Students' Beliefs About the Role of Atoms in Radioactive Decay and Half-life

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ABSTRACT

Contemporary science education research emphasizes the importance of considering students pre-instructional beliefs when designing effective, learner-centered instructional strategies. When scientists teach about dating geological events, most often the concepts of radioactive decay and half-life are presented. However, the research base on student understanding of radiation and radioactivity is currently quite limited. The principal research question used to focus this investigation asked: What are the common difficulties that students experience when trying to learn about radiation and radioactivity? Our research illustrates that students bring to the classroom many inaccurate ideas and reasoning difficulties on the topics of ionizing radiation, radioactivity, and radioactive decay that are well-poised to interfere with students' understanding of how half-life is used to determine geologic time. To uncover the range and frequency of the dominant student beliefs, we performed individual demonstration interviews and administered open-response and multiple-choice conceptual tests to students from a wide-range of science backgrounds. Our results show that students are often unable to differentiate between the ideas of irradiation and contamination, and that many of these students' reasoning difficulties about radioactive decay and half-life stem from their inaccurate mental models regarding the atom.

INTRODUCTION

The topics of radioactivity, radioactive decay, and half-life are foundational concepts in geology, astrobiology, chemistry, physics, biology, paleontology, astronomy, mathematics and planetary science classes. Many laboratory activities (Mak, 1999; Hoeling et al., 1999; Peplow 1999; Russo, 1999; Lumb, 1989; Austen and Brouwer 1997), analogy-based teaching strategies (Wunderlich, 1978; Evans, 1974, Celnikier, 1980; Kowalski, 1981; Priest and Poth, 1983; McGeachy,1988), and calculation or computer-based exercises (Weinberg, 1997; Caon, 1995; Ruddick, 1995; Shea, 2001; Huestis, 2002), are offered in the literature to help students better understand radioactive decay and half-life. However, the fundamental naive beliefs and reasoning difficulties held by many students are poised to interfere with the majority of these novel instruction methods. The underlying problem is that the majority of these materials and teaching strategies are not informed by recent research into student learning and reasoning difficulties on these topics and thus fail to effectively elicit or help students resolve the naive ideas that they hold prior to instruction. In fact, of the greatest potential concern is that many of the activities listed above are likely to enhance or reinforce the student difficulties described here.

The principal research question used to focus this investigation asked: What are the common difficulties that students experience when trying to learn about radiation and radioactivity? Prior research (see Part I) suggests that one student learning difficulty with these topics stems from their inability to correctly differentiate between irradiation and contamination, believing that an object exposed to ionizing radiation will become radioactive. In addition our research suggests that half of college students enrolled in introductory physics courses believe that orbital electrons are causally related to the radioactive state of atoms and to the decay process. Making matters worse, an equal percent of these students believe that the mass and volume of a radioactive substance will decrease in the period of a half-life.

We assert that the students' naive beliefs and reasoning difficulties related to a particular topic which are identified from an investigation conducted in one subject area (such as physics) are certainly also poised to interfere with instruction on the same topic while being covered in a different subject area (geology, chemistry, astronomy etc.) Furthermore the overall population of students who enroll in the introductory non-science major course through the introductory majors course in one subject area (such as geology) may well provide a representative sample of the general population of students that enroll in the same range of courses within any of the other subject areas (listed above) that teach about radiation and radioactivity. We argue that the research herein serves to both identify students' ideas and inform the development of innovative instructional strategies centered on helping students overcome their naive beliefs and reasoning difficulties when being taught in any of these subject areas (Prather, 2000).

PART I - PRIOR RESEARCH FINDINGS

Studies conducted in Europe, with students of middle school and high school age, found that many students have a weak understanding of the transport and absorption properties of radiation and radioactivity (Eijkelhof and Millar, 1988; Lijnse et al., 1990; Millar, 1993; Millar and Gill, 1993; Millar, 1994). This research identified that these students have an inability to properly differentiate between the concepts of irradiation and contamination. The initial stages of our research confirmed that the students' beliefs and reasoning difficulties identified by these European studies were also held by college students enrolled in introductory physics classes here in the United States (Prather and Harrington, 2002). When asked to reason about situations that involved the exposure to, or absorption of, radiation we found that many students inappropriately involve the concept of radioactivity. These students often stated that objects exposed to radiation would either become sources of radiation or have radioactive properties. Some of these students describe ionizing radiation as having the same properties as radioactive materials. Furthermore, we identified that it is indeed possible for students to provide the correct answer to questions involving irradiation and contamination while employing faulty reasoning. Additional studies conducted in the United States and in Europe focused on elementary aged students' and pre-service teachers' ideas about the nature of geological time (Ault Jr., 1982; DeLaughter et al., 1998; Trend, 1998; Trend 2000). The later stages of our research, detailed in Part III, suggest that students' ability to reason about geological time is potentially limited by their naïve beliefs about the concept of half-life.

To properly account for radioactive phenomena, one must have a fundamental understanding of how the atom (or atomic nucleus) behaves during the decay process. Either students do not have a clear understanding of the role of atomic nuclei in radioactive processes or they fail to access this knowledge when asked questions about radioactivity. To move beyond students' ideas about irradiation and contamination our investigation next targeted students' understanding of the role the atom plays in the radioactive decay process. Results from this phase of the investigation will be described in the following sections of this manuscript.

We will describe this research in an atypical format in that we will report our methodologies, research populations and results in a somewhat interwoven manner and sequence. This is done because the research was conducted iteratively with each result influencing the next methodological step. The research tools used and corresponding results provided do not easily lend themselves to conventional quantitative measures of reliability. Rather they are created from a theoretical framework of grounded inquiry and, as such, are based on student' responses from sequential steps of the research.

It is worth noting that the results from all phases of this investigation were used to continually guide the development of instructional strategies and materials including interactive lectures, hands-on laboratory-based activities, and tutorial worksheets. These strategies and instructional materials were structured around a directed inquiry approach and have been shown to substantially increase the understanding of students over conventional lecture and lab methods for teaching about irradiation, contamination, radioactive decay and half-life and are described in detail elsewhere (Prather, 2000).

Part II - STUDENTS' BELIEFS ABOUT THE ROLE OF THE ATOM IN RADIOACTIVE DECAY

Materials that are commonly referred to as "radioactive" contain both stable and unstable atoms. Unstable atoms are also referred to as "radioactive." These atoms contain an unstable nucleus and have a non-zero probability of undergoing a transformation and emitting ionizing radiation. Therefore, a thorough understanding of student beliefs related to radioactive phenomena requires that we investigate their understanding of both stable and unstable atoms. Our research question guided our investigation to focus on the extent to which we could develop a deeper understanding of how students' ideas about radioactive atoms differ from their ideas about stable atoms. Our investigation was designed to elicit whether or not students have a model, or mental picture, that they use to describe the atom in general and in particular how they use their model to account for the radioactive decay process at the atomic level. All students participating in the investigations described in sections A-D below were enrolled in undergraduate physics courses taught at a medium-sized research level-one university located in the Northwestern United States. Specific information on student population numbers and courses will be provided to accompany the specific phase of the research being reported.

Results from Open-response Conceptual Questions on the Stable Atom - In an open-response conceptual question used during a preliminary phase of this research, 180 non-science major physics students were asked to sketch a picture of an atom and label each part of the atom. In addition, students were asked to indicate the location of any particles having a net positive or negative charge and to describe, in words, the location of the particles. In particular we were very interested to see what representations students would choose when trying to describe or draw an atom.

The majority of these 180 non-science major physics students who responded to this preliminary question provided what we considered to be a reasonably complete drawing of the atom involving electrons and a nucleus. Of these students, more than half (56%) drew a Bohr-like representation. These drawings showed a central nucleus composed of protons and neutrons, as well as electrons surrounding or orbiting the nucleus. Approximately one-quarter of these students (23%) drew pictures of the atom that involved two or three different particles in orbit about a central sphere. The orbiting particles provided in these representations included all combinations of electrons, protons, and neutrons. Overall, only about half (51%) of the students correctly stated that electrons have a negative charge, protons have a positive charge, and that neutrons have no net charge. As the results from our further investigations (detailed below) illustrate, students' ability to properly identify the location and state of charge for these atomic particles rests at the core of many of the naive ideas students have about the nature of radioactivity.

Results from Interviews on the Radioactive Atom - Informed by the results described in part A, we shifted the emphasis of this investigation to examine students' ideas about the role that the atom plays in connection with the concept of radioactivity, including the process of decay. As a first step, we conducted a series of six individual demonstration interviews in which students were asked to perform specific tasks, and answer conceptual questions, designed to provide insight into their beliefs about concepts related to radioactivity. A combination of both open-ended and pre-determined protocols was used with each of these interviews, which averaged 1/2 - 3/4 hour in length. Each interview was videotaped for later analysis of students' responses and actions. These interviews were conducted with two students that were enrolled in the introductory calculus-based physics course, two students enrolled in the introductory algebra-based physics course and two undergraduate physics majors who had completed the year long introductory calculus-based physics series and a sophomore level modern physics class in which they had specific instruction on radiation and radioactivity. The information obtained from these interviews was then used to guide the design of open-response and multiple-choice questions administered on pre- and post-instruction questionnaires.

Each interview began by providing the students with three sets of different colored clay balls, which could be used during the interviews at any time. The use of clay balls during interviews was implemented in response to students' initial difficulties with using a drawing to represent their ideas about an atom during a set of pilot interviews. The clay balls could be easily paired together or reshaped and thus provided a way for students to create a three-dimensional physical model to represent their mental picture of an atom (Wefelmeier, 1937). We hoped that students would find the clay balls helpful when trying to describe what makes an atom radioactive and to illustrate more subtle details of the decay process at the atomic level.

When asked to construct their model for the nucleus of an atom we found that students used the clay balls in a variety of ways. While some students used the clay balls to represent the simplest case of the hydrogen nucleus others used several clay balls to represent an atom composed of multiple protons, neutrons and electrons. After students created their clay model atom, they were asked if the arrangement of balls had any significance. The interviewer then asked different questions about the properties and behavior of radioactive atoms during the decay process. The specifics of these questions depended on the type of response provided by students earlier in their interview. Overall we were interested in probing what students thought happens to an atom during radioactive decay, whether or not the atom would change (and if so how) during the decay process, and what might cause the decay process to occur.

From analyzing the interview transcripts we found that overall these students' used a select set of key ideas to describe the role the atom plays in the radioactive decay process. Overall their ideas appear to be connected to fundamental physics concepts or properties of matter (such as force, energy, charge and mass) that they have developed or heard about during prior instruction (both on the topic of radioactivity and on other topics). Students appear to be drawing from ideas that they felt more comfortable or confident with when they were asked to reason about the less familiar topic of radioactivity and the process of decay.

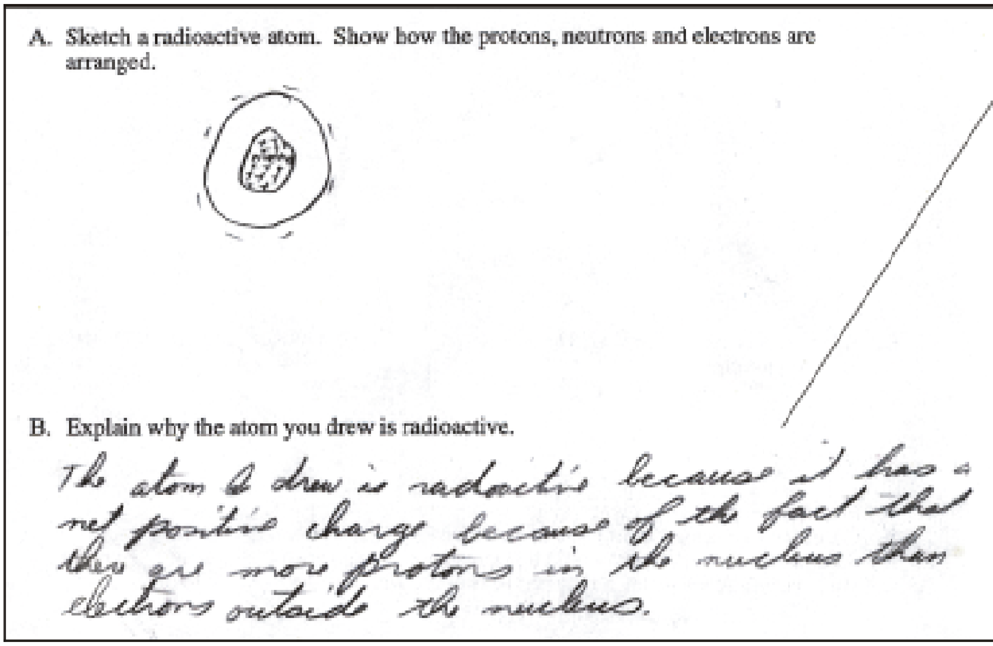
When asked to explain what makes an atom radioactive, students would often reason that the atom was in some way out of balance or unstable. These states of instability in the radioactive atom were typically connected to the arrangement or number of charges (or charged particles) present in the atom. In other cases the state of instability was attributed to an interaction or force between the particles making up the atom. The excerpts from interviews provided below illustrate students beliefs about how protons, neutrons, electrons, and, in particular, the concept of charge and force, are all connected to the idea of radioactivity. Again it is important to attend to how students seem to apply their ideas about one topic (for example electrostatics) to account for the less familiar phenomena of radioactivity.

- The electro-negativities are unstable
- This is unstable because there are two protons and only one neutron.
- The atomic weight, you add up all the masses of the protons and neutrons and if you're above a certain number it's [the nucleus is] radioactive. It would have to have more protons than neutrons to make it [the nucleus] heavier.
- You need the neutrons to shield the protons from each other and if there is not enough of the neutrons, and there are too many protons, and they are all close together, then they start being repelled.
- In like a stable atom you are supposed to have equal numbers of protons and electrons so that it's a neutral atom. Then if you have a lot of electrons and not enough protons then it's gonna be like a negatively charged particle. The excess of negative charge is gonna interact with these [the protons in the nucleus] and make this [the nucleus] unstable in the fact that protons are dealing with each other but also the fact that outside [electrons] is sort of attracted to it.

When asked to describe what would occur during the decay process, students' responses often provided explanations that illustrated a connection to their initial thoughts about what they felt made the atom unstable. Some responses were centered on a change in the atom to bring about a state of balance or change in force or energy to a more stable configuration of protons, electrons and neutrons. In other cases students suggest that the word "decay" may promote a set of colloquial ideas about the process of radioactive decay. The excerpts below are provided to illustrate the variety of ideas used by students to describe how atoms change during the process of radioactive decay.

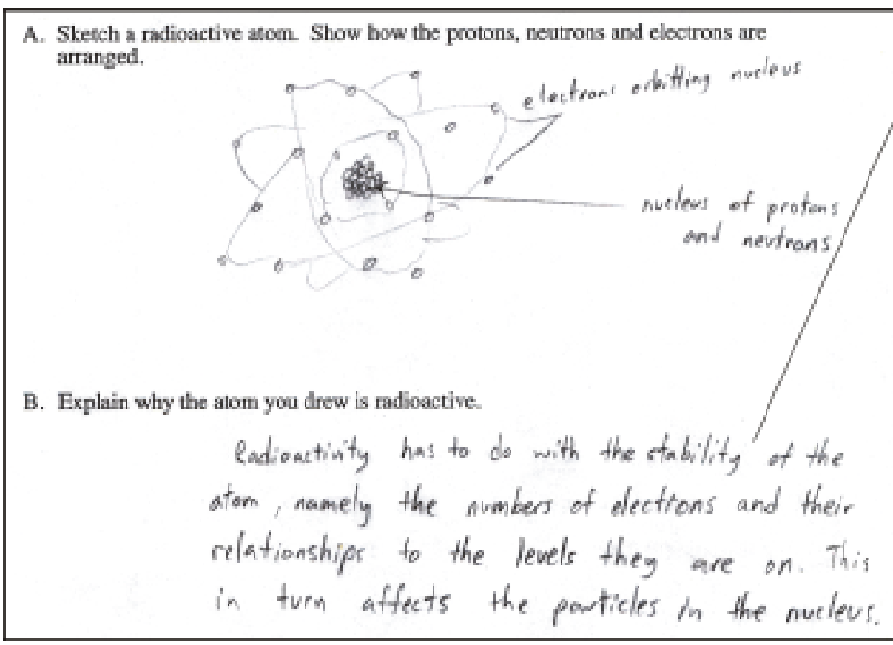
- It's losing pieces, electrons until it disintegrates…I guess it would just get smaller.
- It means that one of the neutrons would be ejected from the nucleus [student removes a clay ball neutron from their clay ball nucleus] and with that there would be some release of energy neutron away. Because the neutron doesn't have any charge they are more easily ejected.
- The electrons in one state will jump up to another state and obviously can't stay there 'cause it's unstable, and then when they drop back down they give off a photon of a certain frequency.
- Well, if you get rid of a proton, and this [the nucleus] isn't too heavy, and there are not too many protons, and there are just enough neutrons, and it [the nucleus] can stick together then it's done. But if you get rid of a proton, and there's still too many protons, and they are still being repulsed you've got to get rid of some more until it gets down to the point where it's relatively stable in terms of the forces inside of the nucleus.
- They are differently charged particles that get ejected, so they change the balance of the charge and everything.

As these excerpts illustrate, overall these students have a weak or incomplete understanding of the radioactive decay process and that they reason about the role the atom plays in radioactive decay in a variety of different ways. The use of the terms "unstable," and to a lesser degree "disintegrate" (perhaps in place of "decay"), indicate that students may have been simply recalling words they have previously heard and associated those words with radioactive phenomena. For some students, the ideas of radioactive instability and decay appear to be connected to the state of charge of the atom and the interaction (energy, motion and forces) of electrons, protons and neutrons. These ideas are characterized by student responses describing radioactivity as having an electron that is in an excited state, and go on to state that radioactive decay is the emission of a photon resulting from the change in energy state of the excited electron. What is particularly interesting about the reasoning used by these students is their inappropriate application of electron-states and the Bohr model of the atom to explain radioactivity. In addition we identified the following three features that appeared to characterize the most common ideas students had about the radioactive nucleus: (1) instability is the result of repulsion between protons, (2) neutrons are able to shield the repulsion between protons and thus limit the instability of the nucleus, and (3) through the emission of protons nuclear instability is decreased. Furthermore it appears that some students' understanding of radioactivity incorrectly involves an interaction between the nucleus



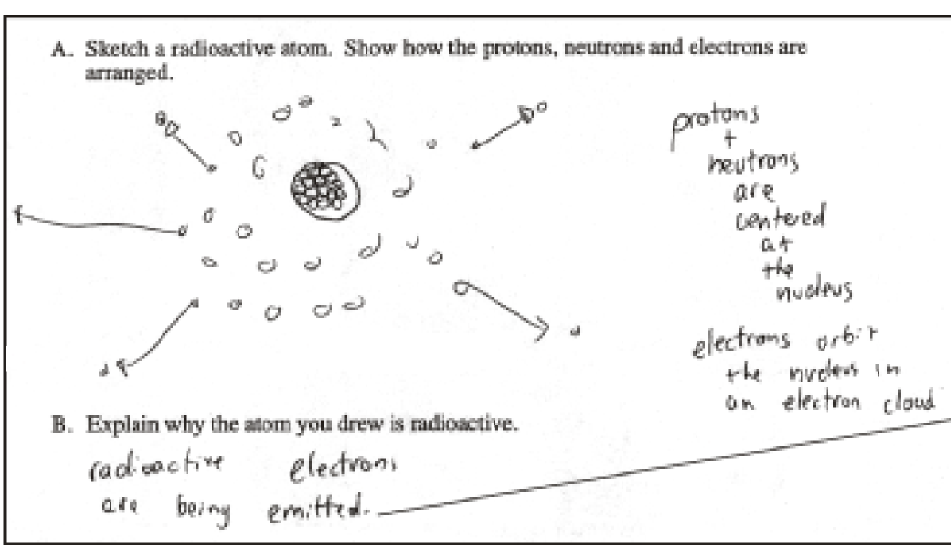
"The atom I drew is radioactive because it has a net positive charge because of the fact that there are more protons in the nucleus than electrons outside the nucleus."

-Excerpt from a calculus-based physics student



"Radioactivity has to do with the stability of the atom, namely the numbers of electrons and their relationships to the levels they are on. This in turn affects the particles in the nucleus."

-Excerpt from an algebra-based physics students



"Radioactive electrons are being emitted"

-Excerpt from a non-science major physics student

Figures 1, 2, and 3. Student drawings and explanations.

	Calculus-Based (N=41)	Algebra-Based (N=53)	Non-Science (N=34)
Responses involving *only* the nucleus	24%	25%	18%
Responses involving valence electrons	54%	48%	61%
Responses involving the emission of an unidentified particle	7%	6%	0%
General statement about isotopes or instability	10%	11%	9%
Other	5%	11%	12%

Table 1. Summary of student respones.

and orbital or valence electrons (referred to as valence electrons from this point forward). For students reasoning this way, an electron-proton interaction appears to exist due to an excess amount of one type of charge, positive or negative (or from an imbalance between the number of protons or electrons). Balance is achieved for this situation through the emission (radioactive decay) of the particle carrying the excess charge, thus restoring stability to the atom. To extend this investigation, we created conceptual questions to identify whether or not the ideas we identified from students' statements during the interviews were prevalent among the much larger population of introductory physics students.

Results from Open-response Conceptual Questions on the Radioactive Atom - Guided by the results of our previous research we designed and administered an open-response conceptual question to students enrolled in the calculus-based course, the algebra-based course, and the course for non-science majors. These questions were administered prior to instruction on radioactivity in each of the courses. In the first part of the question, students were asked to sketch a radioactive atom. Students were also asked to show explicitly how the protons, neutrons and electrons are arranged and to explain why the atom they drew was radioactive.

Approximately 60% of the drawings provided by students from each population correctly identified the location of the electrons, protons, and neutrons (a result similar to the drawings/results given by students when asked to draw and identify the parts of a stable or non-radioactive atom as reported from the preliminary phase of this research.) The ideas expressed in the explanations accompanying these drawings were overall very similar to the responses provided by students during interviews. Figures 1 - 3 illustrate the range of the drawings and explanations provided by students when responding to this question.

By carefully analyzing the drawings and explanations given by students from each population, we were able to organize student responses into categories that were common to students from all three populations (see Table 1).

Student responses involving valence electrons were provided by 54% of the students in the calculus-based course, 48% of the students in the algebra-based course, and 61% of the students in the non-science major course. Again we found that many of the explanations provided were similar to statements made by students during interviews. The majority of these responses described an imbalance or interaction between valence electrons and the particles of the nucleus. While other explanations described the emission of valence electrons.

Approximately 20% of the students from each population attributed radioactivity to the particles in, or structure of, the nucleus. The explanations accompanying these responses typically focused on the abundance of either protons or neutrons. However, these responses were not always given for the correct reasons. As we found during the interviews, some students may refer to the nucleus in reference to radioactivity, even though they may claim that the instability of the nucleus is due to Coulomb forces between protons or neutrons.

While these results provide a good first step toward identifying students' beliefs about the structure of the radioactive atom, the information provided in the drawings and written responses was not always sufficient to infer a clear picture of the students' beliefs about the underlying cause of radioactivity.

Results from Combined Multiple-choice and Open-response Conceptual Question on Radioactive Decay Processes - To obtain a better understanding of what students think about the behavior of an atom during the radioactive decay process, we created a combined multiple-choice and open-response conceptual question shown below. This question was administered prior to instruction to students in the calculus-based course, the algebra-based course, the course for non-science majors, and in addition to students in a high school science course. It is important to note that the language used in choices A-E was designed to best reflect the natural language used by students during interviews and on open response questions. Choices B, C, and E were provided to represent the radioactive decay processes associated with alpha, beta, and gamma radiation respectively. For those students who think valence electrons play an important role in the radioactive decay process, we included choices A and D. It is worthwhile to note that although the events described in these choices (A and D) do not accurately reflect what happens during radioactive decay, these events do occur during other types of atomic processes such as ionization. From a instrument design standpoint, we were careful to couple the phrases "valence electron" and "from an atom" to best match the natural language used by students to describe the emission of electrons from their orbit about the nucleus when accounting for what happens to an atom during decay. By contrast, the phrase "from the nucleus" is provided to allow students aware of beta emission a choice that does not allow for the ambiguity that arises when the language "from the atom" is offered. There was an additional choice F provided for students that did not feel that the choices A-E correctly characterized what happens during the radioactive decay process. Students selecting choice F were asked to provide their own description of what they think happens during the radioactive decay process.

Circle the statement(s) which characterize(s) what happens during radioactive decay.

Response Type	Calculus Course (N=43)	Algebra Course (N=139)	Non-Science (N=76)	High School (N=19)
(1) Responses involving *only* valence electrons.	56%	39%	46%	37%
(2) Responses involving *only* neutrons, protons, and the nucleus.	33%	34%	32%	26%
(3) Mixed responses involving *both* valence electrons and the nucleus.	12%	23%	21%	37%
(4) Other	0%	4%	1%	0%

Table 2. Student responses by type.

If you do not like any of the statements, use the space at letter F to specify what would better characterize radioactive decay.

A. A valence electron is emitted from an atom.
B. Some combination of protons and neutrons are emitted from the nucleus.
C. An electron is emitted from the nucleus.
D. A valence electron drops to a lower energy level, releasing energy (emits a photon).
E. A proton or neutron drops to a lower energy level, releasing energy (emits a photon).
F. Other (specify):Explain your reasoning for each statement you circled.

With each choice, students were asked to explain their reasoning. In their explanations, we hoped that they would describe their thoughts about the underlying reasons or mechanisms that cause radioactive atoms to undergo decay. The following examples illustrate the wide range of reasoning used by students. The three letter acronyms CBS (calculus-based students), ABS (algebra-based students), NSS (non-science major students), and HSS (high school students) will be used to identify the student population associated with each example response. At the end of each example response, located in brackets, are the letters of the choice made by the student.

CBS: When a radioactive atom "decays," one of its valance electrons drops to a lower energy level. A radioactive atom is "unstable", one of its electrons has been moved to a higher electron orbit due to added energy. [A and D]

ABS: I know that valence electrons can drop to lower energy levels resulting in energy. I don't think an electron would be emitted because this would result in a different charge on the molecule, which I don't think happens. Protons and neutrons don't usually move around and they don't have energy levels. [D]

NSS: I would say D due to the release of energy. I'm thinking it can't be C or E because electrons aren't in the nucleus and protons or neutrons aren't in energy levels. [D]

ABS: Radioactive decay involves the disintegration of an unstable nucleus because there is a mismatch of protons and neutrons. So the nucleus ends up giving up one or the other to balance itself out. In doing this, it also gives up energy. [B and E]

NSS: I chose B because huge atoms can be unstable so they split. I chose C because a neutron loses its negative charge and becomes a proton in the nucleus. [B and C]

ABS: Protons and neutrons are emitted as both alpha and beta particles and electrons are emitted as energy. Electrons also give energy when they drop to lower energy levels. [A, B and D]

ABS: There is a decrease in mass during half-life and mass of an atom is in the nucleus, so you would need to release protons and neutrons. There also is a loss of radioactivity, so there must be an attempt at stabilizing the atom, whether it is emitting an electron or dropping it down a field to try to stabilize it. [A, B and D]

NSS: First the electron is lost. Then after enough electrons are lost there isn't enough negative charge so some number of protons and neutrons is released to get the atom back into balance. [A and B]

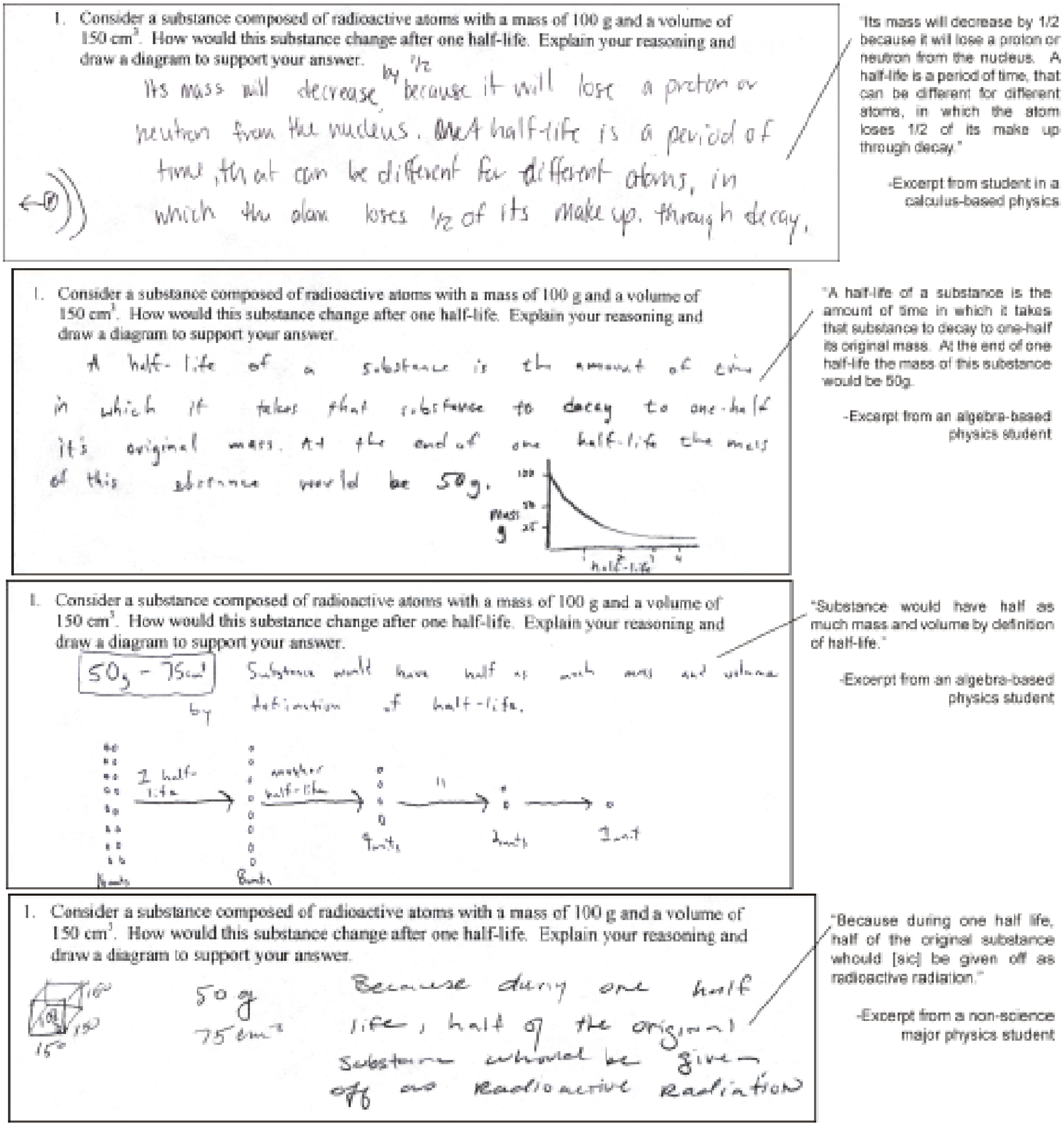
HSS: I chose A, B and D because protons, neutrons and electrons need to be emitted during radioactive decay since the system must get smaller. [A, B, and D]

CBS: The protons breaks down into a neutron and a positron, which is emitted from the nucleus. [F]

ABS: A combination of electrons, protons and neutrons is emitted. The reason is that radioactive elements are the highest number on the periodic table they decay because the electrons are so far from the neutrons that they can't be held in. Neutrons and protons must be emitted if the substance is to lose mass because the majority of the mass of a substance is in the neutrons and protons. [F]

For one analysis of this data, student responses were grouped together using a sorting schema based on four separate categories. The first category (1) reflects choices that involve only valence electrons and includes responses involving only letters A and D. The second category (2) reflects choices that involve protons, neutrons, and the nucleus and includes responses involving only letters B, C and E. The third category (3) reflects choices that include valence electrons as well as protons, neutrons and the nucleus. This category includes responses involving letters A and or D along with any combination of letters B, C and E. The fourth category (4) contains responses created by those students who chose only letter F. For the small number of responses (< 5% for each population) that included letter F along with another choice from letters A-E, the student response was categorized based on the student's choice from letters A-E. A summary of student responses to this question using this four-category sorting schema is provided in the Table 2.

To gain a better understanding of how many students included the idea of valence electrons in their responses we grouped together all answers that included the lettered choices A and D. This grouping includes responses from both categories (1) and (3). Responses involving valence electrons were provided by 68% of the students in the calculus-based course, 61% of the students in the algebra-based course, 67% of the students in the non-science major course and 74% of the students in the high school course. Perhaps most interesting is the low percentage (approximately 30%) of students from each population that correctly provided responses in



Figures 4, 5, 6, and 7. Student explanations of radioactive half-life.

which the process of decay was limited to only the nucleus.

We found that many students' understanding of radioactivity inappropriately involves the idea of the valence electron. Student beliefs regarding the role of the electron in connection with radioactivity typically involve reasoning about:

1. The electric charge of the electron or net charge of the atom due to the number of electrons.
2. The energy associated with the electron, including the emission of radiation due to electron state transition.
3. The interaction of electrons with protons or neutrons.
4. The activity or motion of electrons, including the ejection of electrons from the atom.

Responses that involved only the nucleus were again typically centered on limiting the abundance of, or imbalance between, protons and neutrons. In some of these cases, students used language such as "too heavy," "too many," and "above a certain number" in their responses. Other explanations emphasized changes in the mass of the nucleus or atom. Some students indicated that they were aware of alpha, beta, and gamma radiation; however, these students were typically unable to explain correctly the relationship between nucleons and the radiation emitted.

A small number of students provided responses consistent with the belief that radioactivity could be

Response Type	Calculus Course (N=39)	Algebra Course (N=65)	Non-Science (N=39)
Correct	39%	29%	23%
Little or no decrease in the object's mass and volume	26%	14%	15%
Half the atoms have decayed, transformed or changed. Only half the atoms are now readioactive.	13%	15%	8%
Incorrect	61%	63%	49%
Mass will be .50 g and volume will be 75 cm^3.	51%	51%	23%
The object will now have half the original mass or volume. Half of the original object will be left or lost.	10%	12%	26%
Other	0%	8%	28%

Table 3. Student response to radioactive decay half-life question.

induced in a stable atom. These unexpected, but very interesting, student responses typically attributed this induced radioactivity to either the absorption or emission of energy or particles. In these cases it is worth noting that there were not any students who correctly depicted neutron bombardment and gamma emission in their responses.

Up to this point, we have described how interviews, along with, open-response and multiple-choice questions, were employed in this investigation to triangulate students' understanding of the role the atom plays in the radioactive decay process. Guided by the insights gained from the research results reported thus far we next focused our investigation on students' understanding of radioactive half-life.

STUDENTS' BELIEFS ABOUT RADIOACTIVE DECAY AND HALF-LIFE

The concept of radioactive half-life is one of the most common topics covered during traditional instruction on radioactivity. For this reason, we felt that it was important to find out what students believe happens to a radioactive object as it decays over the period of a half-life. We were also interested in identifying to what extent students' ideas about irradiation and contamination, and the behavior of radioactive atoms during the decay process, would influence or be connected to their ideas about the concept of radioactive half-life. Again note that all students participating in the investigations described in sections A and B below were enrolled in undergraduate physics courses taught at a medium-sized research level-one university located in the Northwestern United States. Specific information on student population numbers and corresponding enrolled courses will be provided to accompany the specific phase of the research being reported.

A. Results from interviews on radioactive decay and half-life - As part of the interviews described in a previous section of this manuscript, we asked each of the students interviewed to provide their definition of half-life and to reason about the resulting changes that a radioactive object would undergo during the period of a half-life. The example responses provided below illustrate the very subtle ways students use the term half when describing what happens to an object undergoing radioactive decay for the period of a half-life.

- The time it takes for an object to become half of what it was before.
- Half-life is the amount of time it takes for the nucleus or a radioactive material to breakdown into half of its original form.
- We have some radioactive substance, after one half-life, only half of it will be radioactive.
- The half-life of an element is the time that it takes for half of that quantity to decay. This is essentially based on probability. You can say that with pretty decent certainty that given this amount of time, that half of this [the radioactive clay block] will be gone

As these examples show, students correctly attempt to incorporate the idea of time into their definition of half-life. Based on the statements: "half of what it was before," "breakdown into half of its original form," and "half of this [the radioactive clay block] will be gone," it is tempting to infer that these students believe that half of a radioactive object disappears after a half-life. We cannot be certain, however, that this interpretation is correct. It is also possible to infer that these students think that half the radioactive material has simply changed into something else.

To gain a better understanding of which interpretation is correct, and to focus this portion of the interviews, students were also provided with a 3 cm x 3 cm x10 cm rectangular block of clay. They were told to imagine that the clay was made of a radioactive substance that was undergoing radioactive decay. They were told that the block had a volume of 100ml and a mass of 100g. We then asked students to describe how much of the block would be left after the substance underwent radioactive decay for a half-life. Each student responded that either the mass and/or volume of a radioactive material would decrease by half in the period of a half-life. The responses provided by students during interviews illustrate how students' incorrect beliefs about radioactive decay can lead to inappropriate predictions about the physical properties of radioactive materials during a half-life.

Next, we will describe our investigation to find out which of the reasoning difficulties demonstrated by students during interviews are common among the general populations of students enrolled in introductory physics courses.

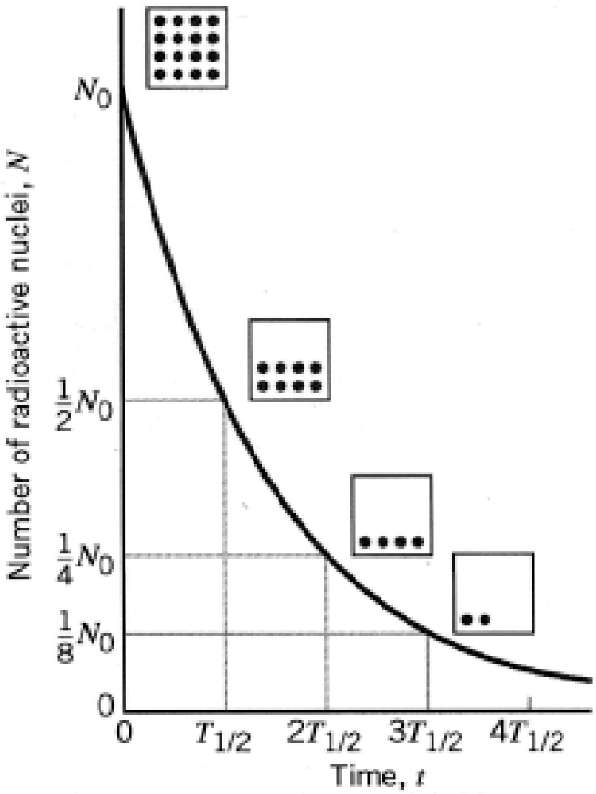


Figure 8. Graphical representation of radioactive decay.

B. Results from Open-response Conceptual Question on Radioactive Decay and Half-life - We designed an open-response conceptual question that was modeled after the mass and volume questions used during interviews. The question was administered to students in the calculus-based course, the algebra-based course, and the course for non-science majors. Students were asked to describe how a substance composed of radioactive atoms, with a mass of 100 g and a volume of 150 cm3, would change after one half-life. To help us interpret the student responses, we also asked students to explain their reasoning and draw a diagram to support their answer. Students were not explicitly asked to reason about the mass or volume of the radioactive object, nor were they instructed to perform any calculations. Figures 4-7 illustrate the types of drawings and explanations provided by students in response to this question.

A summary of student responses to the open-response conceptual question about half-life are provided in Table 3.

On average, half the total number of radioactive atoms in a radioactive object will decay in the period of a half-life. However, the total number of atoms in the object will remain constant. Furthermore, the mass of the emitted ionizing radiation is negligible in comparison to the total mass of the decaying atom. We would then expect the size, mass and volume of a radioactive object to remain nearly constant during radioactive decay. Responses consistent with this line of reasoning were provided by 39% of the students in the calculus-based course, 29% of the students in the algebra-based course, and 23% of the students in the non-science majors course. Students responding in this way typically ignored the information provided in the problem statement about the radioactive object's mass and volume.

Students also provided responses consistent with the belief that an object's mass and or volume will decrease by a factor of two during a half-life. Responses of this type were provided by 61% of the students in the calculus-based course, 63% of the students in the algebra-based course, and 49% of the students in the non-science major course. Note that 28% of the students in the course for non-science majors provided responses that were categorized as other. These responses were dominated by statements describing a decrease in the "life time" or "radioactive life" for the object.

Many students provided responses consistent with the belief that radioactive objects disappear or disintegrate during radioactive decay. These students often predict that the mass, volume, and number of atoms for radioactive objects decrease by half during a half-life. For many students it appears that the word half acts like a mental trigger that leads the student to divide by two. These students appear to perform this division without any further thought about the radioactive decay process. These reasoning difficulties likely stem from students' inability to properly reason about the radioactive decay process at the atomic (or nuclear) level. Unfortunately, even for those students who do have an understanding of radioactivity that involves the atom, they often also predict that half of the radioactive object will disappear after a half-life.

Students' incorrect beliefs may be reinforced by the information provided in the textbooks used in their physics courses. For an example of this see Figure 8. The drawing and description shown come from the textbook used in the introductory algebra-based physics course and were intended to illustrate the idea of radioactive half-life (Cutnell and Johnson, 1998). The description provided is particularly problematic, as it states that radioactive half-life is "the time in which one-half of the radioactive nuclei disintegrate." Also, note the striking similarities between this textbook's drawing and the drawings of students shown in Figures 6.

Potentially misleading statements about radioactive half-life can also be found in textbooks used in other disciplines. As an example, consider the following quote taken from an introductory general chemistry textbook (Kroschwitz and Winokur, 1990).

- Because radioactive elements disappear as they emit radiation and are transmuted into other elements they are said to disintegrate or decay

CONCLUSION

As the results presented here strongly suggest, many introductory science students enter the classroom with many beliefs about the nature of radiation and radioactivity that differ from the scientifically accepted beliefs of the discipline. As concerned instructors and researchers, we would like to better understand how these student beliefs affect the learning and teaching of radioactivity. One insight we can offer comes from a post-instruction assessment of students enrolled in an algebra-based introductory physics course. These students received approximately 3-hours of traditional lecture, 2-hours of recitation (focused on problem-solving) and 2-hours of laboratory investigation on radioactivity. We found that 59% of these students continue to believe that the mass and/or volume of a radioactive object would decrease by half in the period of a half-life. Furthermore, the reasoning and drawings provided with these responses indicate that these students still believe that a radioactive object disappears as it decays. Note that prior to instruction approximately the same percentage of students (63%) from the algebra-based course had responded that the mass and/or volume would change by half (Prather, 2000). These results illustrate how traditional lectures, laboratory experiments and homework problems can have little impact on the naive beliefs of these students. Not surprisingly, these students were able to carry out the necessary experiments, perform the required calculations, reach the anticipated conclusions, and yet emerge from this quite typical and traditional classroom intervention without becoming intellectually engaged at a level sufficient to obtain a fundamental understanding of the phenomena under investigation. This result is not unique to the topic of radioactivity. To the contrary, physics education researchers have shown that many students emerge from introductory level physics courses lacking a basic conceptual understanding of the course topics (McDermott and Redish, 1999).

The research base on student understanding of radiation and radioactivity is currently quite limited. There have been a number of studies conducted in Europe into the beliefs of middle and high school aged students on the topic of radiation and radioactivity. The results described here extend the research base to include the beliefs and reasoning difficulties of college level students in the United States. Furthermore, while our findings complement the findings of others, they also extend the research base to include: (1) students' understanding of the radioactive decay process at the atomic and nuclear level, and (2) students' understanding of the concept of radioactive half-life. And yet the most current articles published on teaching radioactivity not only fail to address these findings but continue to precisely model, if not promote, the naive beliefs students' hold about radioactivity and half-life (Fairman et al., 2003; Jesse, 2003).

If we want our students to develop a powerful understanding of science topics, it is necessary to treat the teaching and learning of science as a complex and interconnected system rather than a one-way transaction between the curriculum and the student. In particular, we must work to create a more effective instructional environment by taking into account student needs including their pre-instruction beliefs. It is, therefore, essential that we better understand and incorporate how students construct their knowledge and how this process is related to their current beliefs about the topics under investigation. Only then can a learning environment be established that appropriately challenges students and motivates deep intellectual engagement.

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