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Identifying Students' Misconceptions about Nuclear Chemistry

A Study of Turkish High School Students

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Students' misconceptions in science constitute a major problem of concern to science educators, teachers, and students *(1)*. Questions concerning the nature of students' misconceptions, the source of these misconceptions, and the effects of instruction have been of interest to educators, researchers, and teachers. Knowledge of common misconceptions (about scientific facts, models, laws, and theories) is particularly valuable to curriculum developers. Misconception research can aid them in designing instructional materials and activities that begin "where the student is" *(2)*.

Skelly and Hall *(3)* defined a misconception as a mental representation of a concept that does not correspond to a currently held scientific theory. They divided misconceptions into two categories: *experiential* and *instructional.* Experiential misconceptions are also referred to as alternative, intuitive, or native conceptions. In experiential misconceptions, a concept has been understood, at least to some extent, through everyday experience and interaction with the phenomenon involved. Examples of experiential misconceptions occur through connections with phenomena such as motion, energy, and gravity.

Misconceptions pertaining to some chemical phenomena, however, are fundamentally different because the existence of atoms and molecules is not directly within the realm of everyday experience. Misconceptions pertaining to these more abstract phenomena result from some instructional experience *(3)*.

According to the Committee on Undergraduate Science Education *(4)*, misconceptions may also be categorized into these five groups: preconceived notions, nonscientific beliefs, conceptual misunderstandings, vernacular misconceptions, and factual misconceptions. *Preconceived notions* are popular conceptions rooted in everyday experiences. *Nonscientific beliefs* include views learned by students from sources other than scientific education, such as religious or mythical teaching. *Conceptual misunderstandings* develop when students are taught scientific information in a way that does not challenge them to confront paradoxes and conflicts resulting from their own preconceived notions and nonscientific beliefs. *Vernacular misconceptions* arise from the use of words that mean one thing in everyday life and something else in scientific contexts. *Factual misconceptions* are falsities often learned at an early age that remain unchallenged into adulthood *(4).* The printed material and textbooks that students are exposed to can also be sources of misconceptions within or outside of the classroom.

Teachers can also be a source of misconceptions. Some teachers fail to provide accurate information to students. Because teachers are considered to be experts, most students will accept that what teachers say to them is true *(5).*

The science education literature contains a number of studies about students' misconceptions in high school science courses. Many chemistry studies have dealt with students' comprehension of atom and atomic structure *(6–8),* the particulate nature of matter *(9),* bonding *(10–12),* stoichiometry *(13),* chemical equilibrium *(14),* and electrochemistry *(15).* However, few studies have examined students' understanding and identified misconceptions of nuclear chemistry concepts *(16, 17).* Examples of such misconceptions include *(16, 17):*

- Irradiated food is radioactive
- All radiation is harmful
- All radiation is anthropogenic
- All uranium can be used as nuclear fuel
- Atoms cannot be changed from one element to another
- Once a material is radioactive it is radioactive forever

Additional work by Taylor *(18)* stresses that there are frequent misperceptions concerning nuclear chemistry in industrial settings. A review of the literature indicates that instruction in nuclear chemistry is limited or lacking in the chemistry curriculum. In fact, most of the literature addresses topics such as how much nuclear chemistry the curriculum should cover or how nuclear chemistry should be taught *(19),* what the content of nuclear chemistry should be *(20),* radioactivity in everyday life *(21),* high school students' preferences and reasoning modes about nuclear energy use *(22)* and informal understandings of radiation and radioactivity within the general public *(23).*

Nuclear chemistry and nuclear physics, which can be considered together as nuclear science, are essential for both chemists and physicists. Atwood and Sheline *(19)* claim that the fields of nuclear chemistry and physics have significantly increased humanity's understanding of the fundamental nature of matter and have benefited medicine, electronics, geology, archaeology, and industry. They stress, however, that very few high school chemistry teachers include nuclear chemistry as a part of their courses. They cite several reasons *(19),* such as teachers' disinclination because of their weak knowledge base; curricular decisions in which the subject is deemed unimportant to students; and a de-emphasis by textbook authors and publishers, who bury this subject in the last chapters of the chemistry textbook. Atwood and Sheline *(19)* note that students are aware of nuclear topics in the news: nuclear waste dumps, radon, star wars, and nuclear weapon treaties. In light of this, they advocate that some basic knowledge of nuclear chemistry would help our students understand these issues.

Although nuclear chemistry itself is not a central focus in high school chemistry, some prerequisite concepts for learning nuclear chemistry (atom, element, isotope, nuclide, atomic number, mass number, proton, neutron, and nucleon) are chemistry fundamentals. If students encounter new knowledge related to concepts of nuclear chemistry that contradicts their misconceptions, it may be difficult for students to accept the new knowledge because it seems to be wrong.

We designed a study to identify high school students' misconceptions in concepts of nuclear chemistry and to determine which misconceptions in basic chemistry concepts cause difficulties in learning the concepts of nuclear chemistry. This study represents the first attempt to elucidate and detail the types of misconceptions relating to basic concepts of nuclear chemistry that high school students hold.

Background and Method

Concepts associated with nuclear science are prevalent throughout the science curricula at all levels of elementary and secondary education in Turkey. These concepts are first taught to students in science lessons in the seventh grade. The formal high school chemistry courses, which are taught for three years, include nuclear chemistry. Chemistry teachers in Turkish high schools usually prefer teaching with conventional techniques. Like most of the high school chemistry classrooms in Turkey, teaching and learning in the observation classrooms is didactic and teacher-centered. Teachers tend to concentrate on solving problems through algorithmic approaches rather than concept learning. It is generally accepted that practicing examples in this way is the best preparation for the university entrance examination (OSS). Besides, high school chemistry teachers tend to overemphasize topics about which there are numerous questions on the university entrance exam. Nuclear chemistry is not a point of emphasis on the OSS and thus is not a focus of classroom instruction. Additionally, the fact that the high school chemistry curriculum prescribes a significant amount of material to be covered is perceived as a real barrier to incorporating teaching methods that promote conceptual learning rather than rote or algorithmic learning.

Subjects

Participants in the study were drawn from eight chemistry classes in four different high schools in western Turkey. The seven-item diagnostic instrument on nuclear chemistry was administered to 157 tenth-grade students (15–16 years old) after the nuclear chemistry unit was taught.

Instrument Development

Prior to developing the items, Turkish high school chemistry textbooks were investigated to ascertain whether they contained statements that could lead to students' misconceptions or learning difficulties. Areas of conceptual difficulty and student misconceptions were further investigated through observations of regular classroom teaching. Initially, we prepared a nine-item diagnostic test consisting of multiple-choice questions with four or five response choices. The incorrect choices were based on areas of conceptual difficulty identified by the high school chemistry textbooks' review and the classroom observations. Following a pilot study to develop the test, two test questions were eliminated. Content validity of the test instrument was confirmed by four experienced high school chemistry teachers. In order to elicit students' own misconception statements, we added an open-ended response section to the test by having students write an explanation for their choices on each question. The diagnostic test questions are included in Textbox 1.

Analysis and Scoring of Test Items

Each student's response choice to an item in the multiple-choice test was assigned a score of 1 if correct or 0 if wrong. The reliability *(24)* was estimated as 0.69 using the Kuder-Richardson formula 20 when multiple-choice responses were analyzed (SD = 1.72, mean = 1.14). Discrimination indexes of items are given in Table 1. We believe that the low discrimination indices for questions 1, 2, and 7 (and the relatively low index for question 4) is a consequence of the degree of difficulty of these questions.

In the open-ended section of the test, each answer was evaluated for both correct and incorrect response combinations selected by the students. After three students' responses to the open-ended part were separately analyzed by the authors, the results were compared and the interrater reliability was found to be greater than 95%.

Results and Discussion

Table 1 presents the distribution of the diagnostic test results of the multiple-choice section based on the percentage of students giving each response.

Table 1. High School Student Response Data for the Multiple-Choice Test on Nuclear Chemistry

Question (Discrimination Index)	Response Chosen (%, *N* = 157)[a] A	B	C	D	E	NR[b]
1	7	52	6	**4**	26	5
2	52	22	**14**	6	—	6
3	5	**35**	10	6	27	17
4	**22**	26	49	9	—	4
5	3	**62**	0	17	9	9
6	3	11	11	**20**	42	13
7	72	**16**	4	3	3	2

[a]Correct response is indicated in boldface type; [b]NR indicates no response

Some major misconceptions have been identified by combining students' responses to multiple-choice questions and written responses. The misconceptions identified are summarized in Textbox 2. These misconceptions are discussed in detail in the following sections question by question.

Questions 1 and 4

Items 1 and 4 tested students' understandings of nuclear stability. The first question examined whether they had any misconceptions related to the factors that affect the stability of the nucleus of an atom. One such factor is related to the numbers of neutrons and protons in a nucleus. The stable nuclei of the lighter elements' atoms contain approximately equal numbers of neutrons and protons, a neutron–proton ratio of 1. For nuclides up to Z (number of protons) equal to 20, the ratio of neutrons to protons is about 1.0–1.1. As Z increases, however, the neutron to proton ratio increases to about 1.5. This increase in the neutron to proton ratio with Z is believed to result from the increasing repulsion of protons from their electric charges. More neutrons are required to give attractive nuclear forces to offset these repulsions. It appears that when the number of protons becomes very large, the proton–proton repulsions become so great that stable nuclides are impossible. Thus, no stable nuclides are known with atomic numbers greater than 83.

Evidence also points to the special stability of pairs of protons and pairs of neutrons. Most naturally occurring stable nuclides have an even number of protons and an even number of neutrons. The shell model of the nucleus in which protons and neutrons exist in levels or shells points to another factor affecting nuclear stability. Experimental evidence indicates that nuclei with certain numbers of protons or neutrons appear to be very stable. These numbers, called *magic numbers,* are associated with especially stable nuclei, and were later explained by the shell model. According to this theory, a magic number is the number of nuclear particles in a completed shell of pro-

Test Questions on Nuclear Chemistry

1. Which of the following is one of the factors that affects the stability of the nucleus of an atom? Explain why you made that choice.
   a. Density of the nucleus
   b. Proportion of the atomic number of an atom to its mass number
   c. Existence of various isotopes that have specific atomic numbers
   d. Having odd or even numbers of the nucleons in a nucleus
   e. Having a full number of valence electrons (2, 8, 18, 32, 50) in the valence shell of an atom

2. Which of the following expressions correspond to binding energy in a nucleus? Explain why you made that choice.
   a. The force that keeps nucleons together in an atom
   b. The energy that is given off when two atoms combine to form a molecule
   c. The energy that is given off when a nucleus is formed from protons and neutrons
   d. The energy that is given off when neutrons and protons are formed

3. Which of the following compounds shows a radioactive character? Explain why you made that choice.
   I. $\mathrm{Mg}^{16}_{8}\mathrm{O}$
   II. $\mathrm{Al_2O_3}$
   III. $\mathrm{Pb}^{16}_{8}\mathrm{O_2}$
   IV. $\mathrm{UO_2}$
   V. $\mathrm{Ca}^{15}_{8}\mathrm{O}$
   VI. $^{10}_{5}\mathrm{BF_3}$
   a. I, II, III
   b. IV, V
   c. I, IV, VI
   d. II, IV, V
   e. I, III, IV

4. Which one of the following atomic nuclei is most stable at the highest atomic and mass number? Explain why you made that choice.
   a. $^{208}_{83}\mathrm{Bi}$
   b. $^{208}_{82}\mathrm{Pb}$
   c. $^{238}_{92}\mathrm{U}$
   d. $^{238}_{92}\mathrm{U}$

5. Of the following atomic nuclei (whose half-lives are given), which is the most unstable? Explain why you made that choice.
   a. $^{131}\mathrm{I}\,t_{1/2}$ = 8.05 days
   b. $^{15}\mathrm{C}\,t_{1/2}$ = 2.4 seconds
   c. $^{60}\mathrm{Co}\,t_{1/2}$ = 5.26 years
   d. $^{137}\mathrm{Ce}\,t_{1/2}$ = 30.17 years
   e. $^{14}\mathrm{C}\,t_{1/2}$ = 2.1 minutes

6. In which of the following examples are radioisotopes used? Explain why you made that choice.
   I. Purifying water
   II. Preserving food
   III. Sterilizing medical instruments
   IV. Determining reaction mechanisms
   V. In nuclear power plants as an electrical energy source
   VI. Determining the ages of historical artifacts
   a. I, II, III, IV, VI
   b. I, III, VI
   c. II, V, III
   d. All of these examples
   e. Only example V

7. Which of the following factors affect the radioactive decay rate? Explain why you made that choice.
   a. Type of the element
   b. Amount of the material
   c. Pressure
   d. The physical state of the substance
   e. Temperature

Textbox 1. Test questions used to identify student misconceptions regarding nuclear chemistry. (Letters for correct answers are in bold.)

tons or neutrons. For protons, the magic numbers are 2, 8, 20, 28, 50, and 82. Neutrons have these same magic numbers, as well as the magic number 126. For protons, calculations show that 114 should also be a magic number *(25).*

In the multiple-choice part of Q1, a majority of students answered B or E (52% and 26% respectively); only 4% of the students selected the correct answer, acknowledging that having odd or even numbers of nucleons in a nucleus affects its stability. This implies that they did not know the factors affecting nuclear stability. Q1, choice B states a misconception that the "proportion of the atomic number of an atom to its mass number" affects the stability of the nucleus of an atom. Even though students in the sample may be aware of the relationship between stability and the neutron to proton (n–p) ratio, they are largely unable to distinguish between the ratio of neutron–proton and ratio of atomic number–mass number. In the open-ended part of question 1, 16% of the students who chose B wrote this explanation "if the n–p ratio is equal to 1, the atomic nucleus is stable". From other explanations which belonged to students who had choice B it can be seen that they had some confusion about atomic number, mass number, proton number, and neutron number. For example, one student said:

> The more protons there are in the atomic nucleus (that is, the greater this ratio of mass number–atomic number), the more stable the atomic nucleus is.

Another misconception addressed in choice E of Q1 is that "having a full number of valence electrons (2, 8, 18, 32, 50) in the valence shell of an atom" affects the stability of the nucleus of an atom. Answer E would lead one to believe that these students had some confusion about the numbers of valence shell electrons and magic numbers used in explaining nuclear stability. Possible reasons include students either not carefully reading the explanations used in the chemistry textbooks (as in the examples below) or not understanding and interpreting these explanations correctly. For example, *Chemistry: A Conceptual Approach (26)* states:

> It is thought that the magic numbers indicate closed nuclear shells in the same way that the atomic numbers of the noble gases indicate stable electronic configurations.

Another text, *General Chemistry (25),* writes:

> The protons and neutrons in a nucleus appear to have energy levels much as the electrons in an atom have energy levels.

Additionally, this misconception indicates that these students thought that the stability of the nucleus of an atom and the stability of an atom or element were the same. They were also confused about atomic structure stability and noble gas stability. In the open-ended part of Q1, 24% of students choosing E wrote an explanation that supports this claim. Their explanation is "if an atom has a filled valence shell, then the atomic nucleus has the stability like the noble gases have".

The results for Q4 are consistent with these for Q1. Q4 was designed to identify whether students could distinguish which atomic nuclei are most stable based on the highest atomic and mass number. Only 22% of the students chose response A, $^{208}_{83}$Bi, which is most stable due to its high atomic and mass number; 39% selected response C ($^{238}_{92}$U)and 26% selected response B ($^{208}_{82}$Pb). In the open-ended part of Q4, 8% of students who chose D wrote this explanation: "Rn belongs to the noble gases so it [its nucleus] is stable". From

Misconceptions about Nuclear Chemistry Identified in This Study

Nuclear Stability

- The density of nucleus of an atom is one of the factors that affect the stability of the nucleus of an atom.
- Proportion of atomic number of an atom to its mass number is one of the factors that affect the stability of the nucleus of an atom.
- The more protons there are in an atomic nucleus, the greater this ratio of mass number–atomic number is, the more stable the atomic nucleus is.[a]
- The number of valence shell electrons (2, 8, 18, 32, 50) is one of the factors that affect the stability of the nucleus of an atom.
- If an atom has a filled valence shell, the atomic nucleus is stable, like the noble gases.[a]
- The larger the atomic number and mass number are, the more stable the atomic nucleus.[a]
- Existence of various isotopes that have specific atomic numbers affects the stability of the nucleus of an atom.

Half-Life

- An atomic nucleus that has the longest half-life is the least stable, contrary to the fact that the least half-life atoms are the least stable.[a]

Binding Energy

- The force that keeps nucleons in the nucleus together is called binding energy.
- The energy given off when two atoms come together to form a molecule is called binding energy.

Practical Applications of Nuclear Chemistry

- Radioisotopes are used only to obtain energy because they are very harmful to humans.[a,b]

Radioactive Decay Rate

- The radioactive decay rate depends on the physical conditions.
- Since each type of matter has a different radioactive decay rate, the radioactive decay rate depends on the type of element.[a]
- The radioactive decay rate depends on the temperature.

[a] Misconceptions taken from the statements expressed by the students in the open-ended part of the test.

[b] Misconception similar to one of the misconceptions cited in references *16* and *17*.

Textbox 2. Example student misconceptions regarding nuclear chemistry by subtopics.

this statement, it could be also said that many students have difficulty in making the distinction between noble gas stability and nuclear stability or the stability of the nucleus of an atom and the chemical stability of an element. We observed that the other misconception, similarly to the first question, stemmed from the confusion about the effect of atomic number and mass number on atomic nucleus stability. Thirty-nine percent of students who chose C and 13% of students who chose B wrote this explanation: “The bigger the atomic and mass number are, the more stable the atomic nucleus is”.

Question 2

The second question tested students’ understanding of *binding energy.* Binding energy is the energy needed to break a nucleus into its individual protons and neutrons. When the nucleons come together to form a nucleus, energy is released. The nucleus has lower energy and is, therefore, more stable than the separate nucleons. According to Einstein’s equation ($E = mc^2$), there must be an equivalent decrease in mass. The *mass defect* of a nucleus is the total nucleon mass minus the nuclear mass. Both the binding energy and the corresponding mass defect are reflections of the stability of the nucleus.

In the multiple-choice part of Q2, a majority of students answered A and B (52 and 22%, respectively). Only 14% of students correctly chose response C, which states that binding energy is given off when a nucleus is formed from protons and neutrons. This implies that most students did not understand the meaning of binding energy. The misconception stated in choice A (and selected by 52% of students) described binding energy as the force that keeps nucleons together. The large number of students choosing this misconception indicates that students confused *nuclear force* (a force of attraction between nucleons that can more than compensate for the repulsion of electric charges and thereby yields a stable nucleus) and *binding energy* (energy given off when a nucleus is formed from protons and neutrons). Textbooks used by the students in this study may be a possible source for this misconception, as *binding energy* has been defined as *nuclear force* in some chemistry textbooks. The following comment is sometimes seen in Turkish high school chemistry textbooks *(27, 28):* “the force that keeps nucleons in the nucleus together is called binding energy”.

The second misconception addressed in choice B, which about 22% of students chose, was that “binding energy is given up when two atoms come together to form a molecule”. Students selecting this response were confused about the difference between bonding in molecules and the binding energy in a nucleus because one word in Turkish serves as a translation of both English words “bonding” and “binding”—and this word is used in everyday language. In the open-ended part of Q2, students gave clear explanations of why they chose this answer. Analysis of these responses identifies that students held similar misconceptions as well. Of the two misconceptions explained above, the first is considered a conceptual misconception, and the second one a vernacular misconception.

Question 3

If a compound contains an element consisting of radioactive atoms, it is expected that this compound will also have radioactive characteristics. The third question focused on the extent to which students grasped that radioactive atoms that are constituents of compounds cause these compounds to have radioactive characteristics. The correct answer was chosen by 39% of the students. Explanations in the open-ended part of Q3 indicate that almost all of the students who had chosen the correct item knew that “radioactive compounds have radioactive atoms”. Other explanations from students choosing incorrect responses for Q3 indicate that students did not know which atoms among the possible choices were radioactive, nor did they understand how the radioactive properties of atoms change according to an element’s isotopes.

Question 5

Question 5 tests whether students understand the relation between nuclear half-life and stability. *Half-life* is defined as the time in which a certain number of nuclei, N_0, is reduced to one-half of the initial number ($1/2\ N_0$). Every radioactive isotope has a specific and constant half-life; radioactive isotopes with short half-lives are more unstable than isotopes with long half-lives. Of the atomic nuclei whose half-lives were given in the choices, 62% of students could correctly ascertain the most unstable nucleus. In contrast, 17% of students chose D, representing the longest half-life. Written explanations on the open-ended part of Q5 noted incorrectly that “the atomic nucleus that has the longest half-life is the least stable”.

Question 6

Q6 explores students’ knowledge about uses of radioisotopes in daily life. A large number of radioactive isotopes have been used both in industry and in many areas of basic and applied research. Previous studies have identified students’ misconceptions about applications of radioactivity in daily life, for example: “radiation causes cancer” thus, it cannot be used to cure cancer; “all radiation is harmful” *(16).* An additional misconception, “irradiated food is radioactive”, is now included in the science education literature *(17)* because of a publicly held concern that irradiated food contains a variety of reaction products, at least a few of which could be harmful.

In the multiple-choice part of this question, a significant number of students (42%) incorrectly chose E. This implies that they think radioisotopes are used only to obtain energy. In the open-ended part of Q6, 45 of 66 students who had chosen E explained that “radioisotopes are used only to obtain energy because they are very harmful for humans”; the rest simply wrote that “energy is released from radioisotopes”. The statements above attest that most of the students know only the harmful results of radioactivity. Such perceptions may arise from the overemphasis regarding the harmful effects of radioactivity in the news from television or other media. These misconceptions can be considered as experiential rather than instructional. Atwood and Sheline *(19)* called attention to this by stating how negative impressions of nuclear chemistry may be heightened by media treatments of topics such as dangerous Rn concentrations in houses, and difficulties with disposing of high-level nuclear waste.

Question 7

The concept of radioactive decay rate was tested in Q7. The rate at which a radioactive sample decays can be measured by counting the number of nuclei disintegrating per unit time. Nuclear decay is a first-order reaction and independent of temperature. That is, the rate of decay is directly proportional to the amount of radioactive isotope present *(29)*. The rate is expressed mathematically as kN_t where N_t represents the amount of radioactive isotope present at time t. Most often, N_t is taken to be the number of radioactive atoms in the sample. The first-order rate constant, k, is characteristic of the radioactive nuclide, each nuclide having a different value *(25)*. The rate of decay, often referred to as the activity of the sample (A), is most often expressed in terms of the number of atoms decaying per unit time. Applying the first-order rate law to radioactive decay, we obtain the following equations: $\ln(N/N_0) = -kt$ and $N = N_0\, e^{-kt}$. These equations enable us to address questions related to persistence, such as: (i) How long should nuclear wastes be stored before they can be considered harmless?; (ii) What happens to all the radioactive elements emitted by nuclear accidents or nuclear weapons' testing?; and (iii) How are archaeological objects dated with the radiocarbon method? *(30)*.

In the multiple-choice part of Q7, a majority of students (72%) answered A. This result demonstrates that students thought radioactive decay rate depends only on the type of element. In the open-ended part of Q7, some of the students who chose A wrote these explanations:

> Each element has a different radioactive decay rate. [29%]
>
> Since matter has varying radioactive decay rates, the radioactive decay rate depends on the type of element. [5%]
>
> Radioactivity is a property of the nucleus of an atom. This property differs for each material. [4%]
>
> The radioactive decay rate is related to the stability of the elements. [2%]
>
> The radioactive decay rate depends on the type of element, that is, the type of isotope. [2%]
>
> Each element has a different atomic number. [2%]

The sources of these students' misconception statements can be clarified as paraphrased below:

1. Students thought that the *decay of the atoms' nuclei is* equal to the *decay of elements or matter*.
2. Students did not fully grasp the difference between chemical reaction and nuclear reaction.
3. Students did not conceptualize the meaning of the equations $\ln(N/N_0) = -kt$ and $N = N_0\, e^{-kt}$.

If the students comprehended the meaning of N and N_0 from the equation, they would have chosen the response referring to the amount of radioactive nuclei. On the other hand, the decay constant k for this process is characteristic of each nuclide. It has been determined that the students think that there is no difference between "characteristic of each nuclide" and "characteristic of each element or material" since they are not able to comprehend the relation between macroscopic and microscopic levels of representing matter and, as a result of this, they use the terms "atom" and "element" or "material" interchangeably. Furthermore, this result identifies that the students have neither comprehended the concept of isotope atom, nor understood that elements may have different naturally occurring isotopes.

The source of this very important misconception might be confusion derived from whether the periodic table refers to either chemical elements or atoms. Supporting this view, Schmidt *(31)* believes that the term "element" is used as a synonym for the "atom" of an element in the periodic table. Additionally, Hughes and Zalts *(30)* cite that in many cases, students are not familiar with exponential mathematics and lack the understanding necessary for interpreting first-order kinetics equations. They point out that because of this, class discussions of the persistence of radiation and its consequences may be quite limited.

Another misconception identified in Textbox 2 under Radioactive Decay postulates that the "radioactive decay rate depends on the temperature", suggesting that students holding this misconception think that a radioactive process can accelerate or slow down depending on temperature, despite the fact that the decay constant k for this process is independent of physical or chemical form. Also, this constant and the decay rate are virtually unaffected by changes in pressure and temperature *(30)*. This lack of temperature dependence implies that the activation energy of any radioactive-decay process is zero. The rate of decay, therefore, depends only upon the amount of radioactive nuclide present.

Conclusions

These findings show that Turkish high school students hold a series of misconceptions both about nuclear chemistry topics related to nuclear stability, half-life, binding energy, practical applications of nuclear chemistry, radioactive decay rate, and prerequisite concepts essential for learning nuclear chemistry. From the constructivist viewpoint, critical steps to promoting meaningful learning involve identifying students' misconceptions and determining students' naïve ideas, in order to build toward scientifically accepted views. One of the two obstacles to effective learning is that concepts and topics related to nuclear chemistry are quite abstract. Lack of prerequisite knowledge also hinders students, who often have problems with concepts such as atomic number, mass number, element, atom, radioisotope, nuclide, and isotope in learning nuclear chemistry. Moreover, students confuse the difference between nuclear and chemical reactions.

Implications

High school chemistry teachers should ensure that students have a solid foundation of knowledge about concepts of atomic number, mass number, nucleons, isotopes, and nuclides before starting to teach topics related to nuclear chemistry. Second, teachers should emphasize the distinction between chemical and nuclear reactions by using examples. As Johnstone *(32)* has indicated, chemistry exists in three levels that can be thought of as corners of a triangle: macroscopic, microscopic, and symbolic corners. Matter, which is observed and can be studied on the macroscopic level, can also be described on the microscopic level. Chemists can represent both the macroscopic and the microscopic levels symbolically through the use of chemical symbols, chemical formulas, and chemical equations as well *(33)*. This situation makes chemistry difficult to learn. The fact that students fail to link among these three levels of chemistry causes them to use the concepts atom, element, and matter interchangeably. This leads to some misconceptions in many chemistry topics and also nuclear chemistry topics.

After ensuring that the concepts of matter, element, atom, and the differences among them have been comprehended by the students, the distinction between atomic nucleus stability and element stability should be emphasized. Furthermore, while using the shell model to explain nuclear stability, the difference between closed nuclear shells and valence shells of electrons should be stressed.

Recommendations for Instruction

Different instructional strategies can be developed based on the type of the misconception. Computer-assisted instruction can be effective for teaching nuclear chemistry topics by both simulating experiments on the computer that are dangerous and very difficult to do in laboratories, and using simulations for teaching some abstract topics at the microscopic level. In addition, the lesson activities should be shifted from the development of lower-order cognitive skills (rote learning, algorithmic problem solving) to higher-order cognitive tasks *(34)*. Thus, students should be encouraged to conceptualize mathematical formulas rather than simply memorizing them. In order to interpret the radioactive decay-rate equation better, Hughes and Zalts *(30)* suggest an “exponential decay graph” that can be constructed quite easily in the classroom, and then used to illustrate discussions about uses of radioactivity, its risks, limitations, and advantages.

The results of this study show that although these students had been taught nuclear chemistry applications in their lessons, some could not distinguish beneficial uses of radioactivity from among the nuclear chemistry topics and applications in daily life. Since some students have misconceptions about the harmful effects of radioactivity, the useful applications of nuclear chemistry in daily life should be identified during lessons. Inquiry tasks related to these beneficial applications could provide meaningful learning opportunities. There is no doubt that the harmful effects of radioactivity are extremely great and have caused human death and suffering as well as environmental degradation. Increasing students’ awareness of these problems is especially important given the environmental concerns regarding nuclear waste.

In conclusion, students must be provided with sufficient knowledge related to basic nuclear chemistry topics, applications, and harmful effects rather than according nuclear chemistry topics the insufficient attention they are usually given in chemistry courses and in textbooks. Teachers should heed Hutchison and Hutchison (*21,* p 501), who recognize radioactivity in everyday life and state:

> It is an inescapable fact—you are exposed to radiation from the moment of conception until the day of your death. The planet Earth is a radioactive planet. … In spite of the fact that Earth has always been and will continue to be radioactive, and that nuclear power and radioactive waste disposal will remain environmentally controversial topics, many students are not getting basic information concerning radioactivity. … However, a basic understanding of radiation may be as useful to the typical students as many of the other topics. … The term “nuclear” does not have to have negative connotations.

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