Teaching Atomic Theory Using Photoelectron Spectroscopy Data

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Abstract: In this paper we describe our non-traditional method for teaching atomic theory in a large introductory undergraduate chemistry course. Using photoelectron spectroscopy (PES) data and teaching methods consistent with Constructivism [1, 2], students constructed an acceptable model of the atom without lectures or following the traditional historical development of the atom method for teaching students. Through test data, surveys, and interviews, we found that students learned atomic theory and had a positive attitude towards our PES Data Method. The PES Data Method is an example of how non-lecture methods can be successfully utilized in a large lecture course.

Atomic theory is one of the many challenging topics found in a first year general chemistry course. The abstract nature of atomic structure makes this topic difficult to understand for many undergraduate students. Because atoms and molecules are extremely small and not visible by the human eye, students are often forced to rely on the instructor who has had the opportunity to review relevant literature, experiments, and data to present a picture for them [3, 4]. This level of reliance means that the instructor has an even greater responsibility to use appropriate instructional methods to teach students about atomic structure than with other more accessible topics. Often, atomic structure, like most other topics in chemistry, is taught using a lecture-based instructional method. Spencer et al. [5] point out that even though lecturing is an efficient method to present material, it does not translate to sufficient learning. A strictly lecture format is a mismatch between the way the professor (expert) is presenting the material and the way the student (novice) learns [6, 7].

Our research group has been working on a new method of teaching atomic theory based on the Constructivist learning theory [1, 2] that attempts to bridge the gap between the instructor, material, and the student. We wanted to move from a teacher-centered lecture-based approach to a more student-centered method in which the students constructed ideas of atomic theory for themselves. Our method involved the students in our large lecture course using actual photoelectron spectroscopy (PES) data, simulated spectra, and a PES data sheet to construct a conceptual understanding of atomic theory. The use of photoelectron spectroscopy data provided an opportunity for the instructor to present authentic data to students for their own interpretation during the class. Through the exercise of interpreting the PES data, students developed the concept of atomic theory somewhat independently and were not as reliant on the instructor and the text as the only sources for their learning.

In this article we begin by exploring the problem we experienced with the traditional lecture method for teaching atomic theory. We then describe the rationale behind our method for teaching atomic theory before describing it in detail. We conclude with the results from data collected to begin the process of validating our method along with recommendations for other teachers looking to change the amount of traditional lecture format used in their classes.

The Problem as We Saw It

The traditional method of teaching atomic theory relies on an instructor presenting the concept in a lecture format that often requires students to take what is being presented as fact and to do so in a passive manner. Often the instructor presents atomic structure similarly to how it is presented in many general chemistry textbooks, which involves the use of a historical development of the atom and atomic structure (for examples see Ebbing and Gammon [8]; Brown, LeMay, and Bursten [9]; or Smoot, Smith, and Price [10]). As seen in these texts and based on our own experiences as both students and instructors of chemistry, instructors often illustrate discoveries or theories by Dalton, Thomson, Rutherford, Bohr, Millikan, and Chadwick. Then the instructor attempts to illustrate the mathematical probabilities of the quantum mechanical model of the atom using pictorial representations and 3-D models or digital renditions of the atomic orbitals. Next, the instructor provides a description of the four quantum numbers and explains how their values are determined. Finally, the focus shifts to describing the electrons using orbital diagrams and electron configuration schemes.

While it has been reported that the lecture method of instruction like that described above is an efficient method for the dissemination of large quantities of material [5], students are not able to make sense out of the material being presented. Spencer et al. [5] reported a study that after the first ten minutes of a typical lecture, 50% of the class is lost or
confused. This conclusion supports a study presented by Felder et al. [11] that states immediately after lecture students can recall 70% of the material presented in the first ten minutes and only 20% of the information from the last ten minutes of class (Also see Revell and Wainwright [12]; Tormey and Henchy [13]).

This disconnect for students is the result of multiple characteristics of traditional lectures. The traditional lecture method is primarily effective for the auditory learner, though for most learners there are two other primary modalities for learning: visual and kinesthetic [13]. Also, the traditional lecture method assumes all students can learn new information at the same rate [5, 7]. Finally, the traditional lecture method lacks any kind of meaningful dialog between the instructor and the students as well as between the students themselves, from which students feel left out and develop negative attitudes towards learning and the course [5, 12]. This type of instruction leads students to memorize facts and equations and focuses the students on learning algorithms in order to solve problems [4, 5, 7, 15].

Due to course constraints, the non-majors undergraduate course in which we were teaching atomic theory was set up in size and setting to be a lecture course. Understanding the problems of traditional lectures as described above, it was necessary for us to find a way to deal with these issues within a lecture setting.

Rationale for our Model

Even forced to work within the constraints of a large lecture, teaching practices can be employed that support the improvement of student learning. Cronin Jones [16] outlined research-based concepts that instructors should consider when lecturing to help deal with the pitfalls of the traditional lecture: active student involvement, relevance, interest, expert/novice differences, cognitive overload, scientific jargon, mental lapses, note-taking skills, confronting misconceptions, and learning modalities. The design of the PES Model for teaching atomic structure predominantly incorporates active student involvement, relevance, and expert/novice differences.

Active student involvement, a vital part of Constructivist theory, has been found to be crucial in students’ abilities to learn [2, 12, 15–17]. In the lecture setting active student involvement means bringing students into the lecture and not allowing them to sit back and attempt to passively take in the material. Active student involvement can take many forms such as having the students ask questions, quizzes the students during the lecture, asking for student interpretations of concepts, and having a student explain his/her understanding of a topic to the rest of the class or in small groups. The important component of student involvement is some sort of dialog about the topic [5, 14, 16, 18]. In our method for teaching atomic theory, we wanted to create a dialogue.

Relevance for the student is also important. Students need to believe that a reason exists for learning the material. This is particularly true for those students who are non-science majors because non-science majors in a science course often have less intrinsic motivation to learn the topic. If the students can see the importance of what they are learning, they are more likely to be able make sense out of the material [7, 15–17]. Our students did not see the relevance in learning atomic theory when we taught it using the traditional presentation of Dalton, Thomson, Rutherford, and Bohr theories. As such, the method we developed for teaching atomic theory did not utilize this approach.

Finally, we wanted to try to give the students some of the information the instructor knows in an attempt break down the division that exists between students and instructor. The instructor is the expert in the classroom. The instructor knows more about the topic than the students do. As such, the instructor needs to help the students connect the abstract concepts to more concrete ideas and periodically check for student understanding. This task is simpler when students are actively involved in the lecture because the tactics used in a student-centered class often provide constant feedback to determine the students’ level of comprehension [5, 7, 12, 14].

These ideas, active student involvement, relevance, and expert/novice differences, along with previous efforts by the fifth author, evolved into the Photoelectron Spectroscopy (PES) Data method for teaching atomic theory.

The PES Data Method

To begin we attempted to illicit prior conceptions and misconceptions of structural parts of atoms and molecules. First, we projected common representations of atoms and molecules (See Figure 1 for examples) and had the students describe what they saw. Students pointed out various parts or thoughts about the pictures. We recorded each comment for the class to see. It is important to note that all comments were posted regardless of whether or not they were correct. Highly controversial comments, like “The things outside the nucleus are brachtons,” often get corrected through the students’ discussion. After the students shared their responses with the class, we explained that they would work with photoelectron spectroscopy data to investigate our current understanding of the atom. We gave the student a sheet containing a schematic diagram representing lithium (Figure 2), a simulated photoelectron spectrum for lithium, and ionization energy data for the first twenty elements on the periodic table of the elements and a PES Data sheet (Figure 3).

We began this part of the lesson by discussing the schematic diagram (Figure 2) of an atom of lithium and explained the basic concept of how the PES data was collected. We showed the students that the location of each peak on the PES graph represents the energy needed to remove the electron and the size of the peak indicates the relative number of electrons that have the same energy. Once we have explained how to interpret the PES graph for lithium, the students were shown the PES graph for hydrogen (Figure 4). The instructor illustrated how to place the data from the PES graph of hydrogen on the displayed copy of the PES Data sheet. This depiction was done by placing a line at the appropriate energy in the column for hydrogen. The numerical value of the energy needed to remove the electron was written directly below the line. The size of the peak on the PES graph illustrates that hydrogen has only one electron and the number of electrons at that particular energy was indicated by placing the number “1” on the line that corresponds to the energy to remove that one electron. (Note: There are several energy values already depicted on the PES data sheet for the purpose of demonstrating the process and setting the energy scale.) Next we showed the students a simulated photoelectron spectrum for helium and plot the data on the PES Data Sheet. After helium, we gave the students a chance to try to interpret and place the data for lithium on the PES Data sheet. Together the instructor
and the students continued to fill in their PES Data sheets for the first eighteen elements on the periodic table (Figure 5).

After the PES Data Sheet was complete, we asked the students to identify any patterns they saw in the data. Students came to the board and wrote the patterns they saw in the data (Table 1). Again any pattern that was identified was listed on the board and became the basis for further discussion. The patterns generated by the students then drove the discussion of how the atom is structured.

Vocabulary was introduced as needed throughout the process. We continued to clarify vocabulary when it became apparent that students were using multiple words to describe the same items. We also used the correct vocabulary to try to clear up any misconceptions observed during the initial conversation about students’ preconceptions about atoms and molecules. The PES method then led to a discussion of orbital diagrams, electrons configurations, periodic table of the elements trends, and bonding.

The PES method seeks to use methods consistent with Constructivist theory and actively engage students in several different ways. From the beginning of the method students described their interpretations of different representations of atoms and compounds. Then the students discussed with their peers the observations made by other students. Conceptions about less scientifically accepted interpretations were politely challenged and corrected by other students. Students then interpreted and recorded data from PES graphs on the PES data sheet. We facilitated the discussion by asking the students questions as well as redirecting students’ questions back to the class at large.

Some students physically moved about the room during the class to help other students. One way in which students help other students was by coming to the front of the class and explaining how to graph the PES data. Once the PES data sheet was complete, we asked the students to identify and display on the classroom board trends they can found in the PES data. Again we acted as a facilitator of the discussion of the trends and worked with the students to help them construct their own knowledge of atomic theory. These actions used in the PES method are common among other non-traditional lecture-based teaching methods. Incorporation of the themes found in the PES method helps to enhance in student mastery of the chemistry content [19, 20].

### Evidence of Student Learning

Based on our research and our own experiences, we felt that the PES Data method for teaching atomic theory would be a successful teaching tool and would be well received by students, but we wanted evidence for support [21, 22]. We administered a pretest and posttest. The pre-test and post-test scores were first examined to see if there were any differences in the students’ performance before and after their exposure to the photoelectron spectroscopy method. Overall, the students’ post-test scores (mean [M]=9.8, standard deviation [SD]=2.2, n=101) were significantly higher than the pre-test scores ([M]=4.1, [SD]=2.0, n=101), t (100) = -25.0, p<0.005. The data from these tests showed that the students answered, on average, about twice as many questions correctly after using the PES method than prior to their experience. The course final exam contained nine questions about atomic structure. The average percentage correct for these nine questions for the exam questions was above 70%.
Table 1. Photoelectron Spectroscopy Data

<table>
<thead>
<tr>
<th>Element</th>
<th>First Peak</th>
<th>Second Peak</th>
<th>Third Peak</th>
<th>Fourth Peak</th>
<th>Fifth Peak</th>
<th>Sixth Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>He</td>
<td>2.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Li</td>
<td>6.26</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Be</td>
<td>11.5</td>
<td>0.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>B</td>
<td>19.3</td>
<td>1.36</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
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<td>1.72</td>
<td>1.09</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>N</td>
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<td>2.45</td>
<td>1.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>52.6</td>
<td>3.12</td>
<td>1.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>67.2</td>
<td>3.88</td>
<td>1.68</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>84.0</td>
<td>4.68</td>
<td>2.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td>104</td>
<td>6.84</td>
<td>3.67</td>
<td>0.50</td>
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<td></td>
</tr>
<tr>
<td>Mg</td>
<td>131</td>
<td>9.40</td>
<td>5.50</td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>157</td>
<td>12.5</td>
<td>8.0</td>
<td>1.10</td>
<td>0.59</td>
<td></td>
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<tr>
<td>Si</td>
<td>184</td>
<td>15.6</td>
<td>10.7</td>
<td>1.51</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>215</td>
<td>19.4</td>
<td>14.1</td>
<td>2.01</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>247</td>
<td>23.5</td>
<td>17.1</td>
<td>2.13</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>283</td>
<td>27.8</td>
<td>21.0</td>
<td>2.53</td>
<td>1.38</td>
<td></td>
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<tr>
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<td>321</td>
<td>32.6</td>
<td>25.1</td>
<td>2.92</td>
<td>1.58</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>361</td>
<td>38.4</td>
<td>30.3</td>
<td>4.08</td>
<td>2.46</td>
<td>0.43</td>
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<tr>
<td>Ca</td>
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<td>42.7</td>
<td>34.0</td>
<td>4.83</td>
<td>3.01</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Figure 5.

We also surveyed 101 students using an internally developed Likert-type survey and interviewed nine students. The students reported a high degree of understanding of atomic theory as a result of the PES Data method. Only one of the 101 reported that they did not understand atomic structure presented. Not only did the majority of students feel that they understood atomic structure, they also felt that by using the PES method they developed conceptual knowledge of atomic structure. Over 94% of the students felt that they had somewhat developed the concept of atomic structure through the use of the PES data. Students commented that they could visualize different elements’ structure by interpreting the data. One student wrote, “I would have been lost if I didn’t see how many electrons go in each level……” During an interview, a student commented that her knowledge of atomic structure “made it clear how you can get two elements to bond together…..” This connection demonstrates the student’s ability to apply her understanding of atomic structure to other topics in chemistry. Most students (74%; n = 101) felt the PES Data method was very useful in developing the concept of atomic structure. The students commented that the PES Data method provided clarity and put atomic structure in perspective for them. One student wrote “[The PES Data method] is simpler to understand and also [is] good because it has given me [an] additional way to visualize atomic structure, which makes it easier to understand.”

The surveys and interviews informed us that not only did students learn from the PES Data method, but they also had a positive attitude towards it. One of the reasons for this was because they were actively involved during class. Students reported that by working through the data together, it made atomic structure easier to understand. The students also enjoyed the instant feedback they received while working with the PES data. Students stated their appreciation and comfort level with being given the opportunity to answer a question and discuss it with other classmates and the instructor. As a result, the students were more confident with the material. Students who work through problems in a collaborative setting experience positive interdependence as a result [23, 24].

Concluding Remarks

As a result of our experience, we have concluded that the PES data method helps students increase their knowledge of atomic structure in a manner they enjoy, and so we continue to use it. Further research with this method is warranted. The PES Data method needs to be examined in different institutional settings involving different instructors and students. It should also be tested against the traditional lecture methods to determine if its effectiveness is less, equal to, or greater than the traditional method.

The PES Data method is grounded in the Constructivist learning theory, which promotes individuals constructing their own knowledge [1, 2]. The students were actively working with authentic data to arrive at their own conclusions about atomic structure with the instructor acting as the facilitator. The PES Data method is one method, among others, that have shown success with promoting active student involvement in the large lecture classroom (i.e. Jones-Wilson [24]; Oliver-Hoyo, Allen, and Anderson [26]. Students desire that we
continue to find methods like this to improve our teaching practice. Even though students admitted to being intermittently frustrated with the PES Data method, there was a general consensus that they were learning more as a result of this teaching style. The shift in teaching atomic structure from an instructor-centered paradigm to a student-centered paradigm is effective for student learning. The instructor is instrumental in equipping the students with the skills to become better learners. As a result, students with better learning skills subsequently become more productive participants in class and we become better instructors.

Institutional Review Board Approval
This research project was approved by the Institutional Review Board of Illinois State University for research with human subjects #2002–0344.

References and Notes