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Exploring Students Thinking of Atoms and Radiation with the Atom Builder Simulator

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Abstract

Although nuclear power is touted as an important future energy source, few Americans understand it. We are developing inquiry materials on radioactivity to address this literacy gap and have uncovered substantial student difficulties with thinking of atoms as sources or as victims of ionizing radiation. Learning about radiation requires understanding the general structure and properties of atoms. We wanted to characterize student concepts and find out whether using a new simulator would help them understand the behavior and structure of atoms. We used mixed methods to infer student ideas. Most students entering a survey level physics course had only vague ideas about the structure of atoms and had great difficulty constructing coherent mental models of atoms. For example, most did not relate atoms to elements. Some drew protons orbing the nucleus and others thought that "electron shells" or "membranes" hold electrons in place. Students knew very little about ions, isotopes and the radioactivity of atoms. These difficulties impair student understandings of the simplest radiation processes - emission and ionization. To scaffold Piaget's formal reasoning among students who reason concretely we developed an inquiry-based atom simulator. Using the "Atom Builder" students manipulate one atom at a time and observe its behavior. New inquiry-based activities guide student investigations into atoms. By the end of the unit student knowledge and understanding of atomic structure and ionization improved dramatically in comparison with lessons without the simulator. We will present ways of thinking about atoms that students brought to the classroom, and demonstrate how they developed using the inquiry simulator. This work is part of a three year curriculum development project supported by NSF DUE grant 0942699. The radiation materials and simulators are available online at www.camse.org/andy/radiation.

Keywords: Learning Research, Inquiry, Radiation

1. Introduction

The renewed push towards nuclear power and the ongoing crisis in Japan are taking place within a populace that is not well informed about radiation. Few non-science major college students can describe the properties and behavior of radiation or even of atoms. Prather uncovered student difficulties with radiation due to incorrect mental models of atoms [1]. When asked to draw a diagram of an atom, only 56% of non-science students in Prather's study drew Bohr-like atoms, and 23% drew atoms that had objects other than electrons orbiting the nucleus. Prather claimed that students' inabilities to correctly identify the locations and charges of parts of atoms influenced their understandings (or not) of the cause and origins of radiation.

Because atoms are so small and so far removed from everyday experience, formal reasoning (using Piaget's definition) [2] is required to understand them well. Ideas about atoms are abstract because they can't be directly observed manipulated. According to Piaget, comparing or relating two abstract ideas requires formal operational reasoning, and understanding atoms without directly experiencing them involves multiple abstract ideas.

Unfortunately, most college students do not reason formally [3]. Thus one can expect that teaching about atoms will raise severe difficulties.

This project has two goals: to address the radiation literacy gap and promote formal reasoning among students. We are developing and testing guided inquiry course materials on radiation and radioactivity for a survey-level college course or for high school physics [4] following the inquiry learning cycle model [5]. The content goals include identifying simple properties of radiation (particulate behavior, randomness, the natural background, no contamination by irradiation) and developing theoretical ideas (radiation ionizes atoms, radiation comes from certain nuclei, ionization as the mechanism for tissue damage, and others). The reasoning goals are for students to be guided by their observations in making explanations and to be able to apply their new ideas in different situations.

In past semesters we noticed students having trouble with theoretical explanations involving atoms. We wondered, "Could it be that these students just don't understand atoms?" Our answer is "they don't at first, but they can!"

2. Setting

The inquiry-based radiation materials are being developed and tested in a survey-level course in a small mid-western university. The current radiation materials have evolved into four main cycles and designed to help students construct a coherent model of atoms, ions, and radiation processes. Cycle 1 addresses background radiation, natural vs. man-made radioactive sources, the question of contamination by radiation, the names for 3 main types of radiation in nuclear waste, and the differences between electromagnetic and ionizing radiation. In Cycle 2 students study the structure of atoms, size, and the nuclear origins of radiation. For understanding atoms Cycle 2 is the most important of the 4 cycles. Cycle 2 helps students construct a viable mental model of atoms. Students in Cycle 3 discover the effects of radiation on matter including the effect on living tissue. One key idea for students is ionization of victim atoms by radiation particles. Cycle 4 focuses on nuclear fission, nuclear power, and nuclear waste. This final cycle brings all the main ideas together to enable students to understand half-lives, fission, and contamination. Our research focused on the radiation-related aspects of the content in Cycle 2**.**

The Atom Builder was created to address learning issues that arose from teaching the origins of radiation and ionization by radiation. It supports inquiry by affording investigation rather than offering explanations. The intent is to allow students to figure out the properties of atoms by doing "virtual experiments" in connection with guidance by documents. It is available at http://camse.bhsu.edu/sims/builder**.**

3. Data and Analysis

The purpose of our research was to identify students' ideas about atoms and find out whether and how the Atom Builder simulator makes a difference in learning. Data collected for this project came from classroom discussions and from students' written work. Homework assignments, weekly journals, quizzes, and exams were examined for clues on how students were thinking about atoms and radiation. Notes were taken in class during discussions and group work and in the Spring 2010 semester we interviewed all the students at the end of Cycle 2. In later semesters some students were interviewed.

We targeted six basic learning goals about atoms and radiation. These targets come from issues and topics that seemed to cause difficulties in past semesters. We believe these are necessary to understand radiation.

- **T1**: Distinguish the parts of atoms - both components and structures
- **T2**: Identify the element with the number of protons in the nucleus
- **T3**: Use electrostatic attraction to explain what holds electrons in atoms
- **T4**: Distinguish atoms from ions
- **T5**: Distinguish ions from isotopes
- **T6**: Associate radioactivity with nuclei

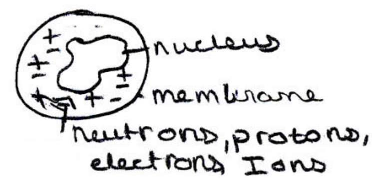
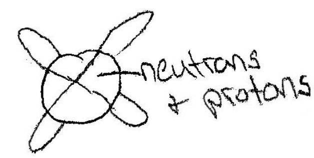
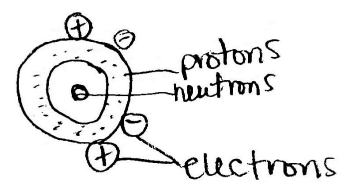
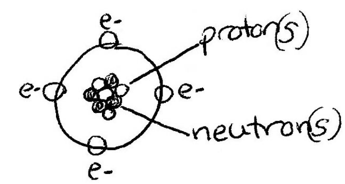
At the beginning of Cycle 2 students were given a sheet of questions and a discussion was held to identify students' initial thinking. The questions quoted below are from this sheet.

T1: *Draw a diagram of an atom, showing what you know about the parts of atom and where these parts are.* We identified the following categories in Table 1 from a sample of 72 student drawings from Spring 2010, Fall 2010, and Spring 2011 courses. 43 out of the 72 models could be used to explain ionization although some were not correct. Only 29 of the students coming into the classroom (40%) drew an atom model that was reasonably canonical.

"Circles" are simply one or more circles with no details offered. "Cell-like" atoms have an outside wall or membrane with atom parts or cell like parts inside. Students appear to be thinking of cells while drawing atoms. Neither of these models afford explanations for behavior of atoms. The Orbital diagrams comprised about 83% of student drawings, but only about 31% of the diagrams were acceptably correct.

Misplaced Particles models are probably a result of a mix of information students remember about atoms but do not show a real understanding of how atoms work. Students could potentially use the Bohr model to explain radiation and ionization. However, at the time students drew these diagrams based on our data most students would not have made those explanations.

TABLE 1. Categories Of Student Atom Diagrams.

Category and Frequency	Example Diagrams
Circles 6 Drawings	
Cell-like 6 Drawings	
Orbital Unlabeled 8 Drawings	
Misplaced Particles 23 Drawings	
Bohr (Reasonably Canonical) 29 Drawings	

T2: When asked *What determines which chemical element an atom is?* Only 6 out of the 74 students correctly pointed to protons alone. Ten students said that the number of protons, electrons, and neutrons determined the element. Many students said atomic number but it is not clear what they meant by "atomic number".

T3: Students were also asked *What holds the outer and inner parts of atoms together?* Eleven students offered explanations that could be interpreted as attraction between protons and electrons. Another 13 wrote something about "bonds" and other individuals mentioned "shells", "walls", or "gravity".

T4, T5, T6: Specific initial questions were not asked of students for these targets but responses on other questions and the discussions during the class suggested very low or no understandings of ions, isotopes, or where radiation comes from.

Also, most students did not initially identify electrons as the components that hold molecules together (important in understanding radiation damage), and in fact some were not clear about the differences between "atom", "molecule", or "element", sometimes combining these words with "cell". Many students also believed that it is not possible to change an atom - representing an element - into a new element. However, a few other students believed that the number of electrons determined the type of element. And as the cycle progressed students frequently surmised that ions must be radioactive.

4. Developing Atom Ideas

After the Initial Atom Ideas Discussion and a sticky-tape activity that introduced electric charge, students worked through an inquiry activity utilizing the new Atom Builder simulator [6]. This new simulator allows the user to build and modify all known atoms/nuclides from hydrogen to dubnium. It separates ionization phenomena from radiation emission and has additional pedagogical affordances. The atom builder identifies the element name of each atom but does not provide explanations for atomic phenomena. It is designed to behave similarly to a real physical object - reliably but mutely demonstrating behavior only. Students must interpret these behaviors.

Because students tend to conflate ionization with radioactivity, the materials separate these two behaviors which enables students to clearly distinguish the two phenomena. The first use of the simulator, (Activity 2.2) focused on the electron-proton balance (ionization). Students determined that any atom with an imbalance of protons vs. electrons would attract and repel other charged objects.

In a later use of the simulator (Activity 2.3), students studied effects of the neutron-proton relationship in nuclei (radioactivity). During this activity, students were able to create neutron-rich or large nuclei and observe radiation emission from their atoms. Students found that neutron-rich atoms emitted high speed electrons (betas) and large nuclei sometimes emitted high speed helium nuclei (alphas). Most emitted gammas as well.

In these activities students were guided to build specific atoms and investigate particular aspects of their behavior. During this activity we observed high levels of interested engagement while students talked about the identities, roles, locations, and numbers of protons, neutrons, and electrons in the their atoms. The students spent time playing with the simulator but started to use it to answer their own questions about atoms. In their explanations of what holds electrons around the nucleus, most student groups - who had done electrostatic experiments with sticky tape [7] - changed to an electrical attraction explanation when asked why electrons in the simulator were attracted to the atom.

5. Results

We used quiz & exam responses and student interviews to determine the extent to which students understood the six target ideas. Each idea was checked with two or more indicators from these data sources. To satisfy each learning target a student had to answer satisfactorily most of the indicators, which often required application of knowledge, not just remembering facts. Overall, we saw significant gains on our target indicators. Data from all three semesters is shown in Figure 1.

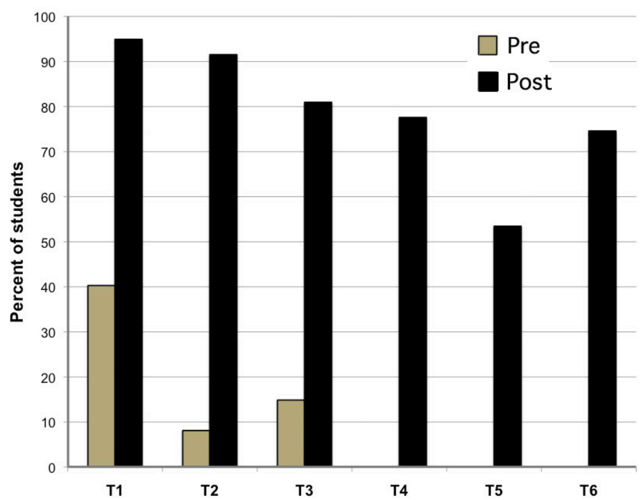


Figure 1. Percentage of students meeting targets pre and post

Students readily learned that protons determine the element name, and nearly 80% of students distinguished between ions and atoms. However, our students continue to have difficulty with two words – ion and isotope.

While we often observe students talking reasonably about numbers of electrons or numbers of neutrons, the terms ion and isotope do not seem to be helpful to them.

We had some interesting data in the 2010 Spring and Fall semesters suggesting the simulator alone is not enough. The exam question, *What does the word "ionizing" mean in the phrase "ionizing radiation"?* is a question that continues to show the difficulty of distinguishing radiation over ionization. Students often respond to this question by describing why a source atom is radioactive, which suggests that they have memorized the word "ionizing" without questioning what it means. The Spring 2010 students did very well answering this question and our Fall 2010 students struggled with it. We attribute the difference between the two semesters to a higher level of interviewing and questioning in Spring of 2010. The materials have been modified to support and require construction of coherent schemata about atoms and radiation and the Spring 2011 student's results showed substantial progress.

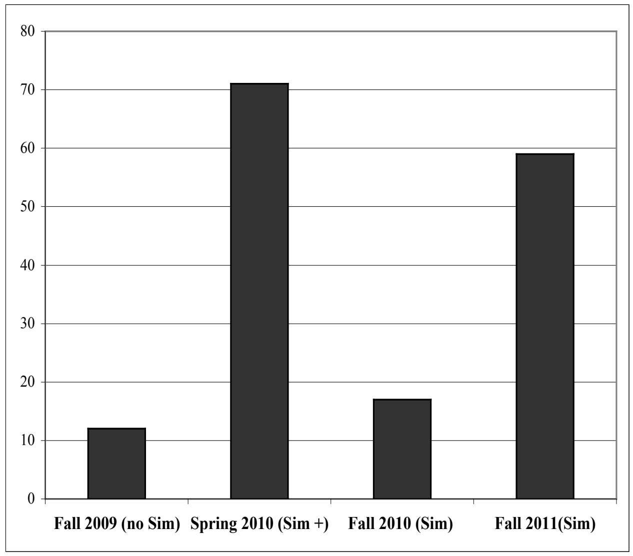


Figure 2: Student success rates on the ionizing question

6. Discussion

Most students entering this course didn't initially understand atoms. Although they had been taught about atoms (probably multiple times by the time they arrive at the course) students rarely had been expected to use atoms in formulating explanations. The majority of students in this class did not walk in with viable mental models of atoms. Instead they seemed to have fragments. Most students' initial explanations were in pieces, vague, or not coherent. Very few explanations were consistent with accepted ideas about atoms. (We have not yet investigated this topic with other groups of students).

Students who lack a working mental model of atoms may find it hard to understand where radiation comes from and what it does to atoms. In order to understand ionization by radiation one must know what an ion is. To understand that radiation comes from nuclei, it helps to know a little about nuclei.

6.1 Supporting student understanding of ionization by radiation

The data support the claim that students do not reason abstractly or fall into Piaget's category of formal operational reasoning. For example the ionizing question requires abstract thinking and it is easy to tell that students have difficulty answering that question. See figure 2. There was a dramatic difference between Fall and Spring 2010. Something fortunately happened either in classroom discussions or with repeated interviews that helped the Spring 2010 students answer this question. The extra interviewing done in Spring of 2010 apparently helped students work out basic details of radiation emission and ionization that allowed them to answer the ionization question correctly.

Most students struggle with developing a model of a radioactive atom emitting a particle from its nucleus and the emitted particle ionizing multiple atoms in its path. It requires that students have created a distinction between two different processes: how the particle is emitted from the source atom and what the radiation particle has the capacity to do to victim atoms.

Most students who failed to answer the ionization question correctly described radiation coming from an unstable nucleus. The process of radiation emission seen in the simulator is very memorable and unusual so perhaps the students related the term "ionizing radiation" to the emission process because of its salience. If students only memorize information but have not worked out basic relationships then they will have not worked out the two different processes or understand how the two processes are connected. They may assume that ionized atoms are radioactive which is not the case. As a result of poor student responses in Fall 2010 the course materials are now modified to better help students work out the important details of radiation. We have made progress - 60% of the class of 2011 gave answers that displayed an understanding of the two different processes.

6.2 Developing student capacity to reason about atoms

The Atom Builder simulator supports student reasoning about the atomic realm by providing an environment for concrete interactions with simulated atoms. According to Fuller et. al. [2], concrete reasoners need to reference familiar actions, objects, and observable properties when working with ideas about these objects. The Atom Builder is a new object that quickly becomes familiar to students even though it provides complex observable phenomena. The atoms portrayed on the screen take the place of abstract ideas that students would otherwise have to maintain for themselves, thus the level of reasoning required to make sense of atoms is lowered in the presence of the simulator.

It seems to fill a need - when students first encounter the Atom Builder, questions fountain from student groups. We have noticed each group spontaneously investigating and often answering questions that came to them. Students use it to investigate their own questions and sometimes figure out answers. (Of course, the guided investigations are helpful as well). The simulator affords a variety of different investigations. Students can decide what experiments to conduct and how to think about the results. Our data indicate that with this support students can develop useful and meaningful understandings about atoms in an inquiry setting.

After using the simulator in two guided activities, students are able to reason about atoms with the simulator present. This is an important success since it is the first time that these students have been able to correctly predict the behaviors of atoms based on their structure and properties. The students are learning to reason about atoms. However, we also want students to be able to reason about atoms without the simulator. A hallmark of formal operational reasoning is the ability to coordinate multiple abstract ideas. After students have worked extensively with the simulators, in-class discussions and homework assignments gradually encourage students to rely on their generalizations of atomic processes first observed in the simulator. Students who do this are developing their ability to reason formally about atoms.

7. Acknowledgments

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