Students’ generated electron configurations of chemical elements: an explorative study

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Abstract. This study aimed to explore students’ understanding about electron configuration of chemical elements based on quantum mechanics atomic model. Sixty students from natural science education department participated in this study. A set of essay questions as was designed and validated through expert judgement and then was integrated into students’ final examinations for the Basic Inorganic Chemistry course within the academic year of 2017/2018. Data of students’ understanding were analyzed both qualitatively and quantitatively. The findings of this study revealed that most students made mistake in writing electron configuration especially when it comes to ions. Based on the analysis of the source of these mistakes, we provided recommendations to improve students’ understanding about this concept in the future learning.

1. Introduction
Electron configuration describes the distribution of electrons within an atom. The concept of electron configuration has been introduced since the discovery of Bohr atomic model. However, the electron configuration referred in this study was one that derived from the later atomic model – the quantum mechanics atomic model. This atomic model was proposed in 1927 based on Schrodinger’s equation, and according to this equation, there are four quantum numbers that should be included in an electron configuration. Those four quantum numbers are principal \( n \), azimuth \( \ell \), magnetic \( m \), and magnetic spin \( s \) quantum number [1]. Each electron configuration must be written in accordance with three basic rules known as the Aufbau’s principle, Hund’s rule, and Pauli’s Exclusion Principle [2]. Therefore, to write electron configuration correctly, students must understands the concepts of quantum numbers and three basic rules they should follow.

The two main concepts mentioned earlier must also be supported by sufficient knowledge of atomic symbol and atomic number; the concept of atom and ion, and also how to recognize the number of proton and electron. Literature reports have shown that students find the topic of electron configuration is difficult to understand [3], [4] which is related with the abstract nature of the concepts, and the need to establish a connection between relevant concepts. None of the students has seen an atom before, so obviously the concepts of atom, proton, electron, and ion are pretty abstract to them. Tsaparlis & Papaphotis even found that students did not have sound understanding about atomic orbitals [5]. Thus, their understanding most likely based on the knowledge from teachers or textbooks.
And this understanding must be related to other relevant concepts as explain earlier in order to construct a better understanding about electron configuration.

It has been known for long that each concept in chemistry has three level of understanding, as proposed by Johnstone, namely macroscopic, microscopic, and symbolic level [6]. Since atom is invisible to their eyes, the concept of electron configuration relies mostly on students’ understanding on both microscopic and symbolic level. This could be one of the reasons why students considered this topic difficult if they lack of understanding on these two levels. However, this difficulty does not always mean that students will fail to write electron configurations. From teaching experiences, we can tell that most students managed to write correct electron configuration for elements with atomic number of 20 or lower. This is not surprising. One possible method to solve chemistry problem is the memorization technique [7], especially because students have studied this topic in high schools. Also, various strategies have been implemented to challenge this difficulty (e.g. using analogies or mnemonic techniques [4] and students have been introduced to various algorithms to solve problems. Nevertheless, writing electron configuration for elements with higher atomic numbers (21 or greater) is another story. In other words, helping students to construct sound understanding about this concept remains a challenge to chemistry educators and researchers.

Elements with atomic number higher than twenty belong to the transition metal groups which occupy the third row in periodic table. Our observations in the field indicate that students often made mistake in writing electron configuration for these elements, especially when it comes to ions. We assumed that these mistakes are related to the pattern of energy splitting for the third energy level in an atom or higher, and also to the effective nuclear charge. From students’ perspectives, these two concepts are new. They probably never heard of the terms until they took the course of Basic Inorganic Chemistry. We believed that students in this study were familiar with the concepts of electron configuration and other relevant concepts since they have studied this topic in senior high schools and in their first year in the university. However, our observation last year indicated that many students still failed to write correct electron configuration of atom and ions, and also failed to explain its connection to the concepts of energy splitting and effective nuclear charge.

The subjects in this study are student teachers from natural science education department which were prepared to be a science teacher in elementary or junior high school. One of the basic competences they should possess is the professional competence, which related to their content knowledge. A science teacher should be able to help students to understand the natural world with its phenomena. Such understanding must be based on the understanding of the very basic material in the universe – an atom. Since the understanding of atom is fundamental, we were interested to explore what kind of mistakes or difficulty that these students have of face in writing electron configuration of chemical elements. There are two research questions we wished to figure out through this study: 1) how do students write electron configuration of chemical elements; and 2) what kind of mistakes or alternative conceptions that the students have regarding the concept of electron configuration?

Alternative conceptions could origin from various sources [8] and students naturally have these conceptions intuitively [9]. Here, we defined alternative conceptions as any scientific views, theories, and explanations that are different from what scientists agreed upon. Finding these conceptions are essential for teaching and learning process because once it is integrated into students’ cognitive structure, it will interfere the future learning process [9]. Students will be difficult to accept new knowledge that is not in accordance with the concepts in their cognitive structure, which could be inappropriate [7]. If these inappropriate understandings were held strongly by the students, they will fail to accept new knowledge and to apply their understanding to solve conceptual problems.

Our findings are expected to bridge the gap between teaching methods and learning outcomes in order to design a more effective lesson to address the difficulty. In particular, we aimed to gain insight on students understanding about electron configuration to be used as a consideration in reflection of learning process and in learning future lesson on the same topic; and to provide information for researchers and chemistry or science educators about students’ difficulty or alternative conception regarding the concept of electron configuration for future research.
2. Methods
Sixty six students from Natural Science Education Department enrolled in the course of Basic Inorganic Chemistry within the academic year of 2017/2018 participated in this study. There were five essay items prepared as our instrument, and these items have been validated through expert judgements prior to our study. These items required students to write electron configuration for both atoms and ions, namely: Co (Z = 27), Cr (Z = 24), Cr²⁺, Cu (Z = 29), Cu⁺, and Fe³⁺ (Z = 26). Though students in this study came from two classes, all of them learn the same material from the same lecture, with the same teaching methods and almost at the same time. In short, there was no different regarding learning process on this topic to all students. Data analysis was conducted both quantitatively and qualitatively. Quantitative analysis was focused on finding the number of correct and wrong answers generated by the students. Meanwhile qualitative analysis was focused on finding the type of mistake found among students’ answers. Based on these findings, we discussed what they indicate and what could be done to overcome such findings in the future.

3. Findings and Discussion
Our quantitative analysis gave result of percentages of correct and wrong answers generated by students, as can be seen in these following tables.
Figure 1. Students’ generated electron configurations for the given atom and ions

All chemical elements in our essay items are third period elements, they are transition metals. These elements were selected for two reasons. One, electron configurations for these elements are often found mistakenly written by the students, both for atoms and ions. Two, most students still failed to write the correct configuration for Chromium and Copper atoms, and eventually this will lead to the configuration for their ionic form. As can be seen in Figure 1, there are pattern in students answers for these elements: students’ answers for both Cr and Cu atoms are the same as well as for Co\(^{2+}\) and Fe\(^{3+}\) ions which means more than half students made mistakes. Even though nearly all students answer correctly for Cobalt atom, these contradictive findings about the other pairs of atoms and ions definitely indicate some misunderstanding or alternative conceptions that these students have.

If we go for more detail, for Cr and Cu atoms and for Co\(^{2+}\) and Fe\(^{3+}\) the numbers of students who wrote electron configurations correctly are slightly different: 28.8% for Cr and 25% for Cu – nearly one third of all students; 2.8% for Co\(^{2+}\) and 3.3% for Fe\(^{3+}\) which means very few students managed to write the configuration correctly. The same patterns also appear for students who made mistake in writing the configuration: 65.2% for Cr and 72.2% for Cu meanwhile 86.1% for Co\(^{2+}\) and 86.7% for Fe\(^{3+}\) which means almost all students failed to answer correctly. As for the configuration for Cobalt atom, 97% students managed to answer correctly while 3% of them made mistake. Overall, general trends in all items showed that almost all students made mistake in writing electron configuration for atoms and ions for transition metal elements.

Since we were determined to figure out what kind of misunderstanding or alternative conceptions that students have, we conducted qualitative analysis on students’ generated electron configurations. Furthermore, we tried to find a relation between electron configuration generated for atoms and ions.

In writing the configuration for Cobalt atom (Z = 27), there were only two students found to make mistake who wrote: 1s\(^2\) 2s\(^2\) 2p\(^6\) 3s\(^2\) 3p\(^6\) and 1s\(^2\) 2s\(^2\) 3s\(^2\) 3p\(^6\) 4s\(^2\) 3d\(^7\). Both answers do not have the correct number of electron which is only 18 and 21 out of the supposedly 27; the second answer has wrong arrangement of atomic shells at which the “2p\(^6\)” was missing. Based on these answers, we inferred that both students did not understand how to apply the quantum numbers in writing electron configuration and what rules they should apply.

Among all correctly written configurations for Cobalt atom, we found two kinds of configurations: one that follows the arrangement proposed by Aufbau (1s\(^2\) 2s\(^2\) 2p\(^6\) 3s\(^2\) 3p\(^6\) 4s\(^2\) 3d\(^7\)) and one that follows the grouping proposed by Slater in calculating the Shielding effect (1s\(^2\) 2s\(^2\) 2p\(^6\) 3s\(^2\) 3p\(^6\) 3d\(^7\) 4s\(^2\)). The first kind of configuration far outnumbered the second type. We predicted the reason behind this finding was because students are more familiar with the first type since they were still senior high school. Either way, both configurations are correct as long as the arrangement and the number of electrons are correctly written.
Electron configurations for Chromium and Copper atom are different to other elements in the third periodic. Following the Aufbau’s principle, their configuration should be \([Ar] \, 4s^2 \, 3d^4\) and \([Ar] \, 4s^2 \, 3d^9\) respectively. However, these two configurations do not match the result of experiment. On the other hand, Hund’s rule of maximum multiplicity requires electrons to be placed in orbitals to give maximum total spin possible (or the maximum number of parallel spin) [6]. Therefore, following Hund’s rule, the configuration for Cr and Cu atoms become \([Ar] \, 4s^1 \, 3d^5\) and \([Ar] \, 4s^1 \, 3d^{10}\) respectively. Most students were introduced to these configurations through the rule of “half-filled and completely filled d-orbital”, which stated that the atom will gain greater stability when its electrons are arranged this way. We assumed that this is the reason why we found some statement from students answer that “half-filled d-orbital is more preferable for greater stability” and such statement also appeared for Cu configuration. Our findings of students’ mistake in writing configuration for Cr and Co are presented in Table 1 below.

![Figure 2. Example of correct configuration for Chromium and Copper atoms](image)

Compared to the case of Cobalt atom, only a few students wrote correct electron configurations for both Cr and Cu. Based on the analysis of students’ wrong answers, we found three type of mistake as presented in Table 1 below. The highest percentages of “not in accordance with Hund’s rule” for Cr and Cu indicate that these students do not really understand the Aufbau’s principle. However, interestingly some students were found consistency in students answers. If they were right for Chromium atom, they must be right too for Cuprum, and vice versa. These facts indicate that these students have partial understanding about the rules for writing electron configuration, especially Hund’s rule. Thus, when it came to applying this rule to write electron configuration, most students failed.

![Figure 3. Consistency found in students’ configuration for Chromium and Copper atoms.](image)

If we go by the concept, this half-filled and completely-filled configuration for Cr and Cu is actually resulted from the energy involved in the configuration. As explained by Rich in [2] which based on Hund’s rule of multiplicity: the repulsive electrostatic force between two electrons in one orbital adds the electron pairing energy. As the nuclear charge increases, the electrons are strongly
attracted and the energy levels decrease so that the configuration becomes more stable. In addition, this greater stability is also associated with the shielding effect among electrons in 3d-orbitals. These electrons have equal energy but different spatial distributions which result in small shielding effect of one another [1]. Thus, the electrons are attracted much stronger to the nucleus when the configuration is 3d5.

| No. | Type of mistake/ example from students’ answers |
|-----|-----------------------------------------------|
| 1. | Wrong number of electron (2.3% for Cr and 7.7% for Cu) |
| a. | [Example image] (total electron = 18) |
| b. | [Example image] (total electron = 22) |
| c. | [Example image] (total electron = 27) |
| 2. | Correct number of electron but wrong arrangement of atomic subshells (14.0% for Cr and 15.4% for Cu) |
| a. | [Example image] (missing the “4s2” part) |
| b. | [Example image] (4s-orbital is filled with three electrons instead of the supposed d-orbital). |
| 3. | Not in accordance with Hund’s rule (83.7% for Cr and 76.9% for Cu) |
| a. | [Example image] |
| b. | [Example image] |

There could be several reasons behind our findings of these three types of students’ mistake, for instance: not knowing the order of subshells according to Aufbau’s principle, not knowing the meaning behind numbers and letters in a configuration (e.g. 3p6), or miscalculation on the number of electrons. However, we found it interesting that even though these students have studied electron configuration twice prior to this course, they still failed to remember that Chromium and Copper have irregularities in their configurations compared to the other third period elements.

Writing electron configuration for ions requires sound understanding about the concept of ions, especially cation in this case. A study by Bio, et.al. found that writing configuration for ions is slightly more difficult than neutral atoms [3]. One possible reason is the process to form a cation which requires an electron to be released. The electron being released is the one that is least attracted to the nucleus (the outer electron). In order to form a cation, for example Co2+ and Fe3+, each atom must release two and three electrons respectively from its outer shell. This outer shell can be determined through its electron configuration. This is the part when students failed the most. Even though students know that outer electron(s) should be released to form a cation, the electron configuration will not be correct unless they know from which outer shell electron should be taken out.
Based on the Aufbau’s principle, electron configuration for Cobalt is \(1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^7\) and for Iron is \(1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^8\). The outer shell in electron configuration is shown by the highest principal quantum number \((n)\) in it. For Co and Fe, the outer shell is the fourth shell \((4s)\). Thus, when they form a cation, electrons in their fourth shell should be released. Therefore, the configuration for \(\text{Co}^{2+}\) should be \(1s^2 2s^2 2p^6 3s^2 3p^6 4s^0 3d^7\) and for \(\text{Fe}^{3+}\) should be \(1s^2 2s^2 2p^6 3s^2 3p^6 4s^0 3d^5\). Just like a self-fulfilling prophecy, in our findings most students wrote: \(1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^5\) for \(\text{Co}^{2+}\) and \(1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^7\) for \(\text{Fe}^{3+}\). Thus, we inferred that most students know two and three electrons should be released, but they failed to determine the outer shell from which the electrons should be released.

**Figure 4.** Examples of correct answer of configuration for \(\text{Fe}^{3+}\) and \(\text{Co}^{2+}\) ions

As presented earlier, very few students managed to write electron configuration for \(\text{Co}^{2+}\) and \(\text{Fe}^{3+}\) ions correctly. The type of mistakes we found is presented in Table 2 below.

| No. | Type of mistake/ example from students’ answers |
|-----|-----------------------------------------------|
| 1.  | Wrong arrangement of atomic subshells (3.2\% for \(\text{Co}^{2+}\) and 34.6\% for \(\text{Fe}^{3+}\)). |
| a.  | ![Example](image) |
| 2.  | Misunderstanding on the arrangement of atomic subshells and its relation to effective nuclear charge (71.0 \% for \(\text{Co}^{2+}\) and 38.5 \% for \(\text{Fe}^{3+}\)). |
| a.  | ![Example](image) |
| b.  | ![Example](image) |
| 3.  | Misunderstanding on the concept of ion (25.8\% for \(\text{Co}^{2+}\) and 23.1\% for \(\text{Fe}^{3+}\)). |
| a.  | ![Example](image) |
| b.  | ![Example](image) |
| c.  | ![Example](image) |
| d.  | ![Example](image) |

Wrong number of electrons could be caused by students’ miscalculation. However, the highest percentage goes to the misunderstanding on the arrangement of atomic subshells and its relation to effective nuclear charge. This type of mistake could be associated with students’ misunderstanding of...
the Aufbau’s principle. Aufbau stated that subshells in a configuration should be arranged based on the increase in energy levels, from the lowest to the highest. It is possible that most students forgot that this arrangement does not mean the last written subshell is the one with the highest principal quantum number especially for third period elements. This is where the students failed the most.

![Figure 5. Student’s predicted thinking procedure in writing configuration for Fe$^{3+}$ and Co$^{2+}$ ions.](image)

From Figure 5a above, despite the mistakenly written configuration, we could see the student simply subtracted the number of electron in 4d-orbital, from 6 to 3. Thus, we could infer that this student knew how that Fe$^{3+}$ is formed when three electrons are removed but he did not understand which electrons should be removed. Slightly different, from Figure 5b, the student initially wrote two configurations. One is based on Bohr’s atomic theory and the other one is based on the quantum mechanics theory. It can be seen that this students took “7” as the number of electrons in the outer shell of Cobalt atom, and those electrons occupy the 3d-orbital, from which he took the two electrons to form Co$^{2+}$ cation. We could infer that this student has two problems. One, he mistakenly wrote the Bohr configuration for transition elements. He should have known that Bohr’s configuration has limitation when it comes to elements with atomic number greater than twenty. The written “2.8.8.7” does not state that there are seven electrons in the fourth energy level of Cobalt atom. Two, this student did not understand the Aufbau’s principle thoroughly, which he mistakenly took 3d instead of 4s as the outer subshell of Cobalt atom. In fact, the configuration in Figure 5b is what we found the most among students’ answers. This finding matches the result of a study by Fitriza & Gazali [8] in which students preferred to write configuration for atoms and ions based on Bohr’s atomic theory than the Aufbau’s principle of the quantum-mechanics theory.

4. Conclusion
From this study we found that most students wrote electron configurations based on the order of fulfilling orbitals from the lowest level of energy to the higher ones (the Aufbau’s principle). However, when it comes to the third period elements (from Scandium to Zinc) whose electrons start to occupy d-orbitals, students must be informed that it is okay to write 3d before 4s or 3d after 4s, as long as the number of electrons is correct. This is hopefully sufficient to avoid misunderstanding on writing electron configuration for ions especially cations.

Among the three rules for writing configuration, students were found to lack in understanding the Hund’s rule of multiplicity. Since this related to the energy of electrons, students found this rule difficult to understand and later on to apply in writing electron configuration. Most students prefer to state the rule as “half-filled and completely-filled d-orbitals are more stable” to explain about multiplicity. Just like the case of the Aufbau’s principle, sound understanding of Hund’s rule could avoid misunderstanding in writing configuration for cations later on.

Despite the fact that students have studied this topic in senior high school and in the first year of university, they still failed to provide appropriate explanation to the given problems. Thus, we recommend that the learning process should be more emphasized on establishing the connection between interrelated concepts and constructing sound understanding. Students should also be introduced to the way of higher order thinking in order to provide appropriate explanation about natural phenomena to achieve the goal of science learning.
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