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A STUDY OF HIGH SCHOOL STUDENTS' CONCEPTS OF ATOMIC STRUCTURE: IDENTIFICATION OF MENTAL MODELS

This article investigates the conceptions and mental models of high school students in mastering the topic of atomic structure. The aim of the study is to identify students' mental models of atomic structure, assess and compare their residual knowledge. The study was conducted with the participation of students in the 10th grade of a state high school in Kyzylorda (n=49).

During the study, students were asked to draw their mental models of the structure of the atom and to provide written responses to questionnaire items related to the topic. The models drawn by the students and the results of the survey were analyzed qualitatively and quantitatively. The data obtained showed that the students' knowledge of the atom is limited to the basic components such as electrons, protons and neutrons. The majority of students still confuse the Rutherford and Bohr models with the model of the Solar System, and the quantum mechanical model is not well mastered. In addition, it was found that their visual and theoretical understanding of atomic models is incomplete.

In conclusion, the need to use visualization, historical context, and modeling methods to explain the topic of atomic structure in the teaching process in secondary schools was identified. This study has important practical and methodological significance in increasing the level of scientific knowledge of secondary school students and creating conditions for effective mastery of complex topics.

Keywords: teaching chemistry at school, atomic structure, atomic models, mental models, scientific knowledge, scientific literacy

Introduction

The education system of the Republic of Kazakhstan has been undergoing modernization in recent decades in line with global requirements. Curriculums with updated content, a national policy aimed at developing functional literacy, and the creation of an education system in accordance with international standards are among the main strategic goals. The development of natural and scientific literacy is given special attention both in the country's development strategy until 2050 and in the concept of education development for 2023–2029.

This issue is also relevant at the global level. UNESCO's Sustainable Development Goal 4 (SDG 4) – "Quality Education for All" – aims to improve students' scientific literacy. However, in OECD, TIMSS and PISA studies, the results of Kazakhstani students in science subjects often remain at an average level. These indicators prove the need to update the content of education and introduce effective methodologies.

Chemistry is a subject of particular importance among the natural sciences, but it is one of the most difficult for students. Among them, the topic of atomic structure is one of the most difficult concepts. This is because connecting the macroscopic world formed in students' worldview with concepts of the invisible submicroscopic level creates great cognitive difficulties.

Currently, due to the increasing volume of information mastered in the educational process in secondary schools and the growing importance of preparing students for independent learning, it is increasingly relevant to study the role of atomic structure in developing students' understanding during teaching. Atomic structure, forming the basis of natural sciences, makes a significant contribution to the formation of a unified scientific picture of the world.

Currently, due to the increasing volume of information mastered in the educational process in secondary schools and the growing importance of preparing students for independent learning, it is increasingly relevant to study the role of atomic structure in the development of students' understanding during the teaching of atomic structure. Atomic structure, forming the basis of natural sciences, makes a significant contribution to the formation of a unified scientific picture of the world and its future development.

Although chemistry is taught in Kazakhstani schools within the framework of an updated curriculum, there is little empirical research aimed at systematizing students' conceptual understandings and misconceptions about atomic structure and systematically analyzing their mental models. In this regard, this issue is considered a relevant scientific and practical direction in modern chemistry teaching methodology.

In recent decades, the topic of atomic structure has played a key role in shaping students' conceptual understanding in chemistry education. The complexity of this topic lies in its abstract nature [1, p. 182], since it is impossible to directly observe the atom. In this regard, many researchers [2, p. 89] have conducted studies aimed at identifying students' understanding of the atom, their mental models, and common misconceptions.

The concept of an atom is one of the most difficult concepts for students to master in chemistry. Numerous studies have shown that students often have misconceptions about this topic [3, p. 245].

Scientists have different opinions about the formation of misconceptions. Thus, researchers argue that if the process of transferring previous knowledge to new situations is influenced by certain factors, then scientifically incorrect concepts may form in the minds of students [4, p. 1].

During the study, it was observed that some students identified the atoms of a substance with the physical properties of that substance. For example, oxygen atoms are explained as a gas, and iron atoms are explained as a solid. At the same time, it is assumed that a water molecule consists of hydrogen and oxygen atoms, and the terms "atom" and "molecule" are used interchangeably. The ideas about the size of an atom are described by comparisons such as "the tip of a needle" or "the head of a pin" [5, p. 165].

Students think that phosphorus atoms are yellow, that phosphorus atoms dissolve when phosphorus is dissolved, and that iron atoms expand when iron is heated [6, p. 465].

One of the main factors influencing the formation of misconceptions is students' mental models. Mental models are a system of visual and imaginative ideas formed in students' minds that help them visualize and explain certain phenomena [3, p. 244].

Johnson-Laird, who first introduced the concept of a mental model into scientific circulation, described it as "an internal cognitive representation that people create in their minds to explain, predict, and act on environmental phenomena". Later, Norman viewed mental models as internal "thought structures" in the process of understanding and controlling technological or natural systems [7, p. 25].

A mental model is a person's internal image or cognitive model used to understand, describe, explain, predict, and sometimes manage a phenomenon [8, p. 2].

Mental models are unstable structures that constantly change during learning and develop according to the student's level of knowledge [1, p. 183].

A common model for representing the atom is the structure of the Solar System, where the Sun represents the nucleus, and the orbital motion of the planets represents the electrons around it [9, p. 326].

Riskiani and Hari showed similarities between the Bohr atom and the Solar System, as can be seen in Table 1 [10, p. 4].

Table 1 – Similarities between the boron atom and the solar system

Solar system	The structure of the boron atom
Sun	Nucleus
Planetary orbits	Electron orbit
Planets	Electrons
Spherical shape of the Sun and planets	Spherical shape of the nucleus and electrons
Constant distance from the sun to the planets	Constant distance from the nucleus to the electrons
Helium and hydrogen as the constituent elements of the sun	Protons and neutrons as components of the nucleus

The general pattern obtained as a result of the analysis of the literature shows that the features of students' representation of the structure of the atom can be classified into five different groups of mental models. From simple to complex, this classification is as follows: The simplest, usually called the "particle model", is a model in which the atom is considered a particle without additional specifications. When the atom is given the characteristics of a living organism and the atom is seen as similar to a cell, a second category, the "atomic cell model", appears. In the "nuclear model", students represent the structure of the atom by including the nucleus and electrons in the structure. The next more complex group includes all representations that include the paths of electrons with or without references to certain levels of orbits or energy quantizations. This is actually a broad category of models known by various terms such as "solar system model", "planetary", "Bohr model". The most complex category is when students represent the structure of the atom probabilistically, taking into account quantum theory. Mental models that fall into this category are the "orbital model", "electron cloud model" or "quantum mechanical" model [5, p. 165].

The development of mental models is a slow, complex process, the adaptation period of which can be shortened or lengthened depending on how often the model is analyzed and evaluated [1, p. 190].

Scientists have different views on the study of atomic structure. While some scientists suggest simplifying students' understanding by comparing the structure of the atom with the solar system, researchers led by C. Nakiboğlu see this approach as a barrier. Their research results show that 60 % of students still use the solar system model or a simple nucleus and electron shell model to explain the structure of the atom. This approach may prevent students from gaining a deeper understanding of the structure of the atom [11, p. 15]; [2, p. 96].

In the case of Kazakhstan, research in this area is still scarce. Although many works have shown the effectiveness of teaching the topic of atomic structure through animations and electronic resources [12, p. 67–77]; [13, p. 176–180], empirically identifying students' specific mental models and misconceptions has not been sufficiently studied.

Currently, there is a lack of systematic empirical research on identifying and analyzing students' mental models of atomic structure in Kazakhstani secondary schools. Existing research in this area is often limited to describing general "misconceptions" and is not aimed at fully identifying students' cognitive structures (i.e., their internal mental models). Therefore, the new study allows us to systematically analyze the features of students' individual perception of the concept of an atom, their levels of thinking, and their figurative understanding, and to characterize their development.

The purpose of the study is to identify mental models of high school students and assess their level of knowledge by examining their understanding of the structure of the atom.

The scientific novelty of the study is that in the conditions of Kazakhstan, mental models of high school students about the structure of the atom were studied systematically for the first time on a comprehensive and empirical basis.

Although it is not possible to obtain a complete picture of the student's understanding of the atomic model in the topic we have chosen, it is possible to gain insight by analyzing the drawings created in response to the student's own drawing task.

Materials and methods

The study was organized as an empirical study with a descriptive and qualitative focus. The aim of the study was to identify the mental models of high school students about the structure of the atom and assess their scientific validity. To achieve this goal, a mixed method was used, that is, data obtained through a questionnaire and graphic-explanatory tasks complemented each other. The design of this study included survey questions, students' mental models, and written responses.

The study was conducted in a state high school in Kyzylorda.The study was conducted in the first quarter of the 2023-2024 academic year on the chemistry subject "Atomic Structure". The study involved 10th grade students (25 boys and 24 girls) (n=49). The students came from mixed socio-economic backgrounds.

Table 2 – Student number indicator table

Indicator	10A-grade	10B-grade
Boys	13	12
Girls	12	12
Everything	25	24

I was introduced to the students' academic performance. Students were informed about the purpose of the study in advance. They were informed that the data obtained would be used for scientific purposes only. All participants voluntarily agreed to participate in the study. The answers were processed anonymously and the students' names were not disclosed.

Data were collected using a paper-and-pencil test designed to assess students' understanding and mental models of atomic structure.

According to researchers, the most effective way to determine students' mental models is to collect data from them using specially prepared tools (for example, interviews or questionnaires) [14, p. 352-381].

The paper questionnaire consisted of two parts:

Part I: Draw a model of the structure of an atom. Label each part.

Part II: 4 open-ended questions – define the concepts of atom, orbital, isotope, and atomic mass.

The test instruments were pre-validated by relevant experts before being used in the study. The content validity of the instruments was checked by (one candidate of chemical sciences, one methodologist teacher, one foreign PhD). The internal consistency index is Cronbach's $\alpha=0.81$, which proves the high reliability of the instrument.

Research progress:

1 Preparation period: research documents (consent form, questionnaire forms) were developed.

2 Main stage: The survey and drawing assignments were conducted in a private classroom after class (duration 40 minutes).

3 Final stage: All the work was collected and the data was digitized.

Students' mental models were identified according to a five-level classification proposed by scientists [7, p. 23]; [15, p. 234]:

1 Zero model

2 Partial-model

3 Mixed model

4 Structural model

5 Scientific model.

Intercoder agreement (Cohen's k=0.86) was considered reliable.

The students' responses to the open-ended questions were classified into the following four categories:

– *correct answer* – a scientifically complete and precise definition or diagram;

– *incomplete answer* – the main idea is correct, but not fully explained or some details are not shown;

– *wrong answer* – contains scientific misconceptions;

– *did not answer* – blank or irrelevant answer.

Frequency, percentage distribution, and t-test methods were used to assess differences and relationships between data.

In the results of this study, the teacher documents many visual and symbolic elements of the structure of atoms in the students' drawings.

The study was conducted with students from only one school (n = 49), so the generalizability of the results is limited. In addition, since the tasks were administered in paper format, it was not possible to fully integrate digital tools.

Results and discussion

The data obtained during the study showed that there is a clear heterogeneity in the understanding of the structure of the atom among 10th grade students. Most of the participants described the atom from a classical point of view - as a structure consisting of a nucleus and electrons moving around it. The data were systematized using the method of content analysis, and the frequency and types of mental models were identified.

The survey was conducted in Kazakh, and selected responses were translated into English.

Students were given simple tools (paper, pencil) and asked to draw a picture of the structure of the atom. Students answered open-ended questions in writing. These answers allowed them to identify the qualitative and quantitative features of their understanding.

In the first stage of the study, students' mental images (drawings) regarding the structure of the atom were analyzed, and in the second stage, their written responses to open-ended questions were evaluated.

After students were asked to draw a mental model of the structure of an atom, they presented their models as shown in Figure 1.

The types of student responses were sorted from inactive (no response) to the most correct answer.

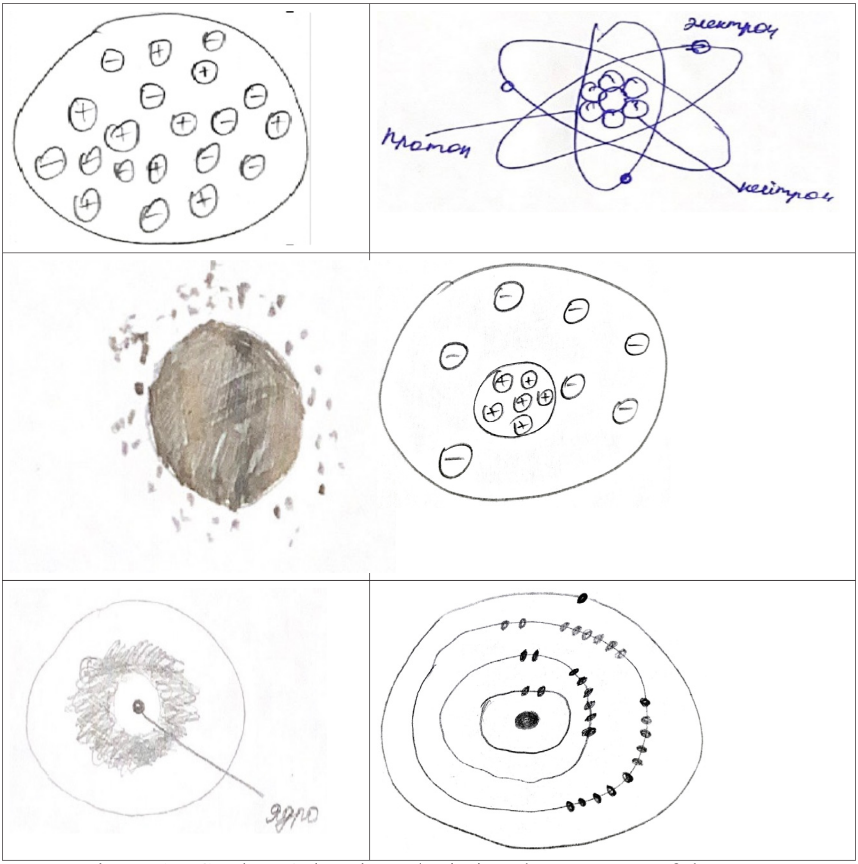

Figure 1 – Students' drawings depicting the structure of the atom

The students who responded to the survey found differences in their opinions and mental models about the structure of the atom. Half of the participants believed that the atom consists of protons, neutrons, and electrons, and that protons and neutrons are in the nuclear shell, and electrons move around the nucleus. One student showed subatomic particles with quarks and wrote their sizes. Two respondents indicated that they knew different historical models of the atom (Dalton, Thomson, Rutherford, Bohr atomic models). 28 respondents (57 %) drew a picture of the nuclear shell of the atom. 12 participants (24 %) showed protons in the nucleus. 11 students (22 %) showed neutrons in the drawing. When describing the location of electrons, 13 students (26 %) referred to orbits. All participants depicted electrons as located in circles or orbits. 41 students (84 %) drew pictures according to the structure of the atom. Several more respondents did not put the charges of electrons and protons. Of the 49 participants, 20 students (40.1 %) drew different shells inside the atom, and 27 students (55 %) showed the location of electrons inside the shells. 8 students (16 %) showed s,p,d,f orbitals as atomic models. The mental models of the structure of the atom that students drew were similar to the shapes they saw in books. 8 (16 %) students drew Rutherford's models. 7 students (14 %) drew them similar to Bohr's atomic model. 3 students (6 %) showed electron cloud models.

Several respondents likened atoms to Bohr's theories of atomic structure. The rest of the respondents depicted the trajectories of electrons as moving randomly or in circles. This situation proves that the probabilistic nature of electron orbitals is not yet firmly established in the students' understanding.

This visualization process is consistent with the analogical thinking strategies identified by scientists [10, p. 5]: students rely on macroscopic analogies to visually explain submicroscopic concepts (e.g., the Solar System model).

These results suggest that most students have mental models that are inconsistent with the atomic models in their curriculum. Their responses reflect mixed atomic models.

Table 3 – Grouping of students' mental models according to a five-level system.

Model level	Description	Share (%)
Zero	The atom is not depicted in the diagram or the symbols are chaotic.	7 %
Partial	There is no connection between the electron, proton, and neutron shown.	26 %
Mixed	Elements of historical models are mixed (e.g. Bohr+Rutherford)	33 %
Structural	The nucleus, shell, charge, and orbits are shown, but the energy levels are distorted.	24 %
Scientific	There are electron clouds, probabilistic properties, and quantum concepts.	10 %

In this table, we have grouped the mental models from Part I into a five-level system.The data in the table shows that 33 % of students have a mixed mental model, 26 % have a partial mental model, and 24 % have a structured mental model.

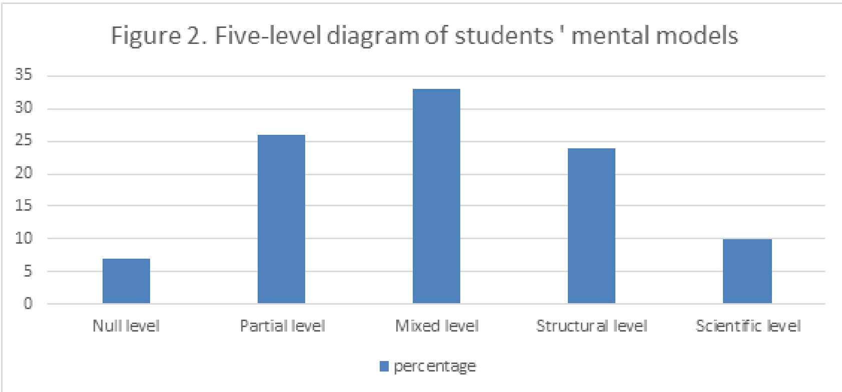

Figure 2

The mean value was calculated by model levels using SPSS: M = 2.38, SD = 0.84, which indicates that the majority of students are at an “intermediate” level (between mixed and structured models).

All students answered the open-ended questions in the second section as shown in the table.

The answers to the open-ended questions also varied.The answers given by different students revealed that their understanding of the structure of the atom was not uniform. However, most students were unable to fully explain this definition.

Some students described the atomic number as the sum of protons and neutrons. These responses showed that they did not understand the difference between mass number and atomic number. Other students simply described the atomic number as “its position in the periodic table”. In addition, a number of responses described the atomic number as simply the number of electrons. While this is somewhat correct in the case of a neutral atom, it is not a complete and scientifically accurate explanation.

The answers to the question “Orbital?” revealed a number of errors and contradictions in students’ mental models of atomic structure.

A number of students interpreted the orbital as an “electron trajectory”, similar to the path of the planets around the Sun. This indicates that they still had a view of the Bohr model in their minds. Some answers described the orbital as a layer or part of the nucleus, which indicates that students did not sufficiently master the concepts at the submicroscopic level. Other students perceived the orbital as a particle limited to a specific number of electrons, which is due to the fact that it is a probabilistic space.

The data obtained showed that students' understanding of orbitals is largely based on classical views.

The results of the study showed that the answers to the question «isotope?» revealed that students' understanding of atomic structure was at different levels and that they often made mistakes.

A number of students perceived isotopes as different chemical elements and failed to distinguish between them as forms of the same element. Some students understood an isotope as a charged particle and confused the difference between an ion and an isotope. In some of the answers, an isotope was described in terms of its electron shells rather than the composition of the nucleus. A certain number of students thought that all isotopes were radioactive atoms and failed to distinguish between stable and unstable isotopes. Overall, these data indicate that students have difficulty distinguishing basic concepts at the submicroscopic level.

During the study, it was found that a significant number of students associated the concept of atomic mass with the volume of an atom. A small number indicated that it is the sum of protons and electrons. It was also found that they confuse atomic mass and mass number.

Table 4 – Percentage of students' responses to open-ended questions in 4 categories.

№	Question	Correct (%)	Incomplete (%)	Wrong (%)	Did not answer (%)
1	Atomic number?	21.8	46.7	21.3	10.2
2	Orbital?	22.9	42.2	25.6	9.3
3	Isotope?	23.0	43.4	24.7	8.9
4	Atomic mass?	22.6	45.8	20.1	11.5

The average correct answers for all four categories were 22.6 %, the proportion of incomplete answers was 44.5 %, the proportion of incorrect answers was 22.9 %, and the proportion of non-answers was 10%. The $\chi2$ analysis showed that the response results depended on the questions ($\chi2 = 19.84$; $p<0.05$) and that students had difficulty with the isotope and orbital questions. The low mean value (M=1.81; SD=0.85) indicates that most students remained at the level of "incomplete" and "incorrect" answers.

The study found that while students performed relatively well at the macroscopic level (e.g., determining atomic number), they struggled at the submicroscopic level (orbitals, electron shells). This was theoretically expected.

These results indicate that most students have a mental model that is inconsistent with the atomic models that are in their curriculum.

The survey results showed that students did not fully understand chemical terms and did not master the content of some topics, which contributed to their decreased interest in the lesson.

When constructing models according to atomic theories, some distortions and limitations in describing the appearance of the atom are likely to occur. In such cases, conceptual errors lead to misunderstandings [16, p. 259].

Students' prior knowledge and experience often lead to misunderstandings of new topics in the classroom, which in turn leads to different mental models being formed during the learning process.

Conclusion

The results of the study showed that high school students' understanding of the structure of the atom is not fully formed. The majority of students explain their knowledge of the structure of the atom based on historical models. The majority of students still confuse the Rutherford and Bohr models with the solar system model, and the quantum mechanical model has not been properly mastered. A study on the subject of «Atomic Structure» in chemistry in secondary school determined the level of understanding of students for each term and model. When assessing the level of knowledge through the conducted surveys, it was noted that students did not fully understand and master chemical terms. In addition, misunderstanding of the content of some topics of the «Atomic Structure» chapter reduced their interest.

The study found that many participants did not have a clear mental model in their minds.

The results of the study showed that despite the development of science and technology in modern times, and the introduction of atomic models based on an improved electronic structure, the vast majority of students are unable to imagine concepts beyond the traditional models based on the atomic theories of Bohr and Rutherford. In this regard, the need to include information in modern textbooks that explains the historical context of each model, the specific purpose for which it was created, and the advantages of the models has been identified.

It is important for chemistry teachers to avoid creating misconceptions among students. The Bohr model is a clear, functional, and effective way to explain basic chemical phenomena. Any modern model of atomic structure must be based on a deep understanding of the theory of quantum mechanics.

This study is one of the first to systematically analyze high school students' mental models of atomic structure in chemistry in Kazakhstan. The results demonstrate the need to use modern visualization, historical context, and modeling techniques, along with traditional methods, to enhance students' scientific literacy.

This study was conducted among 10th grade students from only one school. Therefore, the results cannot be directly generalized to all schools.

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ОРТА МЕКТЕП ОҚУШЫЛАРЫНЫҢ АТОМ ҚҰРЫЛЫСЫ ТУРАЛЫ ТҮСІНІКТЕРІН ЗЕРТТЕУ: МЕНТАЛДЫҚ МОДЕЛЬДЕРІН АНЫҚТАУ

Бұл мақалада орта мектеп оқушыларының атом құрылысы тақырыбын меңгеруіндегі түсініктері мен ментальдық модельдері зереттелді. Зерттеудің мақсаты – оқушылардың атом құрылысы туралы ментальды модельдерін анықтап, олардың қалдық білімдерін бағалау және салыстыру. Зерттеу Қызылорда қаласындағы мемлекеттік орта мектептің 10-сыныбында оқитын оқушылар қатысуымен жүргізілді (n=49).

Зерттеу барысында оқушыларға атом құрылысының менталдық модельдерін сызу және атом құрылысы туралы сауалнама сұрақтарына жазбаша жауап беру тапсырылды. Оқушылардың бейнелеген модельдері мен сауалнама нәтижелері сапалық және сандық талдаудан өтті. Алынған деректер оқушылардың атом туралы білімдері электрон, протон және нейтрон сияқты негізгі компоненттермен шектелетінін көрсетті. Оқушылардың басым бөлігі әлі күнге дейін Резерфорд және Бор үлгілерін Күн жүйесі моделімен шатастыратынын, кванттық механикалық модель дұрыс игерілмегенін көрсетті. Сонымен қатар, олардың атомдық модельдерге қатысты визуалды және теориялық түсініктері толық емес екендігі анықталды.

Қорытындыда орта мектептегі оқыту процесінде атом құрылысы тақырыбын түсіндіру үшін визуализация, тарихи контекст және модельдеу әдістерін қолдану қажеттілігі айқындалды. Бұл зерттеу орта мектеп оқушыларының ғылыми білім деңгейін арттыру және күрделі тақырыптарды тиімді меңгеруге жағдай жасау бағытында маңызды практикалық және әдістемелік маңызға ие.

Кілтті сөздер: мектепте химияны оқыту, атом құрылысы, атомдық модельдер, менталдық модельдер, ғылыми білім, ғылыми сауаттылық

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ИЗУЧЕНИЕ ПРЕДСТАВЛЕНИЙ СТАРШЕКЛАССНИКОВ ОБ АТОМНОМ СТРОЕНИИ: ОПРЕДЕЛЕНИЕ МЕНТАЛЬНЫХ МОДЕЛЕЙ

В данной статье изучены концепции и ментальные модели освоения учащимися средней школы темы атомного строительства. Цель исследования-выявить ментальные модели учащихся по атомному строению, оценить и сравнить их остаточные знания. Исследование проводилось с участием учащихся 10 класса государственной средней школы г. Кызылорда (n=49).

В ходе исследования учащимся было поручено нарисовать ментальные модели атомного строительства и письменно ответить на вопросы анкеты об атомном строительстве. Наглядные модели учащихся и результаты анкетирования прошли качественный и количественный анализ. Полученные данные показали, что знания учащихся об атоме ограничены основными компонентами, такими как электрон, протон и нейтрон. Подавляющее большинство учащихся все еще путали модели Резерфорда и Бора с моделью Солнечной системы, показывая, что квантово-механическая модель не была освоена должным образом. Кроме того, было обнаружено, что их визуальные и теоретические представления об атомных моделях неполны.

В заключении выявлена необходимость использования методов визуализации, исторического контекста и моделирования для объяснения темы атомного строительства в процессе обучения *в средней школе. Данное исследование имеет важное практическое и методическое значение в направлении повышения уровня научных знаний старшеклассников и создания условий для эффективного освоения сложных тем.*

Ключевые слова: преподавание химии в школе, атомное строительство, атомные модели, ментальные модели, научные знания, научная грамотность

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