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Knowledge of Atomic Structure and Visualization: A Research Results from Questionnaire with First-year Chemistry Students

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Abstract: This research study was conducted in order to assess the students' knowledge and ideas about basic concepts in both general chemistry and general physics courses. The research topic was knowledge of atomic structure that students already have and visualization of the atom based on that knowledge. Research examined how students' knowledge of scientific atomic theory has progressed during study year using a questionnaire as pretest and posttest. The study results showed that students' knowledge about atomic structure has predominantly descriptive and simplified character. Students have had their alternative visions of atomic structure based on their knowledge about Rutherford or Bohr model of the atom instead of the current scientific model of the atoms. That was a case even when they successfully completed the atomic structure questionnaire. Only 5% of the first-year chemistry students under this study showed an expected scientific literacy level related to the atomic theory topics after two semesters of study general chemistry and general physics. We propose different learning sequences to exceed this problem in order to help the freshmen to be prepared adequately for further more complex study. This approach is very important for the students' development of abstract thinking that is necessary for the complete scientific literacy.

INTRODUCTION

Atomic theory and atomic structure is an essential student learning topic that is an example of fundamental conceptual understanding of science as a subject matter. If it is based on the historical development and contribution of philosophers and scientists (Leucippus, Democritus, Dalton, Thomson, Rutherford, Bohr, Schrödinger and Heisenberg) it can be used as a supporting approach for helping students to better understand the abstract nature around us (Justi & Gilbert, 2000; Niaz et al., 2002; Park & Light, 2009). A main aim of science educators all around the world should be to teach their students to gain knowledge based on the scientific ideas and content of the contemporary atomic structure theory.

Description of participants and curriculum

Chemistry freshmen at Sarajevo University learn atomic structure theory according to both the *General Chemistry I* syllabus and *General Physics II* syllabus. In both mentioned courses a material is present through a lecture format. In Table 1 is given the *General Chemistry I and General Physics II* courses basic statistics.

Table 1. Course statistics

First-year Course	Academic year	Semester	Hour/ week	ECTS
General Chemistry I	2013-2014	Fall	3	5
General Physics II	2013-2014	Spring	4	4

In Table 2 is presented a list of atom structure related topics that chemistry freshmen learn. Almost the same topics relevant to this study goal are covered in the fall semester course *General Chemistry I* and in the spring semester course *General Physics II.* Both courses are done in a traditional lecture teaching format, and by more teacher-centered then student-centered approach. Average number of students in each class is around one hundred (75% as newly enrolled students and 25% of students retaking a class due to failing grade).

Table 2. List of topics included in two syllabi

Topic	General Chemistry I	General Physics II
Spectroscopy of the hydrogen atom (Lyman, Balmer, Paschen, Pfund series of lines in the spectrum of hydrogen)	-	+
Dalton's atomic theory	+	-
Leucippus -Democritus philosophy	+	+
Historical development of the model of the atom over time.	+	+
Thomson's "plum pudding" model of the atoms	+	+
Rutherford's "nuclear model" of the atoms	+	+
Bohr's "orbit" model of the atoms	+	+
Planck's theory on the quantization of light	+	+
Planck's, Heisenberg's and De-Broglie's contributions to the understanding of atomic structure	+	+
Quantum numbers and associated rules (e.g. Pauli Exclusion Principle)	+	+
Atomic orbital (s, p, d, f nomenclature)	+	+
Electron configurations	+	+
Quantum-mechanical model of the atom	+	+

Learning strategy based on the chemistry-physics knowledge integration is not present at the syllabi for "achieving students' common general physics and general chemistry courses outcomes" (Hadžibegovic & Galijašević, 2013). Aforementioned learning topics covered through numerous research goals appear to be a difficult ones for student attempts to understand the modern quantum theory (Harrison & Treagust, 2000; Taber, 2002).

Literature Background

Among first-year students of science study there are some common misconceptions about atomic theory what results in development of more negative attitudes towards chemistry and physics during the teaching-learning process (Taber, 2002; Tsaparlis & Papaphotis, 2002; Eilks, 2005, Park et al., 2009). In most physics-chemistry education research, the hybrid model of the atom used by students but different then any model of the atom as a curricular model (Justi & Gilbert, 2000) has been identified.

Several research results according to the atomic structure understanding by undergraduate students are selected. Researchers Cervellati and Perguini (1981) found some misconceptions by their Italian research participants related to the quantum-mechanical model of the atom. Some of their first-year university students understood orbitals as energy levels or as electron trajectories. Tsaparlis and Papaphotis (2002) presented in their study the research results about student difficulties related to their understanding of quantum-chemical concepts. They found that their first-year university students did not understand the electron configurations (around 6% of students gave partially correct answers). In the same research, Tsaparlis and Papaphotis identified some misconceptions by their students who showed a lack of a deep understanding of the quantum-chemical concepts (for example about atomic orbitals).

Taber (2002) in his study highlighted the research results by Cros and colleagues implying that university students showed some misconceptions about atomic models because they kept the atomic structure concepts based on planetary-type orbits „even after being taught about more sophisticed models" versus an abstract quantum-mechanical model of the atom.

Purpose

The research topic was the knowledge of atomic structure and visual models of the atom that students already have. Science teachers consider that a literate individual in science need to know what is a current scientific model of the atom after four years of school. This is an average number of years devoted to the learning science at primary and secondary school level in Bosnia and Herzegovina. In the same time, science teachers at university level have an expectation best explained as DeBoer's (2000) individual that is "well informed, cultured, literate individual" and must know after two first-year semesters of studying science that the quantum-mechanical model of the atom is a current scientific model of the atom today. The researchers' goals were to find the answers to the following research questions:

RQ1: What were the learning outcomes of two courses dealing with contemporary atomic theory?

RQ3: What misconceptions were apparent?

To answer these questions the students were given pre- and post-tests to measure their atomic structure and electron configuration knowledge and personal visualization of the atom.

METHOD

Participants

The participants were 75 first-year students (77% of female and 23% of male) at Sarajevo University in Bosnia and Herzegovina. The students were from different regions of Bosnia and Herzegovina completed different secondary school education before their university study as following:

Grammar school (75% of students);
Middle medical school (23% of students) and
Middle technical school (2% of students).

Research Instrument

For the purpose of this study we developed a test as research instrument (The Atomic Structure Questionnaire (ASQ) to measure the students' knowledge and understanding of the atomic structure and atomic models of the atom. Four learning categories were under testing focus:

(1) Atomic structure (electron configurations, shells, atomic orbitals, quantum numbers);

(2) Theoretical atomic models and the history of the atomic models (measured by the number of known atomic models mentioned by each student);

(3) Representation of an atom (measured by quality of an atom illustration according to an atomic model used);

(4) Current atomic theory (measured by the number of students' knowledge elements of quantum theory of atoms);

ASQ was created as a diagnostic test as a set of 12 questions: the first nine in the multiple choice format, one short-answer question related to the Calcium electron configuration, and last two questions as open-ended questions. The student ASQ achievements were evaluated based on 12 points in total (attached in the Appendix).

RESULTS

Quantitative results

ASQ results

The 75 chemistry freshmen among 110 of students who were taking the *General Physics II* class were tested. Students' ranking statistics is presented in Table 3 according to their ASQ correct pretest and posttest answers and values of the normalized gain.

Table 3. ASQ correct answer statistics

Question	Pretest	Posttest	<g>
Q1	53%	66%	0.277
Q2	76%	77%	0.042
Q3	79%	81%	0.095
Q4	76%	76%	0
Q5	58%	63%	0.119
Q6	77%	82%	0.217
Q7	87%	89%	0.154
Q8	93%	93%	0
Q9	85%	89%	0.267
Q10	84%	89%	0.312
Q11	5%	6%	0.011
Q12	5%	6%	0.011

Note: <g>=(posttest%-pretest%)/(100%-pretest%).

Students' knowledge evaluation related to the history of atomic models (Q1 results) and certain values of the angular momentum quantum number (Q5 results) was at the lowest student achievement in both pretest and posttest results. The students showed very weak understanding of the current quantum-mechanical model of the atom and only few of them have developed their scientific atomic theory literacy. The value of the normalized gain factor for each ASQ answer is an evidence of a weak progress after an in-class discussion session and four additional teaching hours related to the topics included in the ASQ questions, and realized as pre-post test application.

By one student was achieved both the lowest number of points (0.5) and the highest number of points (12 points) as Figure 1 shows.

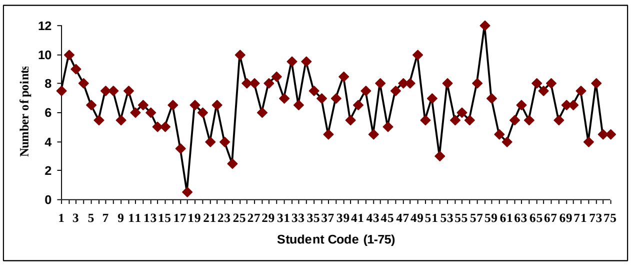


Figure 1. Distribution of the ASQ achieved pretest points by 75 students (12 points as the ASQ highest number of points).

Five categories of students according to the achieved ASQ points (Figure 2) are:

Category A (0 – 4.5 points): The lowest knowledge status.

Category B (5 – 6.5 points): Low knowledge status.

Category C (7 – 9.5 points): Medium knowledge status.

Category D (10 - 11 points): High knowledge status.

Category E (11.5 - 12 points): The highest knowledge status.

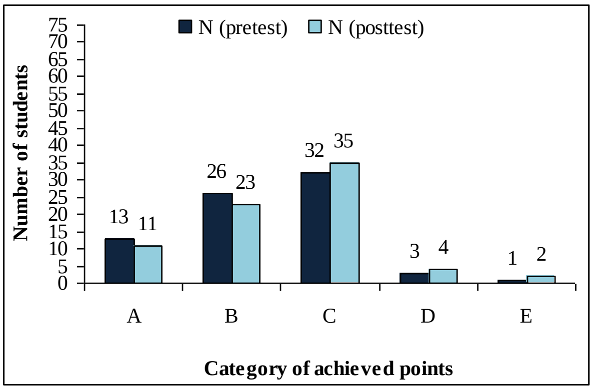


Figure 2. Distribution of the ASQ pretest/posttest points by student category.

Medium knowledge status was showed by the 32 (43%) students, but 39 (52%) students showed a low level of knowledge according to the ASQ (pretest) answers. Similar posttest data set was found presenting a weak progress and remained difficulties especially regarding to the ASQ Section C student answers. For illustration of students' results of remained medium knowledge status is an evidence of the average number of achieved 6.6 points and 7.4 related to the pretest and posttest results respectively. Probably the students under this study need better teaching-learning strategy to help them to achieve learning outcomes as correct ones related mainly the contemporary atomic theory.

Qualitative research results

A selection of pretest qualitative research results is presented here related to the students' visualization of the atom. The pretest ASQ results showed that the 62 (83%) student drawings presented students' ideas of an atom in the section C answers. According to the analysis of student illustrations of an atom four different student models of the atom were presented (Figure 3). Very similar results were found in students' posttest results.

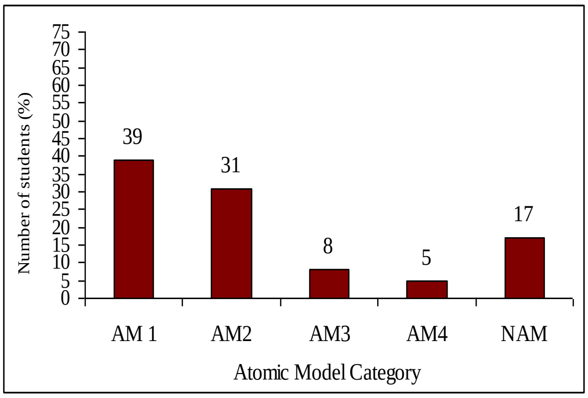


Figure 3. Atomic models presented in the student pretest Q11 illustrations.

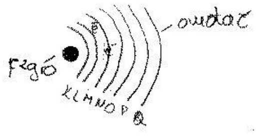
Legend:

AM1: Rutherford model of the atom.
AM2: Bohr model of the atom.
AM3: Thompson model of the atom.
AM4: Quantum-mechanical model of the atom.
NAM: without any atomic model.

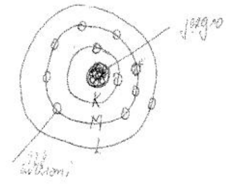
A small number of students who correctly answered the Q11 and Q12 showed students' poor knowledge about the contemporary atomic model (Table 3 & Figure 3). Only four student illustrations contained the students' written descriptions behind their illustrations as principally correct one. Did not a single student provide a proof of the contemporary model of the atom (Quantum-mechanical model of the atom). Only 5% of students showed some elements that could be considered as the AM4. Mostly, the students presented their ideas about the atom similar to Rutherford-Bohr model of the atom (around 50% of students). It is important to note that students learn about six historically important atomic models (Ancient Greek model, Dalton's model, Thomson's 'embedded mass' model, Rutherford's 'nuclear' model, Bohr's 'orbit' model, and Quantum-mechanical model) in *General Physics II* class.

Selection of student drawings of the atoms

A selection of students' pretest atom visualization according to the AM1 is presented in Figure 4. There is a sketch of an atom with a positive nucleus and perception of negative electrons in a correct shell range K, L, M, O, P and Q (Figure 4-a). Other student presented her/his idea of an atom with wrong shell names (Figure 4-b).



a)



b)

Figure 4. Two typical students' atomic structure pretest illustrations related to the Bohr's orbit model.

Figure 5 shows an AM3 illustration presenting textually Thompson's 'embedded mass' model of the atom known as "plum pudding" system.

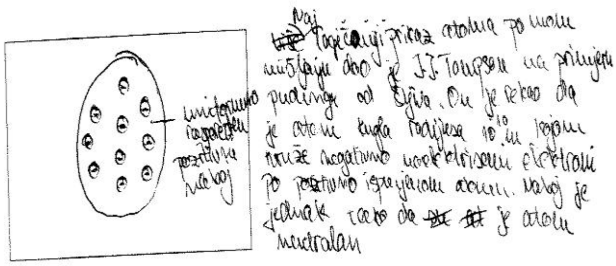


Figure 5. An AM3 pretest example.

Note: Text of student explanation translated from Bosnian into English is following:
In the frame of drawing is written: *uniformly distributed positive charge.*

The text of student's explanation translated from Bosnian into English is:
In my opinion the most logical representation of an atom gave J.J. Thompson taking an example of the plum pudding. He considered that an atom is a sphere radius 10^{-10} m where negative electrons rotate in positive filled atom. The charge is equal so that the atom is a neutral atom.

Figure 6. shows a student's sketch of an atom showing some knowledge of Quantum-mechanical model of the atom.

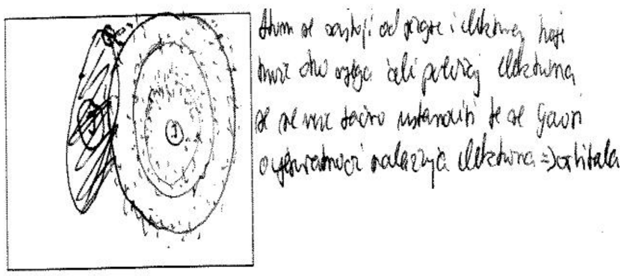


Figure 6. An AM4 pretest example.

Note: The text of student explanation allied to the illustration is translated from Bosnian into English as follows:
An atom consists of its nucleus and electrons rotate around it but electrons' positions can not be accurately identified and it is a talk about probability of electrons' position finding (a symbol for following) orbitals.

ASQ Question 12 Results

Q12: a) *Provide at least three historically significant models of the atom;* b) *Specify which known atomic model is a contemporary/current scientific model of the atom and provide your explanation.*

The pretest answers to the Q12-a are presented in Figure 7 showing the students' answers in the written format and four different categories according to the number of atomic models that they knew about.

Most of the students (42%) in the ASQ Q12-b answers stated that the Bohr model of the atom is a still valid one. Only five students (7%) answered that a current model of the atom is Quantum-mechanical model. The most important and significant is the evidence that 51% of students did not give their Q11 answers.

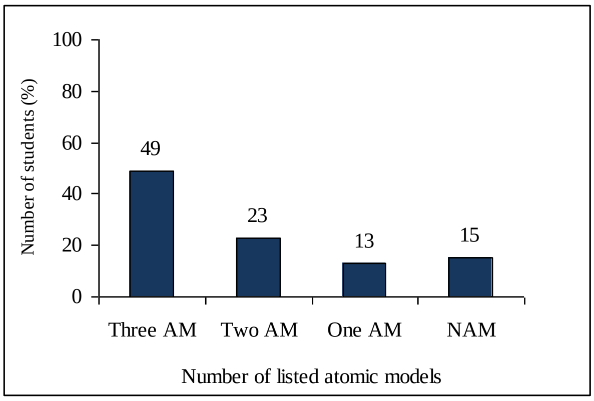


Figure 7. Percentages of student pretest answers to the Q12-a.
Notes: AM = atomic model; NAM= without any AM.

The students gave their reflections after the ASQ implementation during an in-class discussion about atomic models and which one is a current model. In answer to RQ1 around 60% of students did not show any change according to the Bohr model of the atom as a favorite one which does not provide an accurate scientific model of the atom. Probably a main reason for such students' consideration is a powerful influence of syllabi and textbooks that give this theory a significant role in the learning process. Similar results were found when student understanding of Bohr model of the atom looking from "the point of view of the history of science" was tested (Hadžibegović & Galijašević, 2013). According to the Hadzibegovic-Galijasevic findings their research participants (58 chemistry freshmen) had beliefs that Bohr model of the atom appeared "as one the entire time valid scientific model" what is very similar to this study results.

In answer to RQ1 around 30% of the students were at medium knowledge status, but more then 50% of students showed a lower level of the atomic theory knowledge. Since these students are chemistry majors, who have chosen to study chemistry, one can find that the unexpectedly small number of students possessed higher level of knowledge according to the testing questions. A main reason could be that most of enrolled freshmen probably did not come at university with a strong chemistry-physics background. It opens a question of their adequate prior knowledge of physics and chemistry that is required for such kind of study choice.

In answer to RQ2, the students' misconceptions are similar to the findings of several researchers (e.g. Tsaparlis, 1997; Tsaparlis & Papaphotis, 2002; Nakiboglu, 2003):

1. An orbital is a shell in which electrons are placed (30 % of students).
2. Orbitals are electrons' trajectories arranged around the atomic nucleus where electrons rotate (38 % of students).
3. An orbital is an energy level of the electron (8% of students).
4. Students use the Solar System Model or a simple nucleus-electron shell model in explaining the structure of atom (around 55 % of students).
5. The electrons rotate around the nucleus like the planets around the sun (around 50 % of students).
6. Orbitals are equivalent to orbits or shells (around 35 % of students).

It is also important to note that among tested students around 25% of them did not know and probably have had difficulties to understand the meaning of quantum number (n, l, m_l, m_s). In some way, these research results showed a possible confirmation that an entry exam is reasonably needed to select future chemistry freshmen.

CONCLUSIONS

The study results of student knowledge evaluation related to atomic structure understanding are not adequate for chemistry freshmen. Only 5% of first-year chemistry students under this study showed after two semesters of study general chemistry and general physics, an expected scientific literacy level related to the atomic theory topics. As a recommendation what can be changed in both *General Chemistry I* and *General Physics II* one can consider that the instructors need to be focused on meaningful student learning to achieve a coherent student understanding of the same topics relevant for the second-year *Physical Chemistry* course content and other syllabi at higher study years. It is also important to develop a strategy to harmonize two syllabi content in a way that, knowledge needs to be gained in *General Chemistry I* into *General Physics II* using two techniques: integration and differentiation. In such way the chemistry students could much easier make links among related atomic structure concepts to overcome their misconceptions (Tsaparlis & Papaphotis, 2002).

The instructors involved in the teaching general physics and chemistry courses through the teaching-learning process need to bring performances for innovation and creativity in the classroom. They need to motivate students to be actively involved for building competitive learners as future professionals in chemistry. This approach is very important for the students' development of abstract thinking that is necessary for the complete scientific literacy.

According to Taber (2002) to identify a problem of understanding some learning content is "only one step in the process of using research to inform practice". Both chemistry/physics instructor and students need to improve the teaching-learning process for enhancing student's scientific literacy and learning outcomes especially of quantum theory to understand the more complex context of molecular systems at higher years of study.

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Summary/Sažetak

Ova studija se odnosi na istraživanje koje je provedeno da se procijeni znanje studenata i ideje o osnovnim konceptima u oba predmeta, općoj hemiji i općoj fizici. Predmet istraživanja je bilo znanje studenata o atomskoj strukturi i njihove predstave o modelu atoma. Istraživano je znanje studenata o naučnoj teoriji o atomskoj strukturi i kako su studenti napredovali za vrijeme prve godine studija, korištenjem pred-testa, post-testa i individualnih intervjua koji su provedeni s nekoliko učesnika u istraživanju. Rezultati, prikazani u ovom radu, pokazuju da je znanje studenata o atomima i njihovoj strukturi pretežno deskriptivnog i pojednostavljenog karaktera. Studenti su imali alternativne vizije atomske strukture, koje se temelje na njihovom poznavanju Rutherfordovog i Bohrovog modela atoma, umjesto važećeg naučnog modela atoma. To je bio slučaj čak i onda kada su studenti uspješno riješili test o strukturi atoma. Kako bi se pomoglo da studenti prve godine studija hemije prevaziđu probleme razumijevanja atomske strukture predlažemo različite sekvence učenja koje bi pomogle studentima da se adekvatno pripreme za mnogo kompleksnije sadržaje studija hemije. Takav pristup je vrlo važan za razvoj apstraktnog mišljenja za cjelovitu naučnu pismenost studenata.

APPENDIX

ATOMIC STRUCTURE QUESTIONNAIRE

Section A (0.5 point for each correct answer; you should circle only one answer.)

Q1. Niels Bohr scientific contribution in 1913 was:
a) Atom discovery b) Photon discovery c) Equation $E = h\nu$ discovery
d) Discovery of the atomic theory of the electron orbits and those electrons could only have certain energies

Q2. Energy of the 535, 6 nm photon is:
a) $2,28 \cdot 10^{-19}$ J b) $3,57 \cdot 10^{-19}$ J c) $3,71 \cdot 10^{-19}$ J d) $5,63 \cdot 10^{-19}$ J

Q3. *s, p, d, f, g* are symbols to qualify atomic states with the angular momentum quantum number (*l*) values:
a) 0, 2, 4, 6, 8 b) 1, 2, 3, 4, 5 c) 0, 1, 2, 3, 4 d) $0, \pm1, \pm2, \pm3, \pm4, \pm5$

Q4. If value of the principal quantum number is 3 (*n* = 3) an impossible orbital is:
a) 3s b) 3f c) 3d d) 3p

Q5. If value of the principal quantum number is 4 (*n = 4*) the allowed values of the angular momentum quantum number (ℓ) are:
a) 1, 2, 3 b) 1, 2, 3, 4 c) 0, 1, 2, 3, 4 d) 0, 1, 2, 3

Q6. If a value of the angular momentum quantum number is 3 (ℓ = 3), the magnetic quantum number (m_l) allowed values are:
a) 0, 1, 2 b) 0, 1, 2, 3 c) -3,-2,-1, 1, 2, 3 d) -3,-2,-1, 0, 1, 2, 3

Q7. The number of electrons in the *3d* orbital is:
a) 10 b) 2 c) 4 d) 5

Q8. The number of electrons of the $1s^2 2s^2 2p^6 3s^1$ configuration is:
a) 8 b) 6 c) 11 d) 12

Q9. The Potassium atom (K) electron configuration is:
a) $1s^2 3s^2 4s^1$ b) $1s^2 2s^2 3s^2 4s^1$ c) $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$ d) $1s^{19}$

Section B **(0.5 point)**
Q10. The Calcium (Ca) ground state electron configuration is: ______________________________

Section C
Q11. (2 points) Sketch your idea of an atom. Explain each element of your drawings.

Your drawing of an atom | The drawing elements explanation:

Note: If student knowledge of the current atomic model is showed it brings two points.

Q12. (**2 points**) Give at least the names of three atomic models historically relevant ones and which is currently valid one.

Note: If student knowledge of the current atomic model is showed it brings one point