harmful energy that a substance has.	1
4d	It is a type of energy.	3
4e	Energy.	2

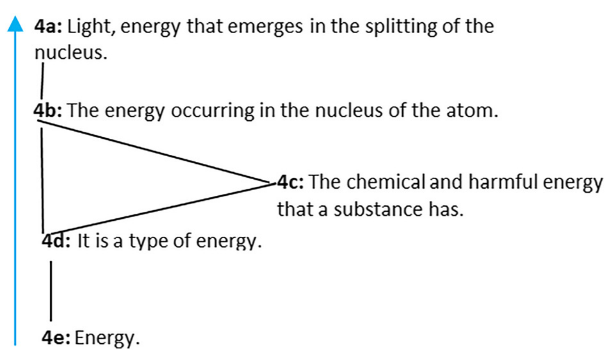

Fig. 9 A graphical representation of the hierarchy of levels of outcome for issue 4.

Table 13 Frequency distribution of levels of issue 5

List of levels		*f*
5a	A substance's tendency to enter into reaction, its closeness to reaction, shows the radioactivity value of that substance.	2
5b	It is the tendency of the atomic nucleus to enter into reaction.	2
5c	A reaction's taking place with radio waves or its formation.	2
5d	Nuclear reactions.	2

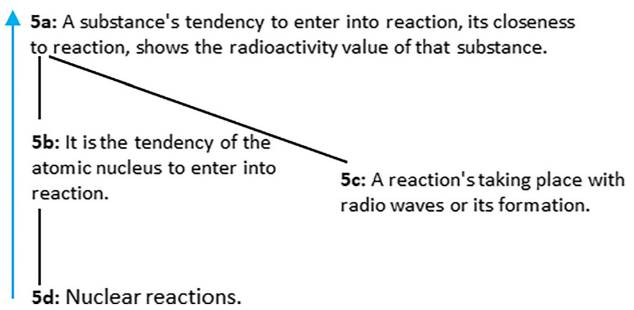

Fig. 10 A graphical representation of the hierarchy of levels of outcome for issue 5.

is framed as a general tendency of substances or nuclei to enter into reactions, integrating notions of process, property, and evaluative judgment without explicit reference to nuclear instability or decay. From this upper level, distinct perceptual pathways emerge, reflecting interpretations grounded in electromagnetic interactions and nuclear reactions rather than evaluative or correctness-based distinctions. Together, these pathways illustrate how reaction-centered perceptions of radioactivity are hierarchically structured within the outcome space.

At the top level, 5a (a substance's tendency to enter into reaction, its closeness to reaction, shows the radioactivity value of that substance) is positioned as the most inclusive level. This is because it frames radioactivity in terms of a general ''tendency to react,'' emphasizing a material's inclination toward reaction rather than narrowing to a specific mechanism or context. In this sense, it combines both process (reaction), property (tendency), and evaluation (radioactivity value) dimensions in a single overarching statement. At the perception level, this framing reflects an experiential conflation of radioactivity with general chemical reactivity, where ''being reactive'' is taken as an intuitive indicator of radioactivity without reference to nuclear instability or decay processes.

From this general entry point, two distinct paths can be observed. The first path proceeds from 5a to 5c (a reaction's taking place with radio waves or its formation). This trajectory reflects a shift from a broad perception of ''tendency to react'' toward a more specific connection with radio waves and reaction processes, indicating how some SPSCTs interpret radioactivity through the lens of electromagnetic or wave-related reactions. The second path extends from 5a through 5b → 5d. At level 5b (it is the tendency of the atomic nucleus to enter into reaction), the focus narrows from the general substance-level tendency in 5a to the atomic nucleus as the reacting entity. The line then continues to 5d (nuclear reactions), where the perception converges on a technical and disciplinary framing, emphasizing nuclear-level processes as the ultimate context of radioactivity. This progression illustrates a partial re-alignment toward scientifically appropriate domains; however, the continued use of ''reaction'' language rather than decay or instability indicates that radioactivity is still perceived through a reaction-based schema rather than a decay-based nuclear process.

According to Table 8, 3 of the 79 SPSCTs perceive radioactivity as ''matter''. The frequency distribution of the levels for issue 6 (6a–6c) is given in Table 14. Fig. 11 reveals the hierarchical organization of the levels for this issue.

Fig. 11 presents the hierarchical organization of the qualitatively different levels through which SPSCTs perceived radioactivity under the category of ''matter.'' At the most inclusive level, radioactivity is framed as a property of substances that undergo decay and emit radiation, integrating process, outcome, and material agent within a single perceptual frame. From this upper level, the hierarchy progressively shifts toward interpretations in which radioactivity is reified as a reactive or passive property of matter influenced by external conditions rather than as an internally driven nuclear process. Together, these levels illustrate how matter-centred perceptions of radioactivity are hierarchically structured within the outcome space.

Fig. 11 shows that when SPSCTs perceive radioactivity under the category of ''matter,'' they construct a hierarchy that begins with an active agent (a substance that decays and emits radiation) and progressively shifts toward an understanding of matter as reacting with or being passively affected by external conditions. At the perception level, this hierarchy reflects a gradual reification of radioactivity, where a dynamic nuclear process is increasingly treated as an inherent or externally induced property of matter.

Table 14 Frequency distribution of levels of issue 6

List of levels		*f*
6a	It is said to the substances that undergo decay and emit radiation to the surroundings.	1
6b	Substances that can give a reaction with other elements or with any effect to be given from outside.	1
6c	They are substances affected by radio waves.	1

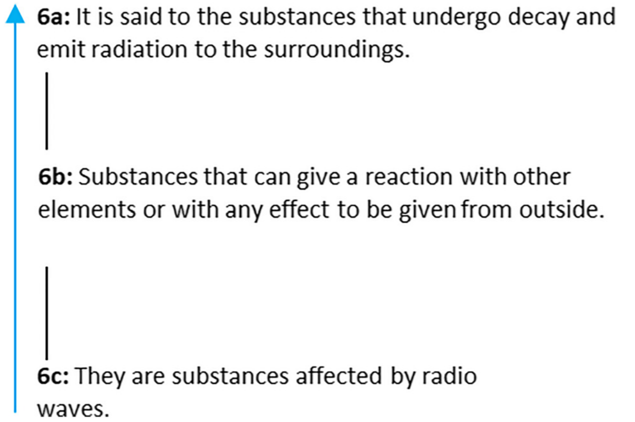

Fig. 11 A graphical representation of the hierarchy of levels of outcome for issue 6.

At the top level, 6a (it is said to the substances that undergo decay and emit radiation to the surroundings) is positioned as the most inclusive level. This is because it defines radioactivity directly through substances that undergo the process of decay and emit radiation, thereby encompassing the process (decay), the outcome (radiation emission), and the agent (matter) within a single frame. At this level, although the phenomenon is still connected to decay, the explanatory focus is already shifted from the nucleus to the material entity itself, indicating an early tendency to locate radioactivity in ''substances'' rather than in nuclear instability. From this entry point, the hierarchy narrows through different attributes of matter. At 6b (substances that can give a reaction with other elements or with any effect to be given from outside), radioactivity is explained in terms of substances reacting with external effects or other elements. This reflects a perception of radioactivity as a property dependent on external conditions. Analytically, this level marks a critical conceptual shift, where radioactivity is no longer understood as an internally driven nuclear process but as a reactive behaviour triggered by interaction with the environment. The final level, 6c (they are substances affected by ...), indicates that the SPSCTs perceive radioactivity as a passive property of matter defined through being affected by external factors. At this stage, radioactivity is no longer seen as an independent process or property but as a form of response dependent on outside influences. This endpoint of the hierarchy reveals a fully materialized and passive framing of radioactivity, which obscures the role of nuclear structure and decay mechanisms and constitutes a structurally robust alternative conception.

Comparison of SPSCTs' perceptions of radiation and radioactivity (RQ2)

The hierarchical outcome spaces constructed for radiation and radioactivity were compared to identify their similarities and differences. Fig. 12 and 13 present the corresponding graphical representations.

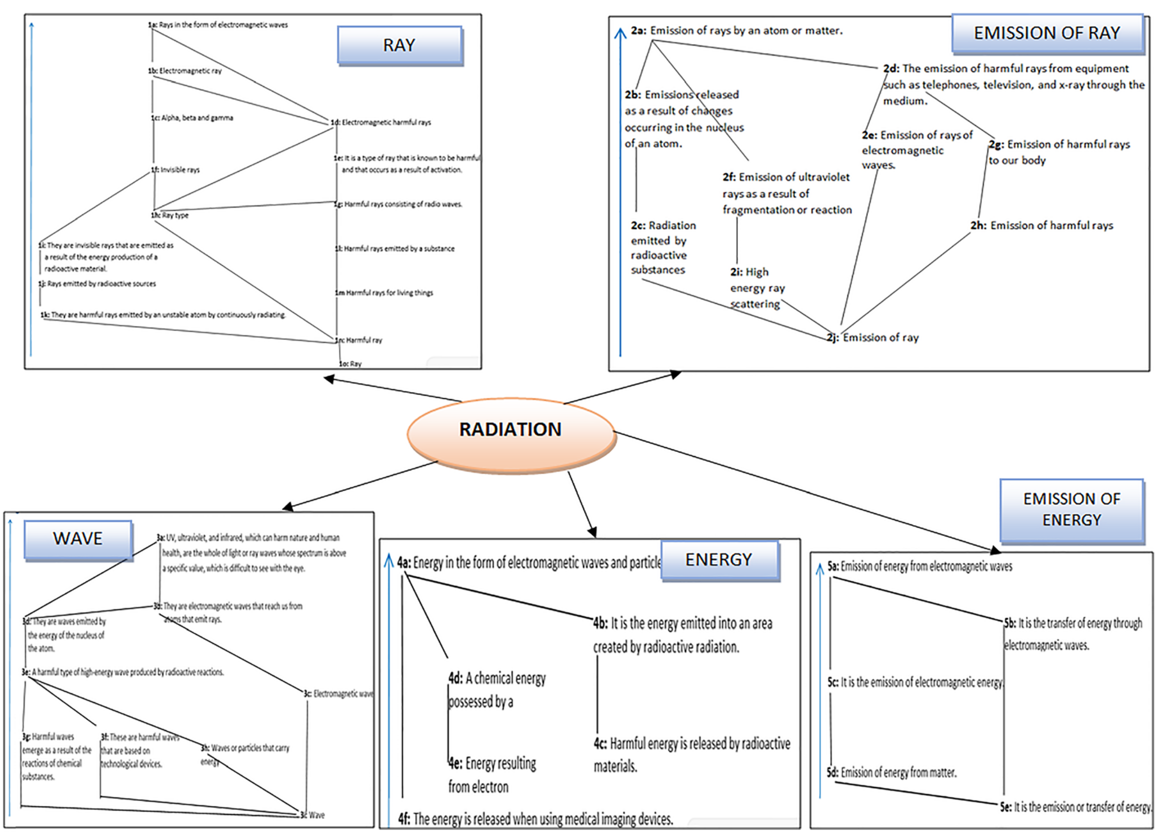

Fig. 12 Graphical representation of the hierarchical outcome space for SPSCTs' perceptions of radiation.

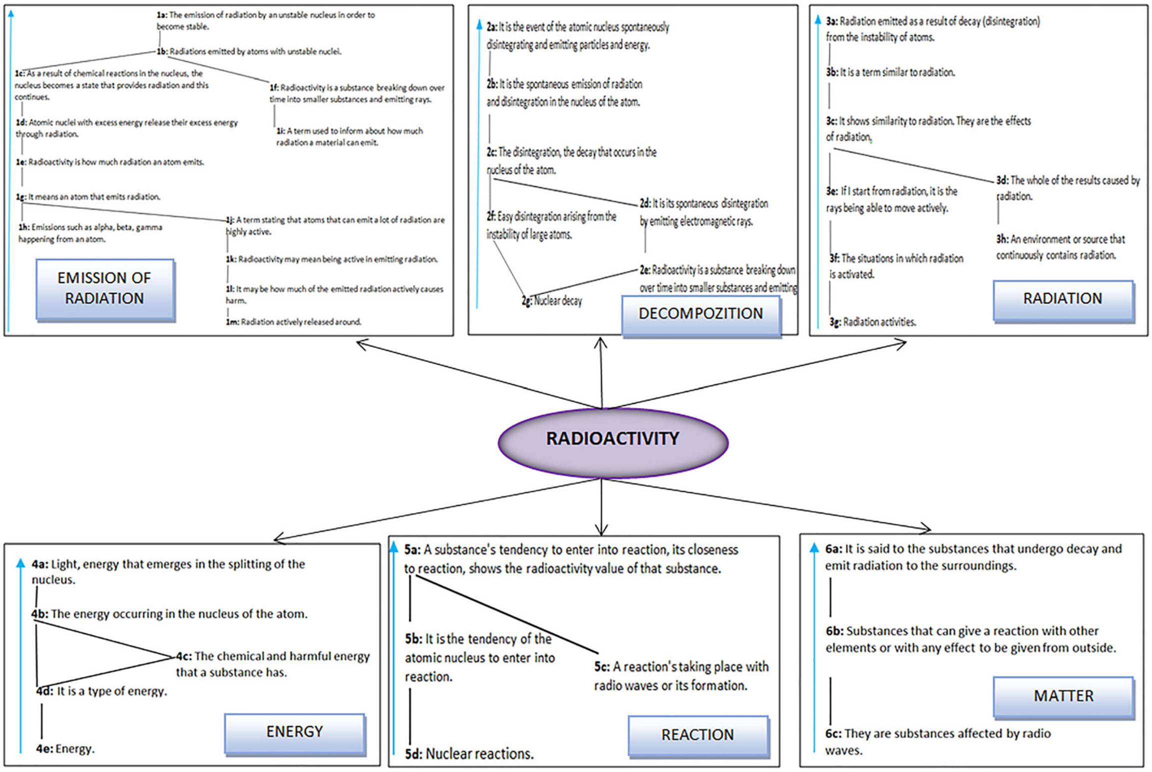

Fig. 13 Graphical representation of the hierarchical outcome space for SPSCTs' perceptions of radioactivity.

When comparing Fig. 12 and 13 according to the criterion of category similarities and divergences, only the "energy" issue is present in both the radiation and radioactivity outcome spaces, and sub-elements such as "harmful energy" and "chemical energy" are seen for both concepts. Issues unique to radiation include "wave," "ray," and "emission of energy," and these sub-elements emphasize the propagation and transmission processes of radiation. Issues unique to radioactivity are "decomposition," "reaction," "radiation," and "matter," focusing on nuclear instability and changes in matter. At the perception level, this comparison shows that SPSCTs position radiation predominantly at higher and more inclusive perceptual levels through observable or transmissive properties (*e.g.*, wave, ray, energy flow), whereas radioactivity is structured at different and narrower hierarchical levels through process-oriented and material transformations associated with nuclear change. This divergence becomes visible because perceptions were first analysed independently of scientific correctness, allowing the dominant perceptual orientations for each concept to emerge hierarchically.

When comparing Fig. 12 and 13 in terms of hierarchical structural differences, the issues within the radiation outcome space show more branching, while numerous parallel branches such as Ray–Wave–Energy–Emission of Energy describe types of rays, wave properties, and modes of energy emission. In contrast, the radioactivity outcome space exhibits a more vertical and causal organization. The chain Radiation Emission → Decomposition → Reaction → Matter forms a hierarchy extending from nuclear decay to the properties of matter.

Alternative conceptions and scientifically inaccurate ideas identified in SPSCTs' perceptions of radiation and radioactivity (RQ3)

Based on the phenomenographic outcome space analyses of radiation and radioactivity (Fig. 12 and 13), perceptions reflecting alternative conceptions or scientifically inaccurate ideas were identified and are summarized in Tables 15 and 16. Importantly, these alternative conceptions were not identified through an *a priori* correctness-based coding scheme, but were derived from the phenomenographic perception categories by examining which meaning-making orientations systematically conflicted with scientifically accepted explanations.

Examining Table 15 reveals that a large proportion of the SPSCTs define radiation primarily as harmful rays or harmful waves, stating that these rays are emitted especially from radio waves, telephones, televisions, and other technological devices. This reflects a widespread perception that technological devices and radio waves pose a direct health risk. In addition, some students stated that harmful waves emerge as a result of chemical reactions, indicating that chemical and nuclear reactions are perceived as equivalent. The expression "Energy resulting from electron movements" in the table shows that radiation is focused only on the electromagnetic radiation aspect, suggesting that the phenomenon is explained merely through energy movements. These alternative conceptions

Table 15 Alternative conceptions identified in SPSCTs' perceptions of radiation based on the phenomenographic outcome space

Issue no.	Issue	Representative alternative conceptions
1	Ray	• Radiation is a type of harmful ray produced by activation of radioactive materials. • Harmful rays emitted by unstable atoms or substances. • Harmful rays consisting of radio waves. • Rays harmful to living things.
2	Emission of ray	• Harmful rays emitted from technological devices such as telephones, televisions, and X-ray machines. • Emission of harmful rays through the human body or other media.
3	Wave	• Harmful high-energy waves produced by radioactive reactions. • Harmful waves emerging as a result of the reactions of chemical substances. • Harmful waves originating from technological devices.
4	Energy	• Energy resulting from electron movements.

Table 16 Alternative conceptions identified in SPSCTs' perceptions of radioactivity based on the phenomenographic outcome space

Issue no.	Issue name	Representative alternative conceptions
1	Emission of radiation	Radioactivity results from chemical reactions in the nucleus, causing the nucleus to emit radiation continuously; radioactivity is defined as how much radiation an atom emits.
2	Decomposition	Radioactivity is an easy disintegration arising from the instability of large atoms.
3	Radiation	Radioactivity is similar to radiation, represents the effects of radiation, or is the total of results caused by radiation.
4	Energy	Radioactivity is the chemical and harmful energy that a substance possesses.
5	Reaction	Radioactivity is a substance's tendency to enter into reaction, or the reaction tendency of the atomic nucleus; it is described as a reaction occurring with radio waves or formed by radio waves.
6	Matter	Radioactive substances are materials that can react with other elements or are affected by radio waves.

emerge at specific nodes of the radiation outcome space where perceptions emphasizing harmfulness, energy, and wave–ray relations converge, revealing structurally fragile points in SPSCTs' knowledge organization rather than isolated factual errors.

Table 16 shows that many SPSCTs describe radioactivity through chemical or reaction-based processes, showing a strong tendency to conflate chemical and nuclear events. Some participants defined radioactivity as originating from chemical reactions occurring in the nucleus or as a continuous emission of radiation, reflecting a misunderstanding of nuclear decay as a chemical process. Another key alternative conception is the direct equation of radioactivity with radiation, where radioactivity is presented as "similar to radiation," "the effects of radiation," or "the total of results caused by radiation," blurring the distinction between the process of radioactive decay and the emitted radiation. Additionally, certain responses conceptualized radioactivity as a type of harmful chemical energy or as a reaction tendency of substances or nuclei, even suggesting that radioactivity can be initiated by radio waves or external influences. These explanations illustrate a persistent belief that radioactivity is an active, inducible reaction rather than a spontaneous nuclear decay process. From an analytical perspective, these findings demonstrate how perception-level categorizations flow into the identification of alternative conceptions by revealing where learners' experiential interpretations are transformed into stable but scientifically inconsistent explanatory frameworks. The perception–alternative conception distinction thus enables a deeper understanding of not only what SPSCTs misunderstand, but how and where these misunderstandings are structurally embedded within their knowledge systems.

Organization of radiation and radioactivity and their related sub-concepts within SPSCTs' knowledge structures (RQ4)

For this purpose, the concepts and issues identified in the outcome space graphs for radiation and radioactivity (Fig. 12 and 13) were systematically identified and relationally examined. Based on these relationships, KSs representing how SPSCTs organize these concepts and their interconnections were constructed. The resulting knowledge structure representations for each concept are presented in Fig. 14 and 15. At this stage of the analysis, the perception–alternative conception distinction functions as an analytical bridge between outcome spaces and KSs, allowing perception-level meaning-making patterns to be translated into structurally organized conceptual networks.

Examining Fig. 14, it is seen that all issues are interconnected through the concept of "electromagnetic wave". In addition, the issues of "wave", "ray", and "emission of ray" are also interrelated through the concept of "the atom". While the issues of "emission of ray" and the issues of "energy" are connected *via* both "radioactive matter" and "UV rays", the issues of "emission of ray" and "wave" are linked through "technological devices". The issues of "emission of ray" and the issues of "ray" are associated through "harmful ray", and it is observed in Fig. 14 that the issues of "wave" and the issues of "emission of ray" are also connected through the "nucleus of atom. These dense interconnections indicate that perceptions emphasizing waves, rays, energy, and technological sources converge around a limited set of core concepts, creating structurally central nodes (*e.g.*, electromagnetic wave, atom, harmful ray) where alternative conceptions are likely to stabilize. Thus, alternative conceptions are not isolated statements, but emerge

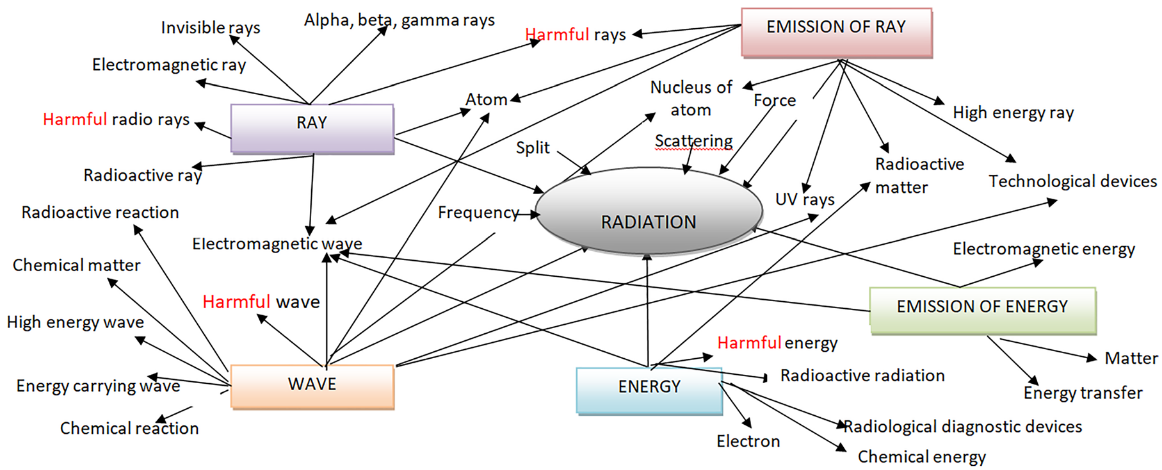

Fig. 14 Graphical representation of the knowledge structure of SPSCTs about radiation.

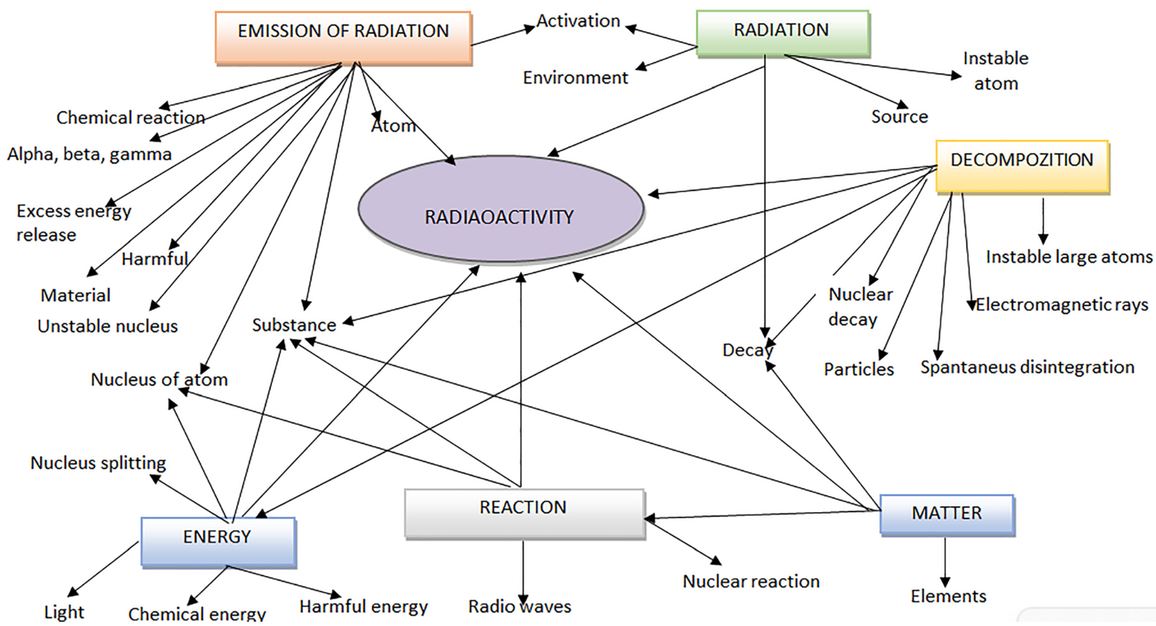

Fig. 15 Graphical representation of the knowledge structure of SPSCTs about radioactivity.

from the way multiple perception-based issues are relationally organized within the KS.

When Fig. 15 is examined, it is seen that, except for the issues of "radiation", all issues are interconnected through the concept of "substance". In addition to the connections of the issues *via* the concept of "substance, there are also links among the issues themselves within the KS map. The issue of "energy" is connected to the issues of "emission of radiation" and "reaction" through the concept of the "nucleus of atom". The issue of "matter" is directly linked to the issues of "reaction", and it is also connected to the "radiation" and "decomposition" issues through the concept of "decay", as can be seen from the map in Fig. 15. Furthermore, the "emission of radiation" and "radiation" issues are related to each other through the concept of activation. Compared to the radiation KS, the radioactivity map exhibits a more vertically organized and causally oriented structure, where perceptions related to process, decay, matter, and activity are sequentially linked. This organization helps explain why certain alternative conceptions, such as treating radioactivity as an inducible reaction or an externally activated process, are more persistent, as they are embedded within coherent but scientifically inconsistent causal chains rather than arising from single misinterpretations.

Conclusions, discussion, and implications

The conclusions of this study, which investigated the perceptions, alternative concepts, and KSs of SPSCTs regarding radiation and radioactivity before starting the nuclear chemistry course, are presented and discussed below under separate subheadings.

SPSCTs' perceptions and alternative conceptions about radiation (RQ1, RQ3)

At the end of the study, it was found that prior to taking a course on nuclear chemistry, the SPSCTs' perceptions of radiation were grouped under five categories: ''ray, emission of ray, wave, energy, and emission of energy.'' In their study with 12th-grade Turkish students, Nakiboğlu and Ölmez (2021) reported that students' perceptions of radiation were clustered into four groups. Three of these, ray, wave, and energy, were consistent with the findings of the present study, while Nakiboğlu and Ölmez (2021) identified a fourth category as the ''substance'' issue. These findings indicate that there are similarities in students' perceptions of radiation across different age groups and diverse educational levels.

The first of these categories was identified as ''ray.'' Examination of the findings regarding the ray issue revealed that a substantial proportion of SPSCTs reduced radiation solely to the concept of ''ray.'' This approach cannot be considered scientifically accurate, as it neglects the fact that radiation occurs both in the form of electromagnetic waves and as particles (alpha, beta, neutron). This alternative conception is also influenced by linguistic factors, particularly in Turkish, where the word ''radyasyon'' is often translated or interpreted as the equivalent of ''ışın'' (ray). The prevalence of this usage can be seen as a fundamental reason for the narrowed approach. Similar findings have been reported in the literature, showing that students frequently equate radiation with ''invisible rays'' and fail to recognize its particulate nature across various contexts (Boyes and Stanisstreet, 1994; Neumann and Hopf, 2012; Nakiboğlu and Ölmez, 2021). Another perception identified under the ray issue was the direct equation of radiation with electromagnetic radiation. Although this view is partially correct, it remains incomplete. Radiation can indeed manifest as electromagnetic waves; however, particulate radiation is also a significant component. The tendency of SPSCTs to focus solely on the electromagnetic dimension may stem from the fact that both textbooks and media representations predominantly frame radiation through X-rays, gamma rays, or ultraviolet rays. The literature corroborates this finding, as previous studies have reported that students commonly associate radiation exclusively with electromagnetic waves while disregarding its particulate aspects (Eijkelhof and Wierstra, 1986 cited in Eijkelhof *et al.*, 1990; Millar and Gill, 1996). A further salient finding under the ray category was that SPSCTs tended to perceive radiation directly as ''harmful rays'' and assumed that all forms of radiation are dangerous. Scientifically, the harmfulness of radiation depends on its type (ionizing *versus* non-ionizing) and the dose of exposure. Yet, SPSCTs failed to make this distinction and equated the concept entirely with danger. This finding is consistent with a large body of research reporting that students often view all types of radiation as hazardous, both at the secondary and university levels, and across various contexts (Boyes and Stanisstreet, 1994; Nakiboğlu and Tekin, 2006; Neumann, 2014; Nakiboğlu and Ölmez, 2021; Siersma *et al.*, 2021). Nakiboğlu and Ölmez (2021) also found that 12th-grade students perceived radiation as harmful, yielding results strikingly similar to those obtained in the present study, such as the conception of radiation as ''invisible harmful rays.'' These findings suggest that nuclear accidents and dominant media discourses have negatively influenced students' conceptual frameworks. Finally, it was observed that SPSCTs frequently associated radiation exclusively with radioactive sources. In reality, radiation originates not only from radioactive materials but also from natural sources such as the Sun, as well as from technological devices like X-ray machines. This narrowed perception may be attributed to the emphasis on radiation within the context of radioactivity in educational settings, or to the tendency to treat the terms ''radiation'' and ''radioactivity'' as interchangeable. Similar findings have been reported in the literature, where students equated radiation solely with radioactive processes and consequently struggled to grasp the broader nature of the concept (Millar and Gill, 1996; Plotz, 2017; Cardoso *et al.*, 2020; Nakiboğlu and Ölmez, 2021; Morales López and Tuzón Marco, 2022). The fact that both Nakiboğlu and Ölmez (2021) and the present study identified the misconception that radiation consists of ''harmful rays emitted from electronic devices'' further supports this interpretation.

The second category identified regarding SPSCTs' perceptions of radiation was termed ''emission of ray.'' In this category, SPSCTs defined radiation as the emission of rays from an atom or matter. This conception is partially correct, since the essence of radiation lies in the emission of energy, and particularly in radioactive decay processes, radiation is released from the atomic nucleus either in the form of particles or electromagnetic waves. However, the limitation of this view is that it associates radiation exclusively with radioactivity. In fact, radiation can also occur independently of radioactive decay for instance, through electromagnetic waves emitted by the Sun or through EM fields generated by technological devices. The literature has similarly reported that students often equate the concept of radiation with the process of radioactivity, thereby overlooking the broader nature of radiation (Eijkelhof *et al.*, 1990; Millar and Gill, 1996). Although some SPSCTs referred to certain parts of the electromagnetic spectrum, such as ultraviolet radiation, this is still an incomplete conception. Radiation is not restricted to specific regions of the spectrum; rather, it encompasses the entire electromagnetic spectrum in addition to particulate emissions. Such narrowing of the concept may be reinforced by the tendency of textbooks and instruction to rely predominantly on UV or X-ray examples. Another striking finding in this category is that SPSCTs often defined radiation primarily in terms of harmfulness, with rays emitted from devices such as telephones, televisions, or X-ray machines being directly labeled as ''harmful.'' This alternative conception can be traced to the widespread conflation of the concepts of radiation and radioactivity within society. Boyes and Stanisstreet (1994) as well as

Nakiboğlu and Ölmez (2022b) demonstrated that students believed everyday devices such as mobile phones and televisions emitted radioactive radiation. This tendency has even led students to classify radiation subjectively as either ''good'' or ''bad.'' For instance, Plotz (2017) found that students divided radiation into ''good radiation,'' associated with natural sources and medical applications, and ''bad radiation,'' linked to nuclear weapons. Such distinctions underscore how deeply cultural narratives and societal discourses shape students' conceptualizations of radiation.

The third category identified regarding SPSCTs' perceptions of radiation was termed ''wave.'' In this category, a considerable proportion of SPSCTs explained radiation through the concept of waves. This conception is partially correct, since electromagnetic radiation indeed has a wave-like nature. Some SPSCTs even described radiation as ''an energy-carrying wave or particle,'' which represents one of the closest formulations to the scientific definition. However, in many cases, the emphasis on the wave aspect led to the neglect of particulate radiation, thereby resulting in an incomplete conception. Similar findings have been reported in the literature, where students have been shown to conceptualize radiation predominantly through electromagnetic waves while overlooking its particulate dimension (Millar and Gill, 1996; Neumann and Hopf, 2012). Within this category, radiation was again perceived as a harmful, radioactive wave. Nakiboğlu and Ölmez (2021) also reported that in the wave category, students considered radiation to be a ''harmful wave,'' consistent with alternative conceptions found in other categories of the present study. They further highlighted that radiation was frequently understood as harmful waves emitted from technological devices, an alternative conception that also emerged here. Another alternative conception identified in this category was the explanation of radiation as ''harmful waves produced by chemical reactions.'' This reflects a different dimension of misunderstanding, indicating that chemical processes were conflated with nuclear processes. Nakiboğlu (2025), in a separate study conducted with the same group of participants, found that a majority of SPSCTs equated nuclear reactions with chemical reactions. Specifically, 64% of the participants believed that nuclear reactions were a type of chemical reaction. When asked to justify this view, their explanations included: that radiation is produced as a result of the reactions; that nuclear reactions generate entirely new phenomena; and that the changes occurring in the nucleus during such reactions are irreversible, meaning that the nucleus cannot return to its previous state therefore, they considered it a type of chemical reaction. These findings highlight a persistent and significant alternative conception in which the fundamental distinction between chemical and nuclear processes is blurred.

The fourth category identified regarding SPSCTs' perceptions of radiation was termed ''energy.'' In this category, some SPSCTs defined radiation as ''energy in the form of electromagnetic waves and particles.'' This conception is scientifically accurate, since radiation is fundamentally an energy transfer phenomenon, which can occur in both wave and particle forms. Such responses indicate that at least a portion of SPSCTs had learned the general definition of the concept from their previous education.

However, most of the perceptions within the energy category were problematic, as they involved either narrowing the concept or associating it with incorrect contexts. Some SPSCTs directly defined radiation as harmful energy emitted by radioactive materials. This view reflects the same tendency observed in earlier categories, namely, the conflation of radiation with radioactivity. The literature has consistently reported that students often equate radiation with radioactivity and, as a result, overlook its other sources (Eijkelhof *et al.*, 1990; Morales López and Tuzón Marco, 2022). Another alternative conception observed in this category was the association of radiation with environmental pollution. Statements such as ''radiation is harmful energy released into the environment'' misrepresent the nature of the concept. These expressions reflect the widespread societal discourse that equates radiation with pollution and show how this perception shapes SPSCTs' thinking. Boyes and Stanisstreet (1994) similarly reported that students perceived radiation as a cause of environmental problems and believed it accumulated in the environment. Other studies have likewise revealed that students associated radiation with issues such as environmental pollution, ozone layer depletion, and climate change (Neumann and Hopf, 2012; Brown, 2018). A further alternative conception involved the conflation of radiation with chemical energy. Some SPSCTs defined radiation as ''the chemical energy possessed by matter'' or as ''the energy released from chemical reactions.'' This alternative conception is closely linked to findings reported by Nakiboğlu (2025), who showed that many SPSCTs tended to conflate nuclear processes with chemical reactions. Another perception in this category was the association of radiation with electron motion. While this explanation is partially correct, since excitation and transitions of electrons can indeed result in electromagnetic radiation, it captures only one aspect of the energy dimension of radiation and thus remains incomplete. Similarly, defining radiation solely as the energy produced by medical imaging devices is scientifically inaccurate. Such narrowed explanations suggest that radiation is often taught only in specific contexts, leading SPSCTs to restrict their understanding to those familiar examples. Siersma *et al.* (2021) also found that students predominantly associated radiation with medical applications, which prevented them from grasping the broader scientific framework of the concept. In conclusion, while a small portion of the perceptions under the energy category aligned with the scientific definition of radiation, the majority reflected alternative conceptions involving the narrowing of the concept, the application of faulty generalizations, or its conflation with other forms of energy.

The fifth category identified regarding SPSCTs' perceptions of radiation was termed ''emission of energy.'' In this category, some SPSCTs defined radiation as the emission or transfer of energy. This conception is among the closest to the scientific definition, since radiation is essentially a process of energy transport and transfer. In particular, statements such as ''radiation is the transfer of energy through electromagnetic waves'' or ''radiation is the emission of energy'' point directly to the core nature of the concept. However, most of these perceptions were found to be incomplete, as they failed to distinguish between mechanisms (wave or particle) or types (ionizing *versus* non-ionizing). Nakiboğlu and Ölmez (2022a) similarly reported that students had difficulty distinguishing between ionizing and non-ionizing radiation. One underlying reason for this confusion is that, in Türkiye, both everyday language and curricula provide limited emphasis on these categories, resulting in a lack of awareness of this classification among students. This interpretation is further supported by Nakiboğlu (2021), who investigated chemistry teacher candidates' knowledge of non-ionizing radiation symbols and found that some candidates mistakenly associated these symbols with radioactivity. Such findings indicate that SPSCTs' understanding of radiation as ''energy emission'' often remains overly abstract, with insufficient differentiation between its sources and types. This aligns with other research showing that students tend to conceptualize radiation primarily as an abstract form of energy, a view that prevents them from fully grasping its scientific nuances (Cardoso *et al.*, 2020).

In conclusion, although SPSCTs generally positioned the concept of radiation in ways that were relatively close to the scientific definition, their perceptions overlapped with the scientific view only partially. Their inability to differentiate between mechanisms and types revealed that their understanding of the nature of radiation remained fragmented and far from comprehensive.

SPSCTs' perceptions and alternative conceptions about radioactivity (RQ1, RQ3)

At the end of the study, it was observed that before taking a course on nuclear chemistry, the SPSCTs' perceptions of radioactivity were grouped under six categories: ''emission of radiation, decomposition, radiation, energy, reaction, and matter.'' In a study conducted with 12th grade Turkish students, Nakiboğlu and Ölmez (2021) found that students' perceptions of radiation were grouped into three categories: decay, instability, and ray. Among these, only the categories of decomposition and decay were found to overlap.

The first category identified in SPSCTs' perceptions of radioactivity was ''emission of radiation.'' When the findings belonging to this category are examined, it is seen that some SPSCTs expressed radioactivity in a way most closely aligned with the scientific definition, as ''an unstable nucleus emits radiation in order to become stable.'' This approach can be regarded as scientifically correct, since it is consistent with the basic definition frequently emphasized in textbooks. However, other perceptions emerging under the same category indicate that the SPSCTs had difficulty conceptualizing the process correctly and resorted to inaccurate explanations at different levels. One of the most common alternative conceptions was the belief that radioactivity occurs ''as a result of chemical reactions in the nucleus.'' In reality, the process that takes place at the nuclear scale is nuclear decay/reaction, not a chemical reaction. This explanation reveals a conflation of nuclear and chemical processes. The fact that students generalize the concept of ''reaction'' learned in chemistry directly to the nucleus, combined with their tendency to use the atomic model outside its proper context, shows that they perceive radioactivity as a process based on chemical energy. Prather (2005) demonstrated that undergraduates sometimes explained nuclear decay through electron excitations and photon emission, and at other times through proton–proton repulsion or by conceiving of neutrons as ''protective shields,'' thereby misapplying the atomic model to inappropriate contexts. Similarly, Nakiboğlu and Tekin (2006) reported that high school students tended to explain nuclear stability in terms of atomic-level concepts such as the number of valence electrons or the ratio of atomic number to mass number. These findings indicate that the conflation of nuclear and chemical processes is not unique to this study, but rather represents a recurring alternative conception across students of different educational levels. Some SPSCTs, on the other hand, defined radioactivity as ''the amount of radiation an atom emits.'' This approach treats radioactivity not as a process, but as a measurable quantity. Scientifically, however, radioactivity is the decay process of unstable nuclei; although the rate of decay and activity can be measured, the process itself is not merely a numerical value. This reductionist view may stem from the fact that half-life and decay rate are often presented in instruction primarily through measurement-based explanations. The literature has similarly emphasized that students reduce the process to a quantitative dimension and overlook the distinction between process and product (Millar and Gill, 1996; Plotz, 2017). Another perception defined radioactivity as ''a substance gradually breaking down and emitting rays.'' This description disregards the nuclear scale and shifts the concept to the macroscopic level of matter. In doing so, radioactivity is reduced to the popular expression frequently used in everyday language that ''radioactive substances decay/break down.'' Such explanations show that students fail to distinguish between atomic and macroscopic levels. Moreover, their tendency to equate radioactivity with the deterioration of matter is reinforced by linguistic and cultural factors. Finally, it was observed that some SPSCTs explained radioactivity as ''atoms that emit more radiation are more active'' or by equating ''activity'' with harmfulness. In scientific terminology, ''activity'' refers to the decay rate; it does not directly mean harmfulness. Whether radiation is harmful depends on its type (ionizing/non-ionizing), energy, and dose. Nonetheless, the tendency of SPSCTs to equate activity with danger may stem from the way radioactivity is presented almost exclusively in terms of risk and harm in the media. The literature has also reported that students classify radiation as ''good'' and ''bad,'' labeling natural and medical sources as beneficial, while associating nuclear weapons or accidents with harm (Boyes and Stanisstreet, 1994; Neumann, 2014; Plotz, 2017; Siersma *et al.*, 2021). This situation shows that SPSCTs' alternative conceptions arise not only from a lack of scientific knowledge, but also from intuitive reasoning patterns and social discourses that foster misleading generalizations.

The second category identified in SPSCTs' perceptions of radioactivity was ''decomposition.'' In this category, some SPSCTs defined radioactivity as ''the spontaneous disintegration of the atomic nucleus accompanied by the emission of particles and energy.'' Nakiboğlu and Ölmez (2021) likewise found that 12th grade students held a very similar conception of radioactivity. This explanation is one of the perceptions most closely aligned with the scientific definition, as radioactivity is indeed a decay process driven by the intrinsic instability of the nucleus, characterized by the emission of particles or electromagnetic radiation. However, this starting point often led SPSCTs to narrow the concept, equating it solely with ''the breaking apart of the nucleus.'' In reality, radioactivity is not limited to disintegration but is a process defined by both particle and energy emission. The origin of this reduction, as noted in the literature (Eijkelhof *et al.*, 1990), lies in the prominence of the term ''disintegration'' in lessons and textbooks, where its focus on breaking apart has tended to overshadow the energy dimension of the phenomenon. Some SPSCTs associated radioactivity with the ease of decay in large atoms. This approach can be considered a scientifically valid observation to some extent, since larger nuclei do indeed exhibit greater nuclear instability and a stronger tendency toward decay. The frequent use of examples such as uranium and thorium in curricula may reinforce this perception. Moreover, familiarity with the instability of heavy atoms in the periodic table may also contribute to this explanation. Nevertheless, attributing nuclear instability solely to atomic size while neglecting other critical factors, such as neutron–proton ratio or nuclear binding energy, poses potential problems for later instruction. Another alternative conception identified in this category was the explanation of radioactivity as ''a substance gradually breaking down into smaller substances and emitting rays.'' This description shifts the concept away from the atomic scale toward the macroscopic scale of matter, presenting radioactivity as if it were a process of ''material deterioration.'' The widespread colloquial expression that ''radioactive substances decay'' is the likely source of this perception. Similar observations have also been reported in the literature, where students have conceptualized radioactivity as a kind of material or environmental degradation (Boyes and Stanisstreet, 1994; Morales López and Tuzón Marco, 2022). Such scale shifts are reinforced by the insufficient emphasis placed in instruction on distinguishing atomic/nuclear processes from macroscopic-level changes. Finally, some SPSCTs reduced radioactivity to a measurable quantity, defining it as ''how much radiation a substance emits.'' This perspective treats radioactivity not as a process but as a numerical value or activity level. Scientifically, however, radioactivity refers to the process itself, with quantitative measures such as activity serving only as indicators of the process. This reductionist view likely stems from the way half-life and decay rate are commonly presented in instruction through numerical data. Millar and Gill (1996) and Plotz (2017) similarly reported that students often overlook the distinction between process and product, tending to equate radioactivity with a quantitative measure.

The third category identified in SPSCTs' perceptions of radioactivity was labeled ''radiation.'' In this category, some SPSCTs defined radioactivity as ''the emission of radiation resulting from the decay of an unstable atomic nucleus.'' This explanation is among the closest to the scientific definition, as the essence of radioactivity lies in nuclear instability leading to decay and the emission of radiation in the process. However, within the same category it was also found that radioactivity and radiation were treated as if they were synonymous. Some SPSCTs explained radioactivity directly as ''similar to radiation'' or ''the effects of radiation,'' indicating that they failed to distinguish between the process itself and its product. Radioactivity is a process, whereas radiation is the emission of energy in the form of particles or waves resulting from that process. Similar findings have been repeatedly reported in the literature. Eijkelhof and Wierstra (1986) and Millar (1994) noted that students used the terms ''radioactive material,'' ''radiation,'' and ''radioactivity'' synonymously, while Boyes and Stanisstreet (1994) demonstrated that students aged 11–16 systematically confused these concepts at the linguistic level. The frequent pairing of these terms in lessons and their interchangeable use in everyday language makes it difficult for students to perceive this distinction. Indeed, language itself appears to play a significant role in this confusion. In Turkish, although the literal translation of radiation is ''ışınım'', both everyday discourse and even textbooks predominantly use the borrowed term radyasyon, while radioactivity is translated as radyoaktivite. Moreover, the terms ionizing radiation and non-ionizing radiation are rarely employed in daily language. These linguistic practices contribute to students' incomplete understanding of the concepts and encourage them to use the terms interchangeably. Similar challenges have been reported across different languages. For instance, Plotz and Hollenthoner (2019) noted that in German, everyday expressions such as ''a shining smile'' or Zahlenstrahl (number ray) carry connotations of radiation, shaping students' associations and highlighting the need for cross-cultural research to disentangle language-dependent motifs from universal ones. Likewise, Toru (2012) reported that in Japanese, the word Hosha-no means radioactivity but is widely misunderstood as a concrete substance, while Hosha-sen refers to radiation, with sen meaning ray. This linguistic conflation prevents students and the public from differentiating between radiation and radioactivity. Toru further argued that cultural beliefs, such as Japan's tendency toward nature worship, reinforce these misconceptions, as students often assume that natural radiation is harmless compared to artificial sources.

This finding reflects an alternative conception already identified in SPSCTs' perceptions of radiation, thereby confirming the consistency of results across both research questions. Some SPSCTs defined radioactivity as ''the totality of the consequences caused by radiation.'' This statement, too, neglects the process dimension of the concept and evaluates it solely in terms of its outcomes. Although the environmental and biological impacts of radiation are indeed important, explaining radioactivity only through these effects obscures its scientific nature as a process. The literature likewise shows that students often associate radiation and radioactivity primarily with environmental damage, even equating them with phenomena such as pollution (Boyes and Stanisstreet, 1994; Neumann and Hopf, 2012). This aligns with the findings on SPSCTs' perceptions of radiation reported earlier, suggesting that an instructional emphasis on the effects of radiation shapes students' understanding into a result-oriented perspective. It was also determined that some SPSCTs perceived radioactivity as ''an environment continuously containing radiation.'' This reduction frames the concept in environmental or spatial terms rather than at the nuclear level. Such perceptions are likely influenced by expressions frequently used in the media, especially following nuclear accidents, such as ''radioactive area'' or ''radioactive environment.'' Toru's (2012) study on linguistic confusion in Japan similarly highlighted that such terminology leads to the conceptualization of radioactivity as an environmental or matter-like phenomenon. Finally, some SPSCTs defined radioactivity as ''activating rays'' or ''the movement of rays.'' These explanations reveal a misunderstanding of the scientific term ''activity.'' Scientifically, activity refers to the rate of decay, not the movement of radiation. However, expressions in everyday language such as ''active rays'' or ''active material'' may generate misleading associations, causing learners to confuse the scientific concept with popular discourse. This problem has also been documented in the literature. Prather (2005) showed that students often employed fragmented and superficial atomic and nuclear models, attempting to explain concepts through intuitive reasoning patterns, which led to inconsistencies and misapplications in their understanding of radioactive phenomena.

The fourth category identified in SPSCTs' perceptions of radioactivity was labelled ''energy.'' In this category, some SPSCTs defined radioactivity as ''the light or energy released during the splitting of the nucleus.'' This statement reflects a partially correct observation, since nuclear fission processes do indeed release large amounts of energy. However, radioactivity is not limited to fission; alpha, beta, and gamma decays are also part of this process. Thus, associating radioactivity solely with nuclear fission results in an oversimplified and narrowed conception. This alternative conception may stem from the frequent emphasis on fission examples in lessons and the tendency of media coverage on nuclear energy to frame the discussion primarily in terms of ''splitting and energy.'' Some SPSCTs described radioactivity as ''the presence of energy in the atomic nucleus.'' This perception is scientifically plausible to some extent, as it implicitly refers to nuclear binding energy. The nucleus is held together by strong nuclear forces acting between protons and neutrons, which results in the existence of considerable binding energy. However, this explanation also reveals that the relationship between binding energy and radioactivity was not fully understood. The tendency of students to perceive the nucleus as a general ''reservoir of energy'' rather than recognizing the specific role of binding energy may be attributed to the abstract and conceptually demanding nature of the topic. Indeed, prior studies have highlighted that students experience significant difficulties in understanding binding energy (Nakiboğlu and Tekin, 2006; Kohnle *et al.*, 2011). More problematic perceptions included defining radioactivity as ''a chemical and harmful form of energy.'' This explanation reflects a conflation of nuclear and chemical processes and equates radioactivity directly with danger. Radioactivity is not a chemical process but a nuclear phenomenon arising from the instability of the atomic nucleus. As noted earlier in the discussion of radiation perceptions, the alternative conception that all forms of radiation are harmful reappears here in another guise. Since the harmfulness of radiation depends on its type and dose, reducing the concept to ''harmful energy'' is scientifically inaccurate. Similar findings have been reported in previous studies, which show that students often equate nuclear processes with chemical reactions (Nakiboğlu, 2025) and systematically associate radioactivity with danger (Boyes and Stanisstreet, 1994; Neumann, 2014). Other SPSCTs directly defined radioactivity as ''a type of energy.'' Scientifically, however, radioactivity is not a type of energy but a process of unstable nuclei undergoing decay, with energy being the product of this process. This illustrates once again how the conflation of process and product leads to conceptual misinterpretation. Millar (1994) and Eijkelhof *et al.* (1990) also demonstrated that students struggled to distinguish process from outcome, often equating radioactivity directly with energy or radiation. Another problematic perception observed within the energy issue was the interpretation of radioactivity in terms of environmental pollution. Statements such as ''radioactivity is harmful energy released into the environment'' misrepresent the nature of the concept. This view can be seen as a reflection of the widespread societal tendency to equate radiation with pollution. Boyes and Stanisstreet (1994) reported that students viewed radiation as a cause of environmental problems, while Neumann and Hopf (2012) found that students linked radiation to issues such as ozone depletion and climate change. Together, these findings indicate that SPSCTs' perceptions of radioactivity within the energy issue are strongly shaped by partial understandings, conflations with other concepts, and socially reinforced associations with risk and environmental harm.

The fifth category identified in SPSCTs' perceptions of radioactivity was ''reaction.'' In this issue, some SPSCTs equated radioactivity with chemical reactivity. Statements such as ''the tendency of a substance to enter into reaction is its radioactivity value'' reflect a direct generalization of the concept of ''reactivity,'' which is frequently emphasized in chemistry, to the nuclear domain. The roots of this alternative conception lie in the heavy instructional focus on chemical reactivity in chemistry courses, which students then project onto nuclear phenomena. The tendency of SPSCTs to interpret energy release in chemical reactions according to the same logic as nuclear processes illustrates that conceptual boundaries between chemical and nuclear changes have not been made sufficiently clear. Some SPSCTs defined radioactivity as ''a reaction formed by radio waves.'' This alternative conception appears to be based on a linguistic misinterpretation of the prefix "radio," which in everyday discourse evokes associations with "radio waves.". Another perception identified in this category was the idea that "radioactivity is the tendency of the atomic nucleus to react." This explanation can be considered partially correct, since nuclear instability is indeed the underlying reason for radioactivity. However, the use of the term "reaction" is scientifically inappropriate; radioactivity is more accurately described as a "decay" process. This indicates that while SPSCTs grasp the concept at a partially correct level, they demonstrate serious errors in terminology. Finally, some SPSCTs equated radioactivity directly with "nuclear reactions." This perception is also partially correct, as radioactivity is indeed a nuclear phenomenon. However, reducing it solely to nuclear reactions is misleading. Radioactivity refers specifically to the spontaneous decay of unstable nuclei, which differs from controlled nuclear reactions such as fission and fusion. The literature has likewise reported that students often learn about radioactivity primarily within the context of nuclear energy production, leading them to equate the concept with nuclear reactions (Eijkelhof *et al.*, 1990; Morales López and Tuzón Marco, 2022). This finding may be linked to the prominence of fission and fusion examples in instruction, which risk overshadowing the broader conceptual understanding of radioactivity.

The final category identified in SPSCTs' perceptions of radioactivity was labelled "matter." In this category, some SPSCTs defined radioactivity directly at the material level, providing explanations such as "radioactive matter is a substance that emits radiation to its surroundings." This statement can be considered partially correct, since radioactive substances do indeed emit particles or electromagnetic radiation into their environment. However, the problem here is that the underlying process of radioactivity occurs at the scale of the atomic nucleus. Radioactivity is not an intrinsic property of matter itself, but rather a phenomenon arising from the instability of the nucleus. The root of this alternative conception lies in the frequent use of the expression "radioactive substance" in textbooks and everyday language. Such usage leads students to perceive radioactivity as a material property rather than a nuclear process. Plotz and Hollenthoner (2019) similarly showed that students often associated radiation and radioactivity with tangible substances, reinforcing this material-based misunderstanding. Some SPSCTs described radioactivity as "a reaction dependent on external influences," stating that "radioactive substances react with other elements or with any effect applied from outside." This perception is scientifically inaccurate, as radioactivity is a spontaneous process that does not depend on external factors. Such an explanation reflects the misapplication of the concept of chemical reactivity to the nuclear domain. The common everyday notion that "a substance deteriorates when influenced from outside" also reinforces this confusion. The literature reports that students frequently equate nuclear processes with chemical processes and often confuse radioactivity with reactivity in various contexts (Cardoso *et al.*, 2020; Nakiboğlu, 2025). Another alternative conception observed in the matter category was the tendency to view radioactivity as a passive property. Statements such as "radioactive substances are affected by external factors" interpret radioactivity as a reactive response to external stimuli. In reality, radioactivity arises from the internal instability of the nucleus and does not require any external trigger. This kind of perception may stem from SPSCTs' inclination to think of radioactivity in terms of "stimulus–response" logic. Media discourse which frequently employs expressions, such as "environmental effects emitting radiation" or "radioactive zone," likely reinforces this alternative conception. Similar findings have been reported in studies showing that students often interpret radioactivity as an environmentally or externally driven phenomenon rather than recognizing it as a spontaneous nuclear process (Eijkelhof *et al.*, 1990; Neumann and Hopf, 2012).

Comparison of SPSCTs' perceptions (RQ2)

The comparison of the perceptions about radiation and radioactivity findings reveals that SPSCTs' perceptions of radiation and radioactivity share certain commonalities while also displaying distinct conceptual patterns. Most notably, "energy" emerged as the only issue common to both outcome spaces, indicating that students fundamentally associate both phenomena with energy. However, issues unique to radiation "wave," "ray," and "emission of energy" highlight that participants primarily conceptualize radiation in terms of observable physical properties and propagation processes. In contrast, the radioactivity-specific issues of "decomposition," "reaction," "radiation," and "matter" show that SPSCTs frame radioactivity as a process grounded in nuclear instability and material transformation.

The comparison of hierarchical structures underscores important differences in cognitive organization. The radiation outcome space exhibits a more horizontal and multi-directional pattern, with numerous parallel branches such as ray–wave–energy–emission of energy describing various forms of rays, wave properties, and modes of energy release. Conversely, the radioactivity outcome space presents a more vertical and causal organization, following the chain radiation emission → decomposition → reaction → matter, which reflects the progression from nuclear decay to material properties. These patterns suggest that SPSCTs tend to perceive radiation as an observable energy/emanation phenomenon, whereas radioactivity is viewed as a process operating at the nuclear level—yet the process and its product are at times conflated.

SPSCTs' KSs of radiation and radioactivity (RQ4)

The fact that all categories of radiation are interconnected through "electromagnetic wave" indicates that, within the SPSCTs' cognitive network, radiation is primarily focused on the electromagnetic wave dimension, while the particle dimension (*e.g.*, alpha and beta particles) remains largely unrepresented. Supporting this finding, the link between wave and emission of ray is also established *via* technological devices and UV rays. In addition, the connection of these two concepts through the "nucleus of atom" suggests that the SPSCTs also associate radiation with another type of ionizing radiation.

Nevertheless, the presence of several relationships cantered on harmful ray in the SPSCTS' KS map leads to the conclusion that the perception of ''all types of radiation as harmful'' is highly dominant.

The findings from the KS map for radioactivity show that, with the exception of one issue, all other issues are interconnected, indicating that the SPSCTs possess a coherent network of associations related to radioactivity. In particular, the linkage of the radiation, matter, and decomposition issues through decay demonstrates that the SPSCTs recognize radioactivity as a decay process. Supporting this interpretation, another key connection is the linkage of the energy, reaction, and emission of radiation issues through the nucleus of atom, which reflects an understanding of nuclear processes underlying radioactivity. However, the association of the emission of radiation issue with radiation *via* activation, when considered alongside expressions from earlier perception analyses, suggests a misleading generalization that radioactivity is the ''activeness'' of atoms emitting large amounts of radiation. This interpretation, where radioactivity is seen as the tendency or rate of decay expressed as ''being active,'' reveals that the SPSCTs' understanding of radioactivity remains superficial and lacks conceptual depth.

When the KSs of the SPSCTs regarding radiation and radioactivity are compared, it is evident that their conceptual networks contain both common and divergent features. For both concepts, the presence of central connections extending to the ''nucleus of atom'' indicates that the SPSCTs associate these two phenomena at least partially with nuclear processes and do not view them as entirely independent phenomena. However, in the radiation map, all relationships are constructed through the electromagnetic wave, and the links are woven through observable physical features such as technological devices and UV rays, revealing that the SPSCTs primarily perceive radiation in terms of electromagnetic waves and energy propagation, while giving limited emphasis to the particle dimension or the different types of ionizing radiation. In contrast, the strong connections among decay, reaction, and matter in the radioactivity map demonstrate that the students conceptualize radioactivity as a process based on nuclear decay; yet the inclusion of terms such as activation within this process suggests that radioactivity is sometimes confused with the amount of radiation emitted or with an ''active'' state. Taken together, these findings indicate that while the SPSCTs are able to establish partial connections between radiation and radioactivity, they struggle to clearly delineate the scientific boundaries of the two phenomena.

Implications and recommendations

Based on the conclusions of this study, the following implications and recommendations are proposed for nuclear chemistry education and teacher preparation programs. In addition to pedagogical implications, the present study provides an analytical contribution that extends beyond the long-established identification of students' alternative conceptions. By systematically comparing phenomenographic outcome spaces and mapping KSs derived from these spaces, the study makes visible how alternative conceptions about radiation and radioactivity are structurally organized, interconnected, and reinforced at the group level. Rather than treating alternative conceptions as isolated ideas, this approach reveals persistent conceptual nodes and patterns of conflation (*e.g.*, process–product confusion, chemical–nuclear overlap) that help explain why certain alternative conceptions remain resistant to instruction.

Beyond its immediate pedagogical implications, this study contributes to chemistry education research by advancing how conceptual understanding is analytically framed and investigated. Rather than positioning phenomenographic findings as purely descriptive, the integration of outcome spaces with knowledge structure representations provides a structural and explanatory perspective on how meanings are hierarchically organized and stabilized within collective knowledge frameworks. In this sense, the study extends phenomenographic analysis beyond method-internal categorization and offers a conceptual basis for examining the persistence and organization of alternative conceptions—an issue central to research on conceptual change in chemistry education.

Implications for teacher education

This study shows that SPSCTs enter the nuclear chemistry course with fragmented conceptions of radiation and radioactivity that are strongly influenced by linguistic factors. Participants commonly unified both phenomena under the idea of energy, yet frequently confused the process (radioactivity) with its product (radiation). These findings indicate that teacher education programs cannot assume conceptual readiness and must explicitly emphasize both the shared energy basis of radiation and radioactivity and the distinction between radioactivity as a process of nuclear decay and radiation as the emitted product. Establishing this distinction as an early and recurring instructional goal will help SPSCTs construct coherent KSs and transfer scientifically accurate explanations to their future students.

Implications for curriculum and course design

The conclusion of the study show that SPSCTs frequently relied on everyday or media-derived expressions such as ''harmful rays,'' ''reaction,'' and ''activity.'' Accordingly, secondary and undergraduate curricula should provide clear instruction on the difference between ionizing and non-ionizing radiation, supported by visual symbols (Nakiboğlu and Ölmez, 2022a). The distinction between chemical and nuclear processes must be highlighted with explicit examples (Nakiboğlu and Tekin, 2006). Furthermore, to counteract the dominance of danger-focused narratives, lessons should integrate beneficial contexts such as medical imaging, astronomy, and everyday technologies (Siersma *et al.*, 2021). In addition, findings from constructivist interventions in nuclear chemistry education demonstrate that instruction based on the constructivists methods significantly increases students' meaningful learning, reduces alternative conceptions, and fosters active participation compared with traditional lecture-based approaches (Nakiboğlu and Bülbül, 2000). Therefore, lessons on radiation and radioactivity should be organized within a constructivist framework in which students work collaboratively, confront their prior knowledge, and apply new concepts to everyday situations.

Addressing students' pre-conceptions

Prather (2005) demonstrated that students often explain radioactive decay through inaccurate atomic models such as proton–proton repulsion, neutrons as protective shields, or electron excitations and photon emission revealing fragmented and superficial reasoning. These results show that traditional information-transmission approaches are insufficient; instruction must instead elicit and reorganize students' pre-existing ideas. Hull and Hopf (2020) further emphasized that the invisibility of unstable nuclei and emitted radiation encourages learners to perceive radiation as an invisible substance and to merge source and emission. Consequently, instruction should employ modelling, simulation, and multiple representations to make these concepts visible and conceptually distinct.

Based on the results of the studies, various instructional strategies can be recommended both before taking a course related to nuclear science and during the courses. Before instruction, diagnostic tools such as concept maps or word-association tests should be used to identify learners' alternative conceptions, and conceptual changes to be made prior to instruction based on these results will ensure better understanding of subsequent topics. In particular, inappropriate perceptions or alternative conceptions that may arise due to the influence of everyday language can thus be revealed. Especially for concepts frequently encountered in daily life such as radiation and radioactivity, as well as for student conceptions related to atomic structure, which is taught in lessons and forms the basis for the instruction of these topics, students' conceptions should definitely be reviewed before instruction. During instruction, the common energy basis of radiation and radioactivity should be consistently emphasized and the process–product separation should be reinforced. Every day and scientific terms (for example, ''ray'' and ''radiation,'' ''activity'' and ''hazard'') should be presented side by side to reveal linguistic pitfalls and to guide students toward precise scientific language. Concepts such as half-life and decay probability should be taught through particle tracks, ensemble-based simulations, and probabilistic reasoning, shifting attention from single atoms to population behaviour (Prather, 2005; Hull and Hopf, 2020).

The literature review in this study has shown that even after traditional instruction, students at different levels still possess significant alternative conceptions about nuclear chemistry concepts. Therefore, strategies and approaches that will make students active in the lesson should be utilized. Laboratory experiences are indispensable for making these abstract processes visible. It has been shown that applied modelling activities, such as different laboratory modelling activities, significantly improve pre-service chemistry teachers' understanding of radioactive decay and reduce alternative conceptions by allowing students to directly observe decay and measure half-life (Yeşiloğlu, 2019). Therefore, the use of laboratory activities is recommended. However, the findings of Bakaç and Taşoğlu (2016) indicate that merely adding modelling into a traditional lecture is insufficient; to achieve lasting conceptual change, modelling must be embedded in a fully constructivist, student-cantered environment. Therefore, cooperative learning strategies can be added to such courses. As shown in the literature, cooperative learning strategies in which small groups solve radioactivity problems provide higher conceptual gains compared with traditional lectures (Omeodu and Utuh, 2018). Within these activities, adopting a constructivist, student-cantered format, including group discussions, real-life applications, and guided inquiry, can enhance motivation and promote durable conceptual change (Nakiboğlu and Bülbül, 2000). It has been found that university research reactor outreach programs involving direct measurement and observation of nuclear phenomena improve both knowledge and attitudes toward radiation (Johnson and Hafele, 2010; Brown, 2018). The use of such programs and similar activities can therefore be recommended. Remote Laboratory implementations, such as the Radioactivity Remote Laboratory Activities (RRLAs), provide real experimental data through online Geiger-counter measurements and enable students to design and monitor experiments in real time, which has been reported to significantly enhance conceptual understanding and motivation (Karpudewan and Chong, 2020).

Author contributions

C. N. conceptualised and designed the methodology. She analysed and visualised all data. She prepared draft and reviewing and editing the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this study were collected from human participants and are not publicly available due to ethical requirements and participant confidentiality. Access to anonymised data may be provided by the corresponding author upon reasonable request, subject to approval from the relevant ethics committee and in compliance with data protection regulations.

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