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100 Years Anniversary of the Bohr Model of the Atom: How Chemistry Freshmen Understand Atomic Structure of Matter

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Abstract: Hundred years ago the Danish physicist Niels Bohr presented his model of the atom for what he received Nobel Prize. His theory led to the revolutionary development of science in the beginning of 20th century. Later one, quantum mechanics developed a new theory explaining all the shortcomings of Bohr's model. However Bohr's atom theory is presented and studied in most introductory General Chemistry textbooks. This anniversary was an opportunity to see how science students understand and visualize the structure of the atom. The data reported in this paper derived from a pilot research with 58 chemistry freshmen, were collected to explore their ideas of an atom, their knowledge about the Bohr model of the atom, and history and philosophy of science approach to Bohr atomic theory. Students' knowledge about Bohr's postulates is in agreement with chemistry textbook content except the part about Bohr's idea of angular momentum quantization, which they discuss within the General Physics 2 course. Using historical point of view when studying Bohr's theory and his model of the hydrogen atom can help students to understand contemporary theory of the atom better.

INTRODUCTION

The 100th anniversary of the Bohr model of the atom is an opportunity to check whether science students are aware of Bohr's contribution to the revolutionary development of science at the beginning of 20th century. In 1922, Danish physicist Niels Bohr received Nobel Prize in the field of theoretical nuclear physics "for his services in the investigation of the structure of atoms and of the radiation emanating from them" (The Nobel Prize in Physics 1922). Victor Weisskopf (1985) placed Niels Bohr at the level of great scientists saying that "his name ranks beside Galileo, Newton, Maxwell and Einstein". Weisskopf highlighted his colossal role in the human problems related to the science, society and politics. Bohr's contribution to science has been important for the understanding of atomic structure and for the development of quantum mechanics ideas (Bentzen, 2000). The Bohr model of the atom has been used for decades as a useful atomic model in physics and chemistry education. Today, this model of the atom has its historical value. It was the first atomic model offering explanation for paradoxical stability of the Rutherford model of the atom (Bohr, 1913; Niaz & Costu, 2009) and explanation of hydrogen line spectrum (Niaz & Costu, 2009). In the Bohr's Nobel Award lecture (December 11, 1922), his two central topics were the periodic table and an atom of an element. According to our present understanding, an atom of an element is built up of a nucleus that has a positive electrical charge and carries the greatest part of the atomic mass. Negatively charged electrons move around the nucleus at the distances that are very great compared to the dimensions of the nucleus or of the electrons themselves. In this picture, we at once see a striking resemblance to a planetary system, such as we have in our own solar system (Bohr, 1922).

In the *Philosophical Magazine,* Niels Bohr published the three papers under common title „On the Constitution of Atoms and Molecules''. The first paper appeared in the July 1913 journal issue where Bohr was focused on the hydrogen atom. His second paper was published in the September journal issue covering the atomic theory of the complex atoms, and Bohr published the last paper in November of 1913 where he considered the structure of molecules. Bohr proposed his atomic theory based on the postulate of stationary electron orbits and frequency postulate. Bohr's theory was successful when applied to the simplest element, the hydrogen atom and ionized helium, but failed for systems such as the hydrogen molecule and helium atom (Kragh, 2011). Bohr's paper on atomic structure was "a highly original and truly revolutionary contribution to physics that more than anything reflects Bohr's own genius" (Bentzen, 2000).

Niels Bohr used an idea, introduced by Planck in 1900, of the atomic quantization for finding a solution for the atomic stability, but he did not try to find a theoretical solution for the Balmer and Pashen line spectra. In that time Bohr was influenced by Planck's and Einstein's quantum theory ideas and by work of many other scientists as he said:

"In the following years many efforts were made to apply the concepts of the quantum theory to the question of atomic structure, and the principal emphasis was sometimes placed on one and sometimes on the other of the consequences deduced by Einstein from Planck's result. As the best known of the attempts in this direction, from which, however, no definite results were obtained, I may mention the work of Stark, Sommerfeld, Hasenöhrl, Haas, and Nicholson" (Bohr, 1922, p. 14).

The Bohr model of the atom is a quantum physics-based modification of the Rutherford model of the atom which replaced the Joseph John Thompson model of the atom based on his first paper "installments on the atomic structure" (Heilbron, 1977). Bohr did not have any intention to explain Balmer's formula for calculating the wavelengths of the spectral lines of the hydrogen atom line spectrum. Victor Weisskopf (1985) highlighted the importance of Bohr's contribution in quantum mechanics and its development that brought „a true revolution in our thinking ...in the new system of concepts and a new way of dealing with atomic structure was introduced; it revolutionized our ideas of material reality".

Several studies were conducted about how models introduced by Thomson, Rutherford and Bohr have been included in the general chemistry textbooks from History and Philosophy of Science point of view (Niaz, 1998; Rodriguez & Niaz, 2002; Niaz & Costu, 2009). The most emphasized textbook contents were based on the experimental details and heuristic principles of the atomic structure and lacks of context on the history and philosophy of science (Niaz & Cosku, 2009). Atomic structure has been found as one of the most difficult concepts for students at high-school and university level of education within both chemistry and physics courses (Niaz, et al., 2002; Taber, 2003; Nakiboglu, 2008). Keith Taber (2003) found that students learn about four atomic theories (theory by Thomson, Rutherford, Bohr, and Quantum Mechanical Theory) using textbooks and shows some difficulties in understanding a basic concept of the atom, very often presented as „ a confused amalgam of historical models".

Igal Galili (2008), answering to the question „Why to teach physics using history?", gave a claim based on his research results, that the history of physics (HoP) is a tool for teaching physics. Galili answering to mentioned question gave his view about three distinguished stages how to include HoP in the process of learning physics.

(1) The HoP helps students to better understand physics. Galili has explained that „the historical contents familiarize students with the way of doing physics, the nature of physics as a method of human exploration and learning about the Nature".
(2) The HoP helps students to use knowledge of physics for practical application in the process of problem solving, using as Galili said „the argumentation employed by scientists in the past in illustrating the contents they teach and persuading their students to consciously reconstruct and build the new for them knowledge".
(3) The HoP is a basic stage for physics knowledge as main structure elements of discipline-culture paradigm that provide a connection between the past and new knowledge in science.

Science teaching and history of science should be connected at four levels: interest level (includes story based information about scientists, experiments, scientific theory developments methods), socio-cultural level (includes connections between science and society), epistemological level (for introducing scientific inquiry concepts by scientist from the history of science), and conceptual level for including information about „historical development of the concepts to help students understand scientific concepts" (Seker, 2011).

Our main aim in this study was to investigate the effects of knowledge integration of history of science dealing with Bohr model of the atom and how knowledge transition from chemistry course to physics course is achieved when students' perception of atoms is used. Learning about atomic models is content of both General chemistry and General physics course syllabi at Bosnia and Herzegovina universities within the first year of science study.

Chemistry freshmen under this study learn about three atomic models (given by Thomson, Rutherford and Bohr) in last year of secondary school and again within both General Chemistry 1 and General Physics 2 as a part of introduction to the quantum mechanical theory (QMT). The data reported in this paper derived from a pilot research with 58 chemistry freshmen, were collected to explore their accepted idea of an atom, knowledge about the Bohr model of the atom, and history and philosophy of science perspective of Bohr atomic theory.

A BRIEF REVIEW OF THE BOHR MODEL OF THE ATOM

There are several interpretation and versions of the Bohr's postulates first presented to the scientific community in 1913, in different textbooks used by student included in this study in both courses (general chemistry and general physics). The Bohr's first and second postulate as a core of his Nobel lecture presented in the Swedish Academy of Sciences in 1922 is as it follows.

Bohr's postulate one (BP1)

„Among the conceivably possible states of motion in an atomic system there exist a number of so-called stationary states which, in spite of the fact that the motion of the particles in these states obeys the laws of classical mechanics to a considerable extent, possess a peculiar, mechanically unexplainable stability, of such a sort that every permanent change in the motion of the system must consist in a complete transition from one stationary state to another".

Bohr's postulate two (BP2)

„While in contradiction to the classical electromagnetic theory no radiation takes place from the atom in the stationary states themselves, a process of transition between two stationary states can be accompanied by the emission of electromagnetic radiation, which will have the same properties as that which would be sent out according to the classical theory from an electrified particle executing an harmonic vibration with constant frequency. This frequency ν has, however, no simple relation to the motion of the particles of the atom, but is given by the relation

$$h\nu = E' - E''$$

where h is Planck's constant, and E' and E'' are the values of the energy of the atom in the two stationary states that form the initial and final state of the radiation process. Conversely, irradiation of the atom with electromagnetic waves of this frequency can lead to an absorption process, whereby the atom is transformed back from the latter stationary state to the former"(Bohr, 1922, p.15).

Textbooks prepared by local or international textbook authors, contain different Bohr's postulate expressions. Basically, Bohr's postulates are included in many investigated textbooks recommended by syllabi in the manner shown here (as Bohr's original postulates marked as BP1 and BP2). But in some textbooks, mostly in physics textbooks, there is an addition to the first Bohr's postulate expression. A difference is related to the size of the allowed electron orbit which is determined by a condition imposed on the electron's orbital angular momentum. The allowed, electron orbits are those for which the electron's orbital angular momentum is given by relation

$$m_e v_n r_n = \frac{h}{2\pi} n$$

where m_e is the electron's mass, v_n and r_n is the electron velocity and radius respectively in a certain stationary state, *h* is Planck's constant, and n is the principal quantum number (Serway & Jewett, 2006, p. 353).

The Bohr's theory had several limitations, but Bohr's model of the atom was "a first picture of what an atom is like" (Giancoli, 1998, 859). The Bohr theory did not explain why intensity of some spectral lines is different, and how atoms are connected in molecules. The Bohr theory was a mixture of classical and quantum theory without a wave-particle duality ideas. In the same time, the Bohr model of the atom and the Bohr theory was an impetus for finding a comprehensive theory to solve theoretical problems opened in the early 1920s, thus giving him a great role in the history of science. The Bohr model of the atom was replaced by the quantum mechanics model based upon the Schrödinger equation in the 1920's.

METHOD

Sample

The sample of this study consists of N = 58 chemistry freshmen (c. 19-22 years of age). Of these students, 80% finished *Gymnasium* (secondary school) education, and 20% of students came at university from the technical secondary school environments. All participating students did not differ in the number of years of studying chemistry at secondary school level (four years).

Students were given a worksheet containing three rubrics and were advised to give answers to the each of three questions. The data collection took place from April to May, in the spring semester of the first year of chemistry study at university.

Worksheet rubrics

The worksheet rubrics created to explore students' knowledge and attitudes toward the Bohr model of the atom contains questions and tasks as follows:

Rubric 1: Draw a sketch of an atom as you imagine it and give the explanation of your idea about atoms.

Rubric 2: In the provided space, you are asked to express your knowledge about the Bohr's postulates that have appeared at scientific scene 100 years ago, according to the Bohr model of the atom as you know it.

Rubric 3: Do you think that Bohr atomic theory was revolutionary idea at that time? If yes, explain why?

Students' concept of atomic structure was included as a target variable for which knowledge integration effect was assumed. It is important to note that a need for knowledge integration and transfer effect related to the students' scientific view of atoms has not been highlighted in both syllabi content (General Chemistry and General Physics course). There are not any highlighted learning strategies for achieving students' common general physics and chemistry courses outcomes. As a numerous research showed, students usually have a difficulties to understand atom structure as is explained by modern quantum theory (Harrison and Treagust, 2000; Taber, 2002).

RESULTS AND DISCUSSION

Worksheet rubric 1 results

In this study, focus was directed to the historical models of atom proposed by: Dalton (the atom as a sphere), Thomson (the atom as a positive sphere filled by electrons), Rutherford (planetary model of atom), Bohr (the atom as a nucleus that electron orbit it) and quantum-mechanical model of the atom or Schrödinger theory (the atom as a nucleus surrounded by an electron cloud).

The students were divided into four groups depending on visual-textual representation of atoms (in students' minds) and giving their personal views of atoms.

Model of the atom 1/MA1: students who built-in the Thomson model of the atom;

Model of the atom 2/MA2: students who presented the Rutherford model of the atom;

Model of the atom 3/MA3: students who presented the Bohr model of the atom;

Model of the atom 4/MA4: students who included in their representations one or more elements of the quantum-mechanical model of the atom (the Schrödinger theory).

Students' answers distribution among such defined groups is shown in Figure 1.

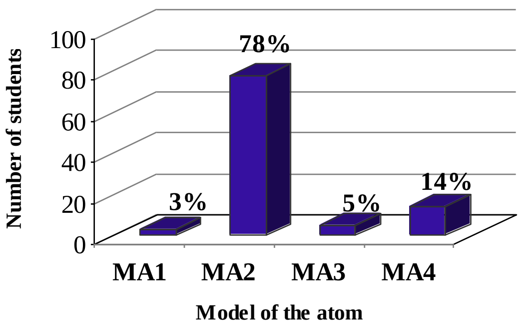


Figure 1. Distribution of student visual-textual representations of model of the atom.

MA1: Students gave a model of the atom that presented their visual-textual representation of atom as a sphere uniformly filled with positive electricity, and with electrons inside the sphere. This model is a characteristic Thomson's classical picture of the atom as whole a neutral particle.

MA2: Students' model of the atom is a planetary model as a system of positive nucleus which is a massive center of atom and with negative electrons distributed that travel about the nucleus along circled trajectories.

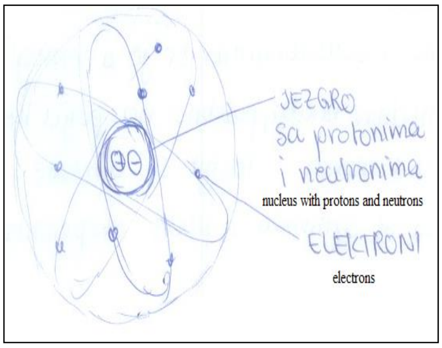
MA3: Students presented their model of the atom as Bohr model of the atom with additional information. They mentioned infinite multitude of electron orbits that are existing as a discrete orbits in the proper quantum conditions. In this stationary state atom does not emit or absorb electromagnetic energy. The emission and absorption of the light occur only if an electron jumps from one energy level to another.

MA4: An atom with its particles is described by wave function where the square of the magnitude of the wave function gives the density of the probability of finding an electron in certain place in area around nucleus. The electrons are in electronic cloud (complex shapes of orbital) without a definite locations and trajectories. In this model of students' views of atoms, characterization of an electron named as s-electron, p-electron, d-electron, f-electron are given.

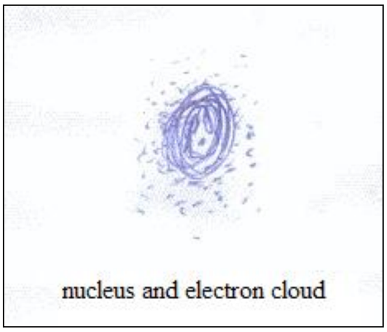
Four students gave textual explanations showing the atom as a sphere (Dalton's approach), but three students wrote down their statements about atoms being the smallest particles of matter.

Students included in this study mostly presented their ideas about atoms using Rutherford's model as an expression of their prior knowledge of the particle model of matter introduced to them in ages 13-15 during their primary school education. A possible reason for the fact that only few of students gave their pictures of atoms according to the modern scientific model of the atom is that, students have usually difficulties to understand the particles of matter which they can not see. In another words, any abstract concept about a matter is too difficult for them to understand. In the literature, one can find that learners showing their view of atoms demonstrate it as a difficult and confusing epistemological obstacle (Taber, 2003).

There are two selected, but typical, student drawings shown in Figure 2. On the (a) drawing is presented student's idea of an atom which has a nucleus contains protons and neutrons and around them orbiting electrons. On the (b) drawing, an atom is presented, which consists of a nucleus and an electron cloud. In summary, 80% of students have presented their drawings depicting an atom as system of nucleus containing positive protons and neutrons and negative electrons around its nucleus.



a)



b)

Figure 2. Two selected drawings of the atom presented by students under this study.

Worksheet rubric 2 results

In this rubric, students had the opportunity to demonstrate their knowledge about the Bohr's postulates after they completed their required assignments and final exam in General Chemistry 1 course.

The analyses of student responses to the second rubric describe students' knowledge about Bohr's postulates. Students have written evidences that they know different number of Bohr's postulates: two postulates was an answer of the 42 students (72% of students), three Bohr's postulates were an answer of five students (9% of students) and a fact that there are four Bohr's postulates was mentioned only by one student. It is important to note that students generally wrote down a textual expression for (1) only one postulate in correct form (8 or 14% of students), (2) two Bohr's postulates (34 or 59% of students), in very similar or the same form that can be found in their textbooks. Among the 16 students who did not give answers about Bohr's postulates, half of them repeated their description of atoms according to the MA3, and other eight students left a blank space on the worksheet.

It is important to note that three students had written a formula ($h\nu = E_m - E_n$) attached to the second Bohr's postulate expression. None of students wrote down Bohr's ideas of discrete values (quantized) of angular momentum of electrons for the allowed orbits in an atom.

Worksheet rubric 3 results

Most of the students understand the concept about a revolutionary role of the Bohr model of the atom. These concepts were not formed through their acquisition of knowledge of the history of science using some arguments. Therefore, most of them did not give any explanation for what Bohr did for establishing the contemporary scientific model of the atom. Only three students left their blank rubric in the answer space. Analysis of the students' answers to the third worksheet rubric resulted by grouping students answers into a four groups as follows.

A Answer: Bohr was the first scientist who introduced the concept of stationary states of electrons in an atom and had explained why the electromagnetic radiation comes from the atom.

B Answer: Bohr's model marked the beginning of spectral analysis as a research method of composition of matter.

C Answer: The Bohr model of the atom had influenced a fast development of atomic physics.

D Answer: The Bohr model of the atom was a revolutionary one because it is still a valid model to explain the structure of matter.

Quantitative data analysis outcome, as answer distribution of 55 students according to the answer category is shown in Figure 3.

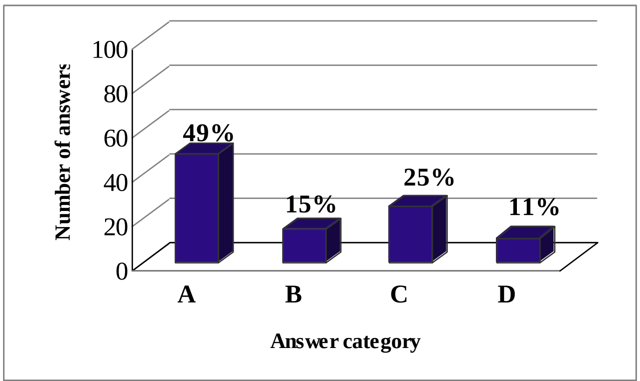


Figure 3. Distribution of students' results by answer category to the third worksheet rubric.

Looking at the students' D answer (Figure 3), one could note that 11% of students in this study did not show their understanding of an importance of Bohr model of the atom looking from the point of view of the history of science. There are still students who think about this model as a model, which is taught in the secondary schools or at the university, as one the entire time valid scientific model. It can be assumed that this group of students does not understand the historical context of the Bohr model of the hydrogen atom. Still, it is the topic in current curricula of both general chemistry and general physics courses.

A total of ten chemistry students gave unacceptable answers and wrong thinking about an atom as structural particulate matter. Several selected answers are as follows.

Significance of Bohr model of the atom is a great because it confirmed that the atom is the smallest particle of matter.

The significance of the Bohr model of the atom because it was the first experimentally confirmed that there is an atom as particulate matter.

When Bohr established his model of the atom all previous studies have lost importance.

According to the obtained students' answers it may be noted that 80% of students who did not know how to express Bohr's postulates have given nevertheless their comments about revolutionary and historic role of this model. Several students' statements are as follows.

Bohr introduced new ideas in physics and chemistry.

Bohr gave the best picture of the atom at the time.

Bohr made a flourishing of science, and his ideas still apply.

Bohr's model of the atom initiated at the time of new experiments in atomic physics.

Comments from both, students who had acceptable or unacceptable answers to the third worksheet rubric are very poor according to the number of sentences used in their writings. It is a proof that they did not show well developed ability to express complex ideas in writing. The students' justifications and comments were in accordance with authors' experiences that students can not easily express their thoughts and knowledge using more sentences and other ways for presenting their knowledge contained in their written test.

Number of 15% of students who gave the answer B is significant evidence that there are chemistry students that were aware of the importance of spectral analysis for research and investigation using optical methods in chemistry and physics.

CONCLUSION

The first and second stage of using history of science in science learning showed by worksheet rubric results that 86% of students failed to give their pictures of atoms according to contemporary scientific model of atom based on quantum theory. Since this is a large percentage of the students, future knowledge integration of students' learning outcomes according to the content of both general chemistry and general physics syllabus has to be a main strategy of curriculum implementation in chemistry study.

Students need to understand the historical context of previous models of the atom, and that, these historically significant models of atoms are used to understand the process of scientific theories creation and scientific knowledge gaining.

Presented students' evaluation results about showed knowledge of Bohr's postulates introduced by Bohr in 1913 are not quite satisfactory. Around 60% of students attached their answers about Bohr model of the hydrogen atom with quantized energy levels and electron moving in circular orbits corresponding to the various allowed energy levels. Students showed knowledge that Bohr suggested that the electron could jump to a different orbit by absorbing or emitting a photon of light with exactly the correct energy content. Each of 60% students knew that Bohr's postulate has explanation of the energy levels in the hydrogen atom represented certain allowed circular orbits. Students' knowledge about Bohr's postulates is in agreement with chemistry textbook content except for a part about Bohr's idea of angular momentum quantization which they will discuss within the General Physics 2 syllabus.

Using historical point of view the Bohr theory and his model of the hydrogen atom can help that students better understand development of contemporary theory of the atom. Students should learn that Bohr's main objective in the process of creating his model was to give an explanation to the stability of the Rutherford model of the atom, instead to learn an incorrect interpretation that Bohr had intention to explain the Balmer spectral formula and the hydrogen line spectrum. Students need to learn "that progress in science evolves through competition between rival and conflicting frameworks, and the work of Thomson, Rutherford, and Bohr is particularly illustrative of this tentative nature of science"(Niaz, 1998, p. 548).

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Summary/Sažetak

Obilježavanje 100 godina Bohrovog modela atoma je prilika da se skrene pažnja studentima o doprinosu Bohra i revolucionarnom razvoju znanosti početkom 20. stoljeća. Podaci prezentirani u ovom radu su rezultati jednog početnog istraživanja u kojem je sudjelovalo 58 studenata prve godine studija hemije, a prikupljeni su da se istraži kako studenti zamišljaju atom, kakvo je njihovo poznavanje Bohrovog modela atoma i historijsko-filozofskog značaja Bohrove teorije. Znanje studenata o Bohrovom modelu atoma se slaže sa sadržajima u udžbenicima koje studenti koriste, osim u dijelu o Bohrovoj ideji kvantizacije momenta količine kretanja elektrona, koji se izučava u okviru kursa Opće fizike 2. Koristeći historijski aspekt Bohrove atomske teorije i njegovog modela atoma vodika, može se pomoći studentima da bolje razumiju razvoj savremene teorije o atomu.