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Assessing the State of Modern Physics Education: Pre-test Findings and Influencing Factors

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Abstract

Technology and our conceptions of reality have both been significantly impacted by modern physics. However, due to a variety of issues, such as disparities in educational resources, differing emphasis on science education, cultural attitudes, and language obstacles, students in Latin America, including Ecuador, have a limited understanding of modern physics. The present work exposes a pre-test methodology to evaluate students' knowledge and pinpoint their areas of weakness. The analysis of the results indicates that most students received lower grades, while a smaller proportion obtained higher scores. Our findings reveal significant knowledge gaps, misconceptions, and uncertainty among the participants regarding various topics related to the constituent and stability of the nucleus, quantum behavior, nuclear models, radioactive decay, and natural radioactive sources. Additionally, it was statistically demonstrated (Kruskal-Wallis H test) that misconceptions, uncertainties, and knowledge gaps are not significantly related to learning styles. The type of college substantially impacts academics, with private university students typically receiving higher grades. These results offer insightful information about student performance, how learning styles and college types affect academic achievement in modern physics, and the effects of living area and academic level.

Keywords:

Modern Physics;
Pre-test;
Misconceptions;
Learning Styles.

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1- Introduction

Modern physics, a subsection of physics that emerged in the late 19th and early 20th centuries, seeks to describe the universe beyond the scope of classical physics [1, 2]. Key areas of modern physics include [3–5]. (i) quantum mechanics, which deals with the behavior of particles at the smallest scales; (ii) relativity theory, which revolutionized our understanding of space, time, and gravity; (iii) particle physics, which explores the fundamental particles and forces in nature; and (iv) cosmology, which studies the origin and structure of the universe. Beyond the goals of physicists and chemists committed to advancing modern physics, students' goal until the end of the 20th century was to gain a deeper understanding of its impact on contemporary thought [6]. Nowadays, knowledge of the fundamentals and ideas of modern physics is essential for every professional working at the cutting edge of research, technology, and innovation [7]. This presents a dilemma since, in order to speed the democratization of modern physics, teaching approaches must be established and improved [8, 9]. After all, mastering these concepts is essential to becoming an informed citizen.

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Prior knowledge can have a significant impact on how students learn and how they build new information [10–12], especially when acquiring ideas about modern physics. In the case of quantum physics, for example, macroscopic conceptions and observations can lead to mental models that contradict the behavior of matter at the molecular or atomic level. Another example would be understanding the principles of relativity, which require you to let go of the idea that space and time are absolute and instead adopt the idea that these variables depend on the observer. As a result, the modern physics learning process is significantly impacted by the student's previous knowledge. In this context, conceptual diagnostic tests serve as invaluable tools for assessing students' comprehension and comparing the effectiveness of different teaching strategies [13]. These surveys employ standardized, validated, and meticulously crafted multiple-choice questions, featuring distractors that mirror common misconceptions held by students [14]. Educators and researchers can identify these misconceptions by analyzing survey responses. Although standardized diagnostic tools have been developed for various physics disciplines, such as mechanics [15], electromagnetism [16], and quantum mechanics [17], there has been limited exploration of the foundational concepts in modern physics [18, 19].

In order to enhance modern physics learning, we have embarked on an initial endeavor by developing a diagnostic survey focused on the fundamental concepts of modern physics. The survey was administered to students enrolled in various academic disciplines across different universities in Ecuador, employing a pre-test methodology. The pre-test is a survey formed by single-choice, multiple-choice, and dichotomic questions to collect responses, which were subsequently subjected to statistical analysis for evaluation. Applying a pre-test methodology to enhance modern physics learning is important as it establishes a baseline assessment of students' knowledge, identifies weaknesses, and allows tailored curriculum adjustments [20]. It enables the evaluation of curriculum changes, provides feedback on effectiveness, and helps identify common misconceptions, known as partial knowledge measurement [19]. Additionally, it promotes personalized, student-centered instruction [21, 22], leading to improved learning outcomes in modern physics education.

On the other hand, the relatively lower knowledge of modern physics among students in Latin America, including Ecuador, can be attributed to various factors [23]. These include educational resources and infrastructure differences, varying emphasis on science education within the curriculum, cultural perceptions of science, and language barriers [24]. In the case of Ecuador [25], limited resources, outdated materials, and inadequate teacher training may contribute to the challenges in teaching and learning modern physics. Additionally, societal attitudes and limited recognition of science careers may discourage students from pursuing physics. Addressing these issues requires increased investment in science education, improved resources, enhanced teacher training, and fostering a culture of scientific curiosity [24].

2- Research Methodology

At the initiation of the current investigation, a delineation of the domains within modern physics was undertaken. Subsequently, a systematic formulation of diverse inquiries ensued, culminating in the structured assembly of a diagnostic test. The ensuing phase involved the validation of the formulated questions through rigorous scrutiny. Finally, the determination of the minimal requisite sample size essential for the attainment of the study's objectives was executed (see Figure 1).

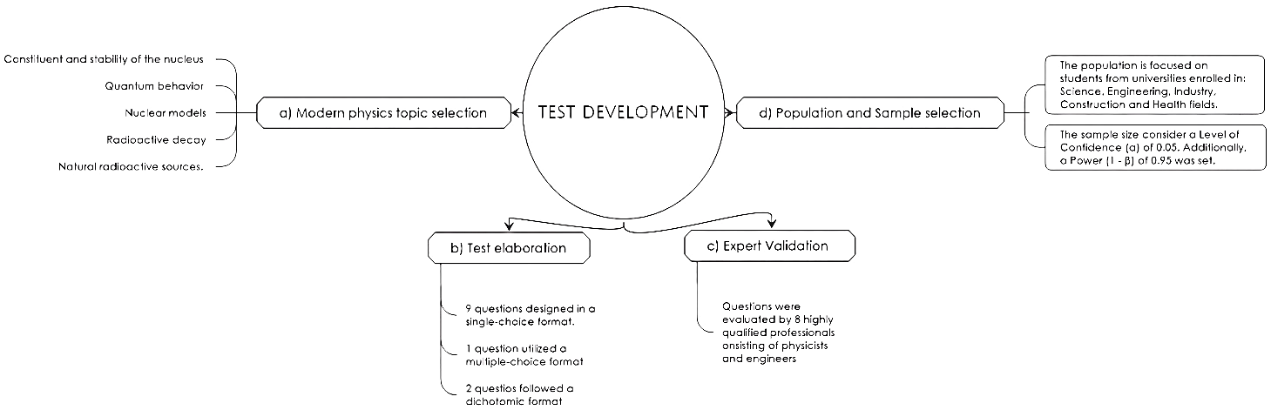

Figure 1. Methodology conceptual-map

2-1- Pre-test Development

The modern physics diagnostic test was made, drawing on our lecturing experience, educational research literature, and analysis of modern physics forum discussions [26]. It comprised 12 questions that explored the fundamental topics of modern physics:

- Constituent and stability of the nucleus;
- Quantum behavior;
- Nuclear models;

- Radioactive decay;
- Natural radioactive sources.

The survey employed a variety of question formats to effectively evaluate students' understanding. One question utilized a multiple-choice format, providing respondents with multiple options to choose from. Two questions followed a dichotomic format, requiring students to determine whether statements were true or false. The remaining questions were designed in a single-choice format, where participants selected the most appropriate answer from four options. By incorporating different question formats, the survey sought to assess students' knowledge and critical thinking skills across a range of scenarios, encouraging a comprehensive evaluation of their understanding of modern physics.

To ensure the effectiveness and reliability of the pre-test, careful consideration was given to the construction of single-choice questions.

- Commonly incorrect choices were intentionally included in the list of options. By including these distractors, we aimed to assess students' understanding more accurately and identify common misconceptions or areas of confusion. This approach allows us to gain valuable insights into the specific challenges our students face and address them effectively in the teaching and learning process.
- Each single-choice question consisted of five response options, including the deliberate inclusion of "I don't know" as a response option. The purpose of including this option is dual:
- Firstly, it provides respondents with the opportunity to recognize when they lack knowledge or feel uncertain about a specific question or topic. This promotes honest self-assessment and encourages students to recognize and reflect on their understanding.
- Secondly, including "I don't know" as a response option allows us to differentiate between respondents who genuinely lack knowledge or are unsure and those who might be guessing or providing random responses. This differentiation is crucial for accurately assessing students' proficiency levels and tailoring instructional strategies accordingly.

It is important to note that question number 7 (see Table 1) deviates from the others, as all the choices provided were correct. This deliberate design choice challenges students to apply their knowledge effectively and identify the multiple correct answers. It serves as a valuable assessment tool to determine students' ability to recognize and comprehend complex concepts, fostering higher-order thinking skills.

Table 1. Overview of the Initial Pre-test (12 Questions)

Topic	Question	Options	Format
On the constituent of the nucleus	Which elements compose the atomic nucleus?	– Neutrons and protons – Neutrons, protons and electrons – Neutrons and positrons – Neutrons and electrons – I don't know	single-choice
	There is a nucleus with 8 protons and a mass number of 19. What nucleus do this data relate to?	– Oxygen 19 – Oxygen 16 – Fluorine 19 – Lithium 8 – I don't know	single-choice
On the isotopes of the nucleus	Complete the sentence. The nuclei hydrogen 1 (protium), hydrogen 2 (deuterium), and hydrogen 3 (tritium) are_________.	– Isotones of hydrogen – Hydrogen isobars – Isotopes of hydrogen – Hydrogen ions – I don't know	single-choice
	Indicate whether the following statement is true or false: Isotopes of an element show the same chemical behavior.	– True – False – I don't know	single-choice
On the stability of the nucleus	Which of the following nuclei exhibits higher stability?	– Carbon 12 (binding energy per nucleon = 7.47 MeV) – Carbon 14 (binding energy per nucleon = 7.05 MeV) – Carbon 13 (binding energy per nucleon = 7.25 MeV) – Carbon 11 (binding energy per nucleon = 7.04) – I don't know	single-choice
	Indicate whether the following statement is true or false: The energy required to force an electron out of an atomic orbital is substantially lower than the energy required to force a proton out of its nucleus.	– True – False – I don't know	single-choice

On the quantum behavior of the nucleus	Choose the arguments for why the atom's nucleus is considered a quantum system. (Multiple options could be selected as correct)	– Since processes such as alpha decay and nuclear fission have been understood thanks to quantum effects such as tunneling – Since the de Broglie wavelength is approximately 9 fm, for a 10 MeV nucleon. – due to the intrinsic angular momentum of nuclei. – Since nuclei can only occupy specific energy levels. – I'm not sure.	multiple-choice
On the nucleus models	Complete. The so-called magic numbers (Z/N=2, 8, 20, 28, 50, 82, 126) are predicted by the nuclear shell model, and they have the connotation of a_____.	– Less probability of radioactive decay (very high binding energy) and greater abundance in nature. – Very high electron binding energy corresponds to noble gases. – Full orbital levels, therefore, do not perform chemical bonds – Very low neutron separation energies and therefore very radioactive. – I don't know	single-choice
On the radioactive decay	In which of the following situations does negative beta decay occur?	– When a nucleus has an excess of neutrons and internally transforms a neutron into a proton plus an electron of nuclear origin and an electron antineutrino. – When a nucleus has an excess of protons and internally transforms a proton into a neutron plus a positron of nuclear origin and an electron neutrino. – When there is the same number of protons and electrons but they are at different energy levels – When there is the emission of a photon for the de-excitation of the nucleus. – I don't know	single-choice
On the natural radioactive sources	What are the sources of natural radioactivity to which we humans are exposed?	– Cosmic rays, food, water from natural springs, and the Earth's crust – Radioactive materials from hospitals, tomography, X-rays, nuclear power plants, and smoke detectors. – Food irradiation plants, synchrotrons, nuclear medicine units, and radiotherapy units. – Radio and television antennas, cell phones, LED screens, and radio frequency generators. – I don't know	single-choice
	Complete. Most of the primordial natural radionuclides present on Earth are originated from families headed by _____:	– Uranium 238, Uranium 235, and Thorium 232 respectively. – Uranium 232, Neptunium 239, and Thorium 234 respectively. – Uranium 234, Radium 226, and Radon 222 respectively – Radon 222, Polonium 218, and Bismuth 214 respectively. – I don't know	single-choice
	Which cosmic particles produce the highest equivalent dose at sea level?	– Electrons/photons – Charged pions – Neutrons – Muons – I don't know	single-choice

2-2- Population and Sampling

Population: The present study focused on students from various public and private universities enrolled in different fields of education, including Science, Engineering, Industry, Construction, Health, and Social Services. The study encompassed Higher Education Institutions throughout Ecuador, such as Universidad Técnica Particular de Loja, Escuela Superior Politécnica de Chimborazo, Universidad Yachay Tech, and Universidad San Francisco de Quito, among others (see Table 2).

Table 2. Enrollment Statistics of Ecuador's Higher Education Institutions as of October 29, 2019 (SENESCYT-Ecuador [27])

Field of Education	Men	Women	Total
Sciences	27620	18241	45861
Engineering, Industry, and Construction	70928	26694	97622
Health and social services	41682	78132	119814
Total	**140230**	**123067**	**263297**

By including students from diverse disciplines within the selected fields of education, the study aimed to provide a comprehensive understanding of modern physics comprehension among a broad range of learners. This approach allowed for valuable insights into the specific challenges and misconceptions that students across different disciplines might encounter when studying modern physics. Furthermore, the substantial population size of 263,297 students [27] ensured a robust sample for the study, enabling rigorous statistical analysis and enhancing the generalizability of the findings. By considering a wide representation of students from Higher Education Institutions across Ecuador, the study sought to capture a comprehensive view of modern physics understanding among university students throughout the country.

Sampling: To determine the appropriate sample size for the study, statistical considerations were considered. A Level of Confidence (α) of 0.05 was selected, indicating a desired confidence level of 95%. This means that there was a 95% probability that the obtained results would fall within the chosen confidence interval. Additionally, a Power ($1 - \beta$) of 0.95 was set, corresponding to a 95% power level. This signifies that the study was designed to have a 95% likelihood of detecting a true effect, should it exist within the population.

By calculating the sample size based on these parameters, the minimum recommended size was determined to be 384 students. However, for this particular study, a sample size of 400 university students was chosen. As stated, this sample included students from the faculties of health, engineering, and science, ensuring representation from diverse academic backgrounds.

In addition to the main focus of the study, data on socio-demographic variables, such as age, as well as information related to access to the internet, use of technologies and equipment, and learning styles, were collected. This comprehensive data collection allowed for a more holistic understanding of the factors that may influence students' modern physics comprehension.

2-3- Expert Validation of the Diagnostic Survey in Modern Physics

In the validation process of the questionnaire's content, we sought the expertise of eight highly qualified professionals who specialized in Modern Physics. These experts, consisting of physicists and engineers, possessed a deep understanding of the subject matter and had a median age of 45 years. Their collective experience in applying or studying Modern Physics exceeded 10 years, showcasing their extensive knowledge and engagement in the field. The panel of experts encompassed a diverse range of specialties within Physics, including Medical Physics, Didactic Physics, Quantum Computation, Solid-state Physics, and Nuclear Physics. This breadth of expertise ensured a comprehensive evaluation of the questionnaire, bearing in mind various aspects and perspectives relevant to Modern Physics education.

While seven of the experts hailed from Ecuador, one expert brought an international perspective, representing the Czech Republic. This international representation added valuable cross-cultural insights and enriched the validation process by incorporating diverse perspectives and experiences.

3- Results and Discussion

In the subsequent section, we engage in a comprehensive analysis of the outcomes related to specific individual questions that have the potential to reflect prevailing misconceptions. Our attention is directed toward the examination of common incorrect choices encountered in the pre-test. By exploring these choices, we aim to gain a deeper understanding of the multifaceted nature of misconceptions that students commonly possess. This investigation aligns with the principles of multimodality in teaching and learning, as it recognizes the importance of considering various modes of representation, such as verbal explanations, written comments, and visual cues, to unveil the cognitive processes underlying students' misconceptions [28].

3-1- On the Constituent of the Nucleus

Question 1 focuses on the composition of the atomic nucleus, which primarily consists of neutrons and protons, collectively known as nucleons. Understanding this fundamental aspect of atomic structure is crucial, as it forms the basis for more advanced concepts in physics, chemistry, and other scientific disciplines.

Figure 2-a provides an overview of the student responses. Among the participants, 40.3% correctly identified neutrons and protons as the components of the atomic nucleus. However, 34.9% of students erroneously included electrons within the nucleus, indicating a degree of confusion or misconception. Additionally, 4.5% of students mistakenly believed that the nucleus comprises electrons and protons or positrons and neutrons (answer: Other).

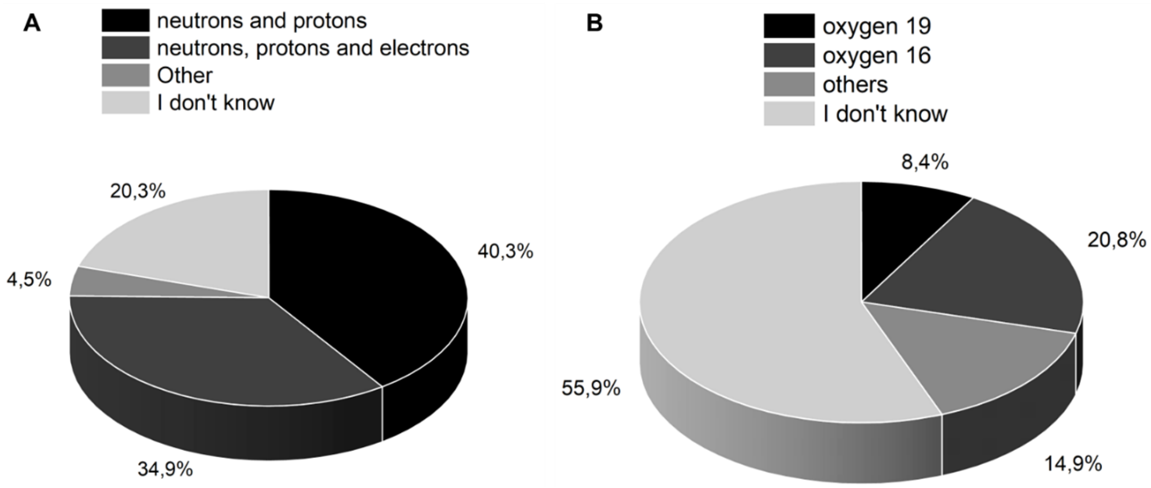

Figure 2. Survey results of (A) question 1 and (B) question 2 (see Table 1)

In particular, the inclusion of electrons within the nucleus by some students may stem from a variety of factors, including misconceptions or confusion about atomic structure. Here are a few possible reasons for this misunderstanding:

- Lack of clarity about the roles of electrons and protons: Students might not have a clear understanding of the distinct roles of electrons and protons within an atom. Since both electrons and protons are present in an atom, students may mistakenly assume that electrons are also part of the nucleus.
- Misinterpretation of diagrams, representations, or erroneous mental models: Students might have encountered diagrams or representations of atoms that inaccurately depict electrons within the nucleus. Misinterpretation of such visuals can contribute to misconceptions about the composition of the nucleus.
- Insufficient instruction or misconceptions about atomic structure: Students may not have received adequate instruction on atomic structure or may have developed misconceptions along the way. These misconceptions can persist if not addressed through effective teaching and clarification of concepts.

The fact that 20.3% of students were unable to identify or name the constituents of the atomic nucleus underscores the existence of a substantial knowledge gap. These statistics emphasize the importance of education in dispelling myths and reducing such knowledge gaps. Addressing these misconceptions requires targeted instruction and clarification of atomic structure concepts. Teachers can employ strategies such as hands-on activities, visual representations, and interactive discussions to help students develop a more accurate understanding of the roles and locations of electrons and protons within an atom.

Question 2 asks about the identification of an element based on a nucleus with 8 protons and a mass number of 19. The atomic number (Z) represents the number of protons in an atom's nucleus, determining the element's identity. It allows for differentiation between elements and categorization within the periodic table. The mass number (A) indicates the total protons and neutrons in the nucleus. Isotopes of an element have the same atomic number (Z) but differ in their mass number (A) due to varying numbers of neutrons. Understanding the atomic number (Z) and mass number (A) is crucial for identifying elements, distinguishing isotopes, predicting nuclear stability and radioactivity, analyzing nuclear reactions, and exploring energy and particle interactions. These concepts form the foundation for various scientific disciplines, including chemistry, environmental sciences, physics, and nuclear science.

Figure 2-b displays the answers provided, indicating a limited understanding among the respondents regarding atomic number (Z) and mass number (A). Only 8.4% correctly identified oxygen-19 as the element with 8 protons and a mass number of 19. Oxygen-19 consists of 8 protons and 11 neutrons. However, 20.8% of respondents incorrectly associated oxygen-16 as the isotope, highlighting confusion or a lack of awareness about isotopes. It should be noted that oxygen has multiple isotopes, including oxygen-16, oxygen-17, and oxygen-18. Furthermore, 14.9% of respondents mistakenly associated oxygen-19 with other elements such as lithium-8 or fluor-19 (answer: Other), indicating a lack of understanding about the specific properties and composition of atomic elements.

A significant portion, 55.9%, admitted not knowing the correct answer, suggesting a general lack of knowledge or familiarity with atomic number (Z), mass number (A), or the specific isotopes mentioned in the question. The reasons behind this lack of knowledge may include:

- Limited familiarity with isotopes and related concepts.
- Insufficient understanding of the atomic structure.

- Lack of knowledge about specific elements such as oxygen.
- Limited exposure to the topic.

To address these issues, effective teaching and learning strategies should focus on atomic structure, isotopes, and specific elements. Clear explanations, visual aids, experimental measurements, and ample practice opportunities can help improve understanding and knowledge in these areas.

3-2- On the Isotopes of the Nucleus

Question 3 relates to the isotopes of hydrogen. Isotopes are different forms of a chemical element with the same number of protons but varying numbers of neutrons in the atomic nucleus. Understanding isotopes is crucial for comprehending element diversity and their behaviors in chemical reactions, biology, and nuclear reactions. Isotopes have practical applications in medicine, such as radiometric dating, diagnostic imaging, and cancer treatments, as well as in environmental science for tracking pollution sources, studying geology, and understanding ecosystems. Isotopes have interdisciplinary connections with scientific fields such as chemistry, physics, geology, biology, archaeology, and environmental science. Understanding isotopes fosters interdisciplinary thinking, broadens perspectives, enhances collaboration, and encourages holistic problem-solving.

Figure 3-a displays the obtained results, revealing that 36.1% of respondents correctly identified the hydrogen isotopes. This indicates a reasonable understanding among a significant portion of the participants, who recognize deuterium and tritium as isotopes of hydrogen. However, 7.2% of respondents mistakenly identified deuterium and tritium as isobars of hydrogen, confusing them with atoms of different elements that share the same mass number but different atomic numbers. Moreover, 11.6% of respondents incorrectly associated deuterium and tritium with isotones of hydrogen or hydrogen ions. Isotones refer to nuclei with the same number of neutrons but different numbers of protons, while hydrogen ions represent charged forms of hydrogen atoms.

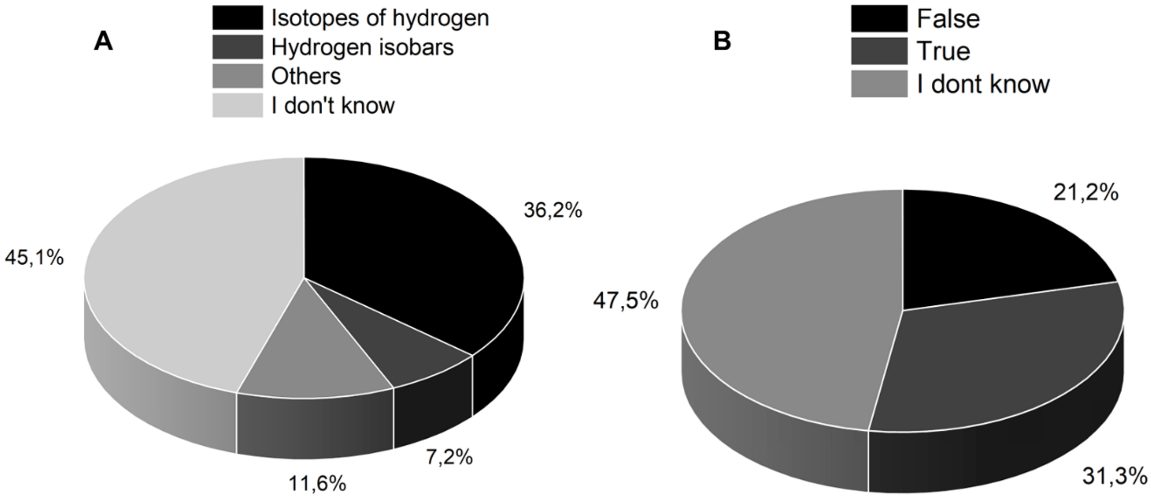

Figure 3. Survey results of (A) question 3 and (B) question 4 (see Table 1)

A notable 45% admitted to not knowing the correct answer, indicating a lack of familiarity or knowledge about hydrogen isotopes. Possible technical reasons for this lack of understanding include limited exposure or prior knowledge of isotopes, insufficient instruction or explanation about hydrogen isotopes, and unfamiliarity with terms such as "protium," "deuterium," and "tritium."

Addressing these technical reasons involves revisiting the curriculum, providing clear explanations, using effective learning materials, and addressing any pre-existing misconceptions or confusion through targeted instruction and clarification.

Question 4 addresses the chemical behavior of isotopes, which is crucial for understanding the concept of isotopes and their connection to the atomic structure and properties of elements. This knowledge enhances comprehension of atomic theory and the behavior of elements in chemical reactions. As mentioned, isotopes find significant applications in environmental and biological studies. For instance, stable isotopes are utilized to track the movement of elements in ecosystems, identify sources of pollution, and study food webs. Recognizing that isotopes with the same chemical behavior offer insights into environmental and biological processes underscores the practical implications of isotopes in these fields. As well, understanding that the chemical properties of an element's isotopes are identical enables us to predict isotopic properties and interactions in various contexts, such as compound formation and chemical transformations.

Based on the data presented in Figure 3-b, approximately 21.2% of respondents believed the statement to be false, indicating their understanding that isotopes of an element can exhibit different chemical behaviors. They may be familiar with instances where isotopes display variations in reactivity or behavior due to differences in their nuclear properties. Around 31.3% of respondents considered the statement to be true, suggesting their understanding or belief that isotopes of an element share the same chemical behavior. They likely recognize that chemical properties and reactions primarily depend on electron arrangement, which remains consistent regardless of isotopic composition.

The largest proportion of respondents, 47.5%, expressed uncertainty about whether the statement was true or false. This indicates a lack of familiarity or uncertainty regarding isotopic behavior, emphasizing the need for further education or clarification on the topic. It is important to recognize that the concept of isotopes can be complex, and individuals may have varying levels of exposure to this topic based on their academic background.

3-3- On the Stability of the Nucleus

Question 5 explores the significance of nuclear stability in understanding atomic behavior. The stability of atomic nuclei can be determined by evaluating the binding energy per nucleon. Higher binding energy per nucleon indicates greater stability, allowing for the identification of existing nuclei and those prone to radioactive decay. Understanding nuclear stability is essential for predicting and controlling reactions such as fission and fusion, which have implications in fields such as nuclear energy, medicine, and scientific research.

Nuclear stability also influences the release of energy during nuclear reactions. Reactions involving nuclei with lower binding energy per nucleon, such as nuclear fission, result in the release of energy as a heavy nucleus splits into lighter fragments. Conversely, reactions involving nuclei with higher binding energy per nucleon, such as nuclear fusion, release energy as light nuclei combine to form a heavier nucleus. Knowledge of binding energy per nucleon provides insights into the energy potential of nuclear reactions, which is crucial for harnessing nuclear energy. Furthermore, nuclear stability plays a vital role in stellar processes, such as nucleosynthesis, where fusion reactions power stars by converting hydrogen into helium and facilitating the synthesis of elements.

Regarding the specific question of carbon isotopes, Carbon-12 (12C) is the correct answer as it is more stable than Carbon-14 (14C). 12C is a stable isotope with six protons and six neutrons in its nucleus, remaining unchanged over time. It constitutes approximately 99% of naturally occurring carbon, making it the most abundant isotope.

In Figure 4-a, the majority of respondents (56.7%) indicated a lack of familiarity or understanding regarding the stability of carbon isotopes. Approximately 21.7% believed that 12C was the most stable, while 15.5% responded that 14C was the most stable. These responses could be influenced by factors such as misinformation, casual observations, or popular beliefs. For example, the association of 14C with radiocarbon dating might lead some to assume it is more stable. Additionally, individuals may mistakenly think that a higher mass number corresponds to greater stability without considering the nuanced factors affecting nuclear stability.

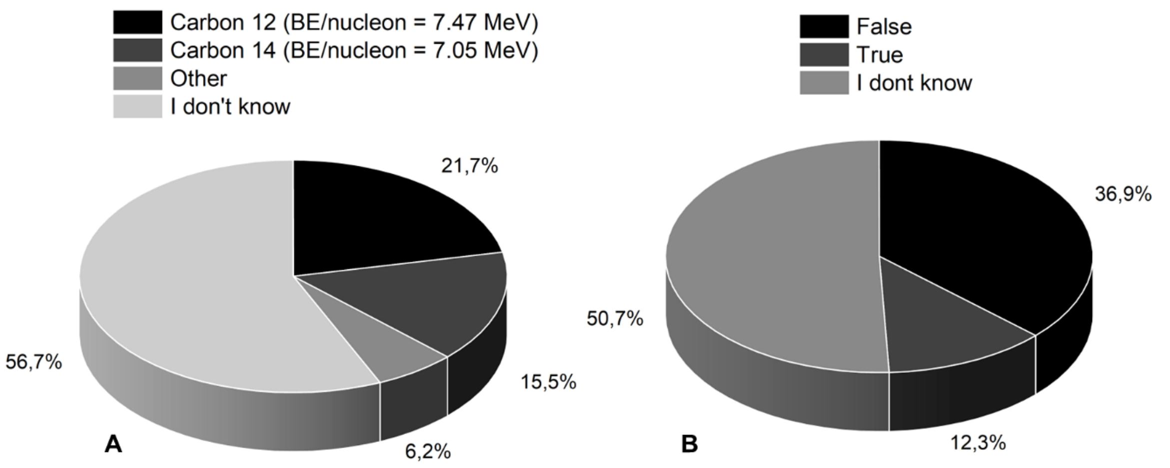

Figure 4. Survey results of (A) question 5 and (B) question 6 (see Table 1)

One common misconception, particularly among students, is the association of 14C with radiocarbon dating, leading them to assume it is more stable. Additionally, misconceptions based on mass numbers can contribute to the belief that higher mass numbers correspond to greater stability. It is worth noting that popular culture, including science fiction movies, sometimes inaccurately portrays 14C as more stable, further perpetuating this misconception.

A small percentage (6.2%) of respondents indicated that both 13C and 11C are the most stable, reflecting misconceptions or a lack of knowledge regarding the stability of carbon isotopes.

Question 6 examines the comparison of energy requirements for removing an electron from an atomic orbital versus removing a proton from its nucleus. Electrons play a central role in chemical bonding and reactions, while protons contribute to overall atom stability and identity. Understanding the energy needed to remove an electron, known as ionization energy, is crucial for comprehending ionization processes across fields such as chemistry, physics, and biology. Instead, the energy necessary to remove a proton from the nucleus is significantly higher than that required to remove an electron from an atomic orbital, primarily due to the strong nuclear forces that bind protons together within the nucleus.

In Figure 4-b, the majority of respondents (50.7%) indicated a lack of knowledge or understanding regarding the energy difference between removing an electron from an atomic orbital and removing a proton from its nucleus. This suggests a significant knowledge gap among the student population in grasping this concept. Notably, 36.9% of respondents believed that the statement about the energy difference between electrons and protons was untrue, indicating potential misconceptions or incorrect beliefs regarding the relative energies needed to remove electrons and protons.

A smaller percentage of respondents (12.3%) correctly recognized that the energy required to remove an electron from an atomic orbital is substantially lower than the energy required to remove a proton from the nucleus. These students demonstrate a better understanding of atomic structure and the nature of electron and proton binding energies.

3-4- On the Quantum Behavior of the Nucleus

Question 7 explores the characteristics or arguments supporting the notion of the atom's nucleus as a quantum system. By considering the nucleus as a quantum system, researchers can apply principles of quantum mechanics to describe and predict nuclear phenomena, including structure, reactions, and decay processes. Quantum effects such as tunneling, specific energy levels, the de Broglie wavelength, and intrinsic angular momentum are crucial in understanding the nucleus. Quantum mechanics plays a vital role in explaining phenomena such as alpha decay and nuclear fission, where particles can tunnel through energy barriers. The de Broglie wavelength associates' wave-like behavior with nucleons, reinforcing the quantum nature of the nucleus. Intrinsic angular momentum (spin) governs nuclear magnetic resonance and transition rules. Specific energy levels, quantized due to quantum mechanics, determine the stability and properties of atomic nuclei.

Among the respondents, Figure 5 shows that a small percentage (0.74%) selected all the correct items, demonstrating a strong understanding of the nucleus as a quantum system. Some respondents recognized the importance of internal structure and energy states (0.99%), quantum effects, wave-particle duality, angular momentum (0.98%), intrinsic angular momentum (1.23%), quantum effects and intrinsic angular momentum (1.47%), specific energy levels (1.97%), wave-particle duality and intrinsic angular momentum (3.69%), quantum effects and wave-particle duality (5.66%), and quantum effects like tunneling in processes such as alpha decay and nuclear fission (10.3%).

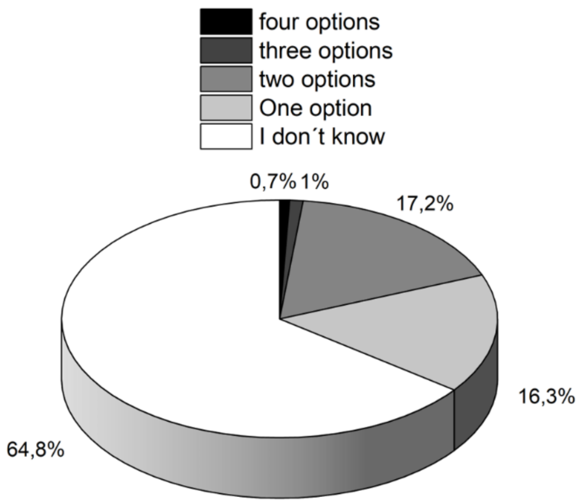

Figure 5. Survey results of question 7 (see Table 1)

However, the majority of respondents (64.77%) indicated a lack of knowledge or awareness regarding the characteristics of the nucleus as a quantum system. Understanding the nucleus as a quantum system can be a complex topic that may not have been extensively covered in their education, requiring a solid understanding of physics.

3-5- On the Nucleus Models

Question 8 pertains to the connotation associated with the "so-called magic numbers" predicted by the nuclear shell model. The concept of magic numbers in the nuclear shell model refers to specific numbers of protons or neutrons that result in highly stable configurations of atomic nuclei. These numbers play a crucial role in understanding nuclear stability and behavior. By studying magic numbers, scientists can gain insights into the binding energy, nuclear structure, and overall stability of different isotopes.

Magic numbers provide a framework for predicting and explaining various nuclear properties, including nuclear spin, magnetic moments, and nuclear reactions. The shell model helps determine the energy levels and arrangement of nucleons within the nucleus, influencing these properties. Exploring magic numbers allows researchers to investigate how these numbers relate to observable phenomena and make predictions about nuclear behavior. Addressing the concept of magic numbers in the nuclear shell model presents an opportunity to promote scientific literacy and education. Educators can introduce students to atomic nuclei, quantum mechanics, and the complexities of nuclear structure. This fosters a deeper understanding of the fundamental principles governing subatomic behavior.

Among the respondents, Figure 6 exhibits that 12.1% correctly identified that magic numbers indicate a lower probability of radioactive decay (high binding energy) and greater abundance in nature. This demonstrates an understanding of the relationship between magic numbers and nuclear stability. Elements with magic numbers of protons or neutrons tend to have higher binding energies, making them more stable and less prone to radioactive decay. Additionally, isotopes with magic numbers often occur more frequently in nature.

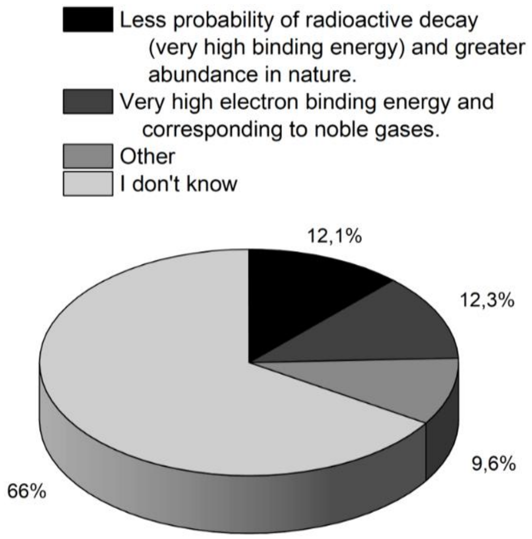

Figure 6. Survey results of question 8 (see Table 1)

However, 12.3% of the respondents provided an incorrect answer, associating the magic number with very high electron-binding energy and noble gases. This response indicates a misunderstanding of the concept. Magic numbers specifically pertain to the number of protons or neutrons in the atomic nucleus, not electron-binding energy or noble gases. Furthermore, 9.6% of the respondents suggested that magic numbers denote full orbital levels, resulting in the inability to form chemical bonds, and indicate very low neutron separation energies, leading to high radioactivity. These responses demonstrate a partial understanding. While it is true that magic numbers correspond to full orbital levels, influencing the chemical behavior of elements, the relationship between magic numbers and neutron separation energies is not accurately described. Magic numbers do contribute to nuclear stability, but their association with radioactivity is more complex and not solely dependent on neutron separation energies.

The majority of respondents (66%) indicated that they do not know the meaning of the magic number. This suggests a lack of familiarity or understanding of the concept, highlighting the need for further education and awareness regarding nuclear structure and the significance of magic numbers.

3-6- On the Radioactive Decay

Question 9 applies to beta-minus decay, a fundamental process in nuclear physics. It occurs when a nucleus has an excess of neutrons, causing one neutron to transform into a proton. During this transformation, an electron (referred to as a beta particle or beta-minus particle) and an electron antineutrino are emitted. The emitted electron carries away both excess energy and the charge resulting from the transformation. The electron antineutrino, being the antiparticle of the neutrino, also emerges during the process. It is important to note that the electron antineutrino has minimal interaction with matter and typically escapes without further interaction. Beta-minus decay is crucial for studying nuclear structure, radioactive decay, and the behavior of isotopes in various applications such as medicine and nuclear energy. It plays a significant role in maintaining the balance between protons and neutrons within a nucleus and contributes to the overall stability of atomic nuclei.

Regarding Figure 7, 11.1% of the respondents correctly identified that negative beta decay occurs when a nucleus possesses an excess of neutrons. In this situation, one of the neutrons transforms, releasing an electron (a beta particle) and an electron antineutrino. This description accurately represents beta-minus decay. However, 11.1% of the respondents mistakenly indicated that negative beta decay occurs when a nucleus has an excess of protons, causing one of the protons to transform into a neutron. This process, known as positron emission, is a form of radioactive decay but not negative beta decay. Additionally, 6.2% of the respondents described a scenario where there is an equal number of protons and electrons occupying different energy levels. This description does not align with negative beta decay; instead, it refers to electronic transitions in atoms, where electrons transition between energy levels. Furthermore, 2.7% of the respondents mentioned the emission of a photon for the de-excitation of the nucleus. This phenomenon corresponds to gamma decay, which involves the emission of high-energy photons (gamma rays) from an excited nucleus.

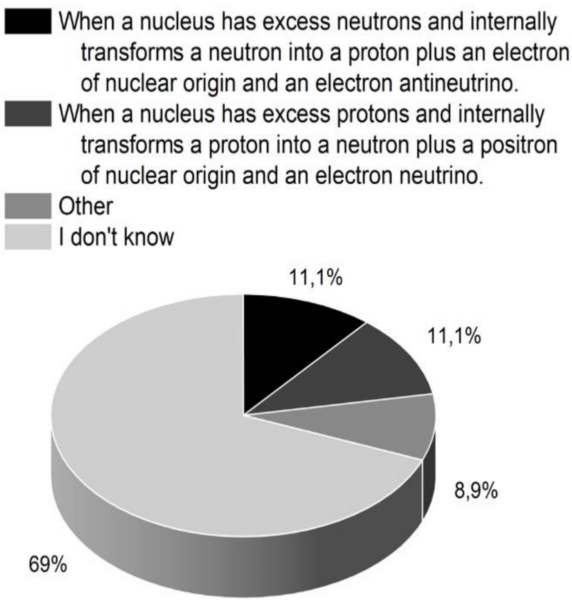

Figure 7. Survey results of question 9 (see Table 1)

The majority of respondents, 68.97%, expressed uncertainty by indicating that they do not know the correct answer.

3-7- On the Natural Radioactive Sources

Question 10 connects to the sources of natural radioactivity to which humans are exposed. Humans are exposed to natural radioactivity from various sources in our environment. One significant source is cosmic radiation originating from outer space, which bombards the Earth's atmosphere. These cosmic rays, composed of high-energy particles, contribute to our background radiation exposure. Terrestrial radiation also plays a role, as certain elements present in the Earth's crust, such as uranium, thorium, and radon, emit radiation. Radon gas, in particular, can accumulate in buildings and pose a risk, especially in areas with high levels of uranium and thorium in the soil. Additionally, natural radioisotopes can be found in foods such as bananas, nuts, and seafood, as well as in natural water sources [29].

Regarding Figure 8-a, 20.9% of students provided the correct response, identifying cosmic rays, food, water from natural springs, and the Earth's crust as sources of natural radioactivity. This reflects an accurate understanding of the sources contributing to natural radiation exposure. However, 13.79% of respondents mistakenly indicated that radioactive materials from hospitals, tomography, X-rays, nuclear power plants, and smoke detectors are the sources of natural radioactivity. This response is incorrect, as these sources are associated with artificial radiation, rather than natural radioactivity. It suggests a misunderstanding of the distinction between natural and artificial sources of radiation. Furthermore, 4.68% of respondents mentioned that food irradiation plants, synchrotrons, nuclear medicine units, and radiotherapy units are the sources of natural radioactivity. This response is also incorrect, as these sources pertain to artificial radiation used in various applications such as food preservation, research, and medical treatments. It indicates a lack of knowledge regarding the distinction between natural and artificial sources of radiation.

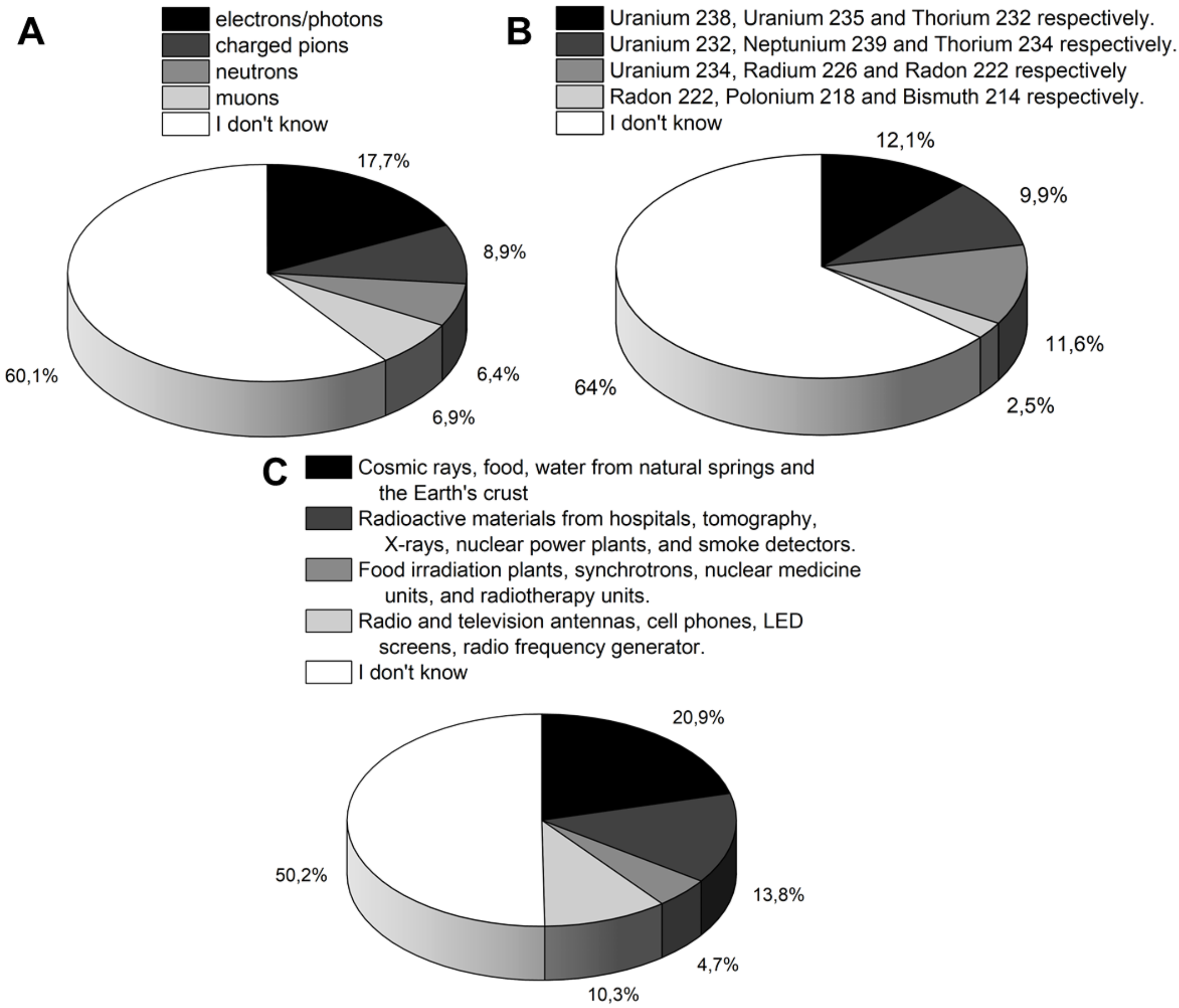

Figure 8. **Survey results of (A) question 10, (B) question 11, and (C) question 12**

In addition, 10.34% of respondents incorrectly stated that radio and television antennas, cell phones, LED screens, and radio frequency generators are the sources of natural radioactivity. This response is inaccurate, as these devices emit non-ionizing radiation and are not sources of natural radioactivity. It suggests a misconception or confusion between different types of radiation. The majority of respondents, 50.25%, indicated that they do not know the sources of natural radioactivity. This suggests a lack of awareness or knowledge about the topic among these respondents.

Question 11 refers to the origin of most of the primordial natural radionuclides present on Earth. These radionuclides are associated with specific decay series families, and their origins can be identified accordingly:

The Uranium-238 series family undergoes a series of radioactive decay until it reaches a stable isotope of lead, Lead-206, passing through several intermediate isotopes including Thorium-234, Protactinium-234, and Uranium-234.

The Thorium-232 family also follows a chain of decay until it reaches a stable isotope of lead, Lead-208, with intermediate isotopes such as Radium-228, Actinium-228, and Radium-224.

The Uranium-235 family, on the other hand, represents a shorter decay series. It goes through various isotopes including Francium-223, Radium-223, and Lead-207 before reaching a stable isotope of lead.

These three-decay series collectively contribute to the presence of various natural radionuclides on Earth, with Uranium-238 and Thorium-232 being the most abundant and significant in terms of radioactivity.

Figure 8-b evidence that 12.07% of the respondents correctly identified that most of the primordial natural radionuclides on Earth originated from families headed by Uranium-238, Uranium-235, and Thorium-232. This is accurate since these isotopes are part of the uranium and thorium decay series, which contribute to the natural radioactivity of the Earth's crust. However, 9.85% of the respondents incorrectly stated that most of the primordial natural radionuclides on Earth originate from families headed by Uranium-232, Neptunium-239, and Thorium-234. While uranium and thorium are correct, neptunium-239 is not a primary contributor to natural radionuclides on Earth.

Furthermore, 11.58% of the respondents mentioned that most of the primordial natural radionuclides on Earth originated from families headed by Uranium-234, Radium-226, and Radon-222. While uranium and radium are part of the natural decay chains, radon-222 is an intermediate decay product and not the head of a decay series. In addition, 2.46% of the respondents indicated that most of the primordial natural radionuclides on Earth originate from families headed by Radon-222, Polonium-218, and Bismuth-214. While radon and polonium are indeed part of the uranium decay series, bismuth-214 is not a head isotope in any significant decay series. The majority of respondents, 64%, indicated that they do not know the correct answer, suggesting a lack of understanding about the origins of primordial natural radionuclides on Earth.

Finally, Question 12 pertains to cosmic particles that produce the highest equivalent dose at sea level. At sea level, the primary cosmic particles responsible for the highest equivalent dose are muons. Muons are subatomic particles originating from cosmic rays, which are high-energy particles originating from outer space. When cosmic rays enter the Earth's atmosphere, they interact with atmospheric molecules, resulting in the production of a cascade of secondary particles. Among these secondary particles, muons are abundant and long-lived. They possess significant penetration power, allowing them to reach the Earth's surface.

Concerning Figure 8-c, 17.73% of the respondents incorrectly identified electrons or protons as the cosmic particles producing the highest equivalent dose at sea level. This response is inaccurate since electrons and protons, while present in cosmic radiation, are not typically the primary contributors to the equivalent dose at sea level. Furthermore, 8.87% of the respondents mistakenly indicated charged pions as the cosmic particles responsible for the highest equivalent dose at sea level. While charged pions are present in cosmic radiation, they are not the primary contributors to the equivalent dose at sea level. Additionally, 6.40% of the respondents mentioned neutrons as the cosmic particles producing the highest equivalent dose at sea level. Neutrons, although significant in cosmic radiation due to their ability to cause radiation exposure, are not the dominant contributors to the equivalent dose at sea level.

On the other hand, 6.90% of the respondents correctly identified muons as the cosmic particles producing the highest equivalent dose at sea level. Muons, being highly penetrating charged particles, are one of the primary components of cosmic radiation and make a substantial contribution to the equivalent dose at sea level. The majority of respondents, 60.10%, indicated that they do not know the correct answer, suggesting a lack of awareness or knowledge about the specific cosmic particles responsible for the highest equivalent dose at sea level.

3-8- Analysis of the Scores

Here we use the Kruskal-Wallis H test, which is a non-parametric statistical test used to determine if there are significant differences between two or more independent groups when the dependent variable is measured on an ordinal or continuous scale. It compares the ranks of the observations across the groups, rather than the actual values of the variable, and calculates a test statistic (H) to assess the differences.

Figure 9 shows the histogram that represents the grades obtained by the students, measured on a scale of 0 to 10 points (score out of 10). The histogram displays a right-skewed distribution, characterized by a tail on the left side and a peak on the right side. This indicates that the majority of students received lower grades, while a smaller proportion obtained higher scores. The mean grade is 1.98 points, which is higher than the median of 1.66 points, and both of these measures are higher than the mode, which is 0 points. This suggests that there are a few students who received extremely high scores, pulling the mean and median towards the lower end of the distribution. The left skewness in this context implies that only a few students performed relatively well on the questionnaire, with outliers the majority of students scoring poorly.

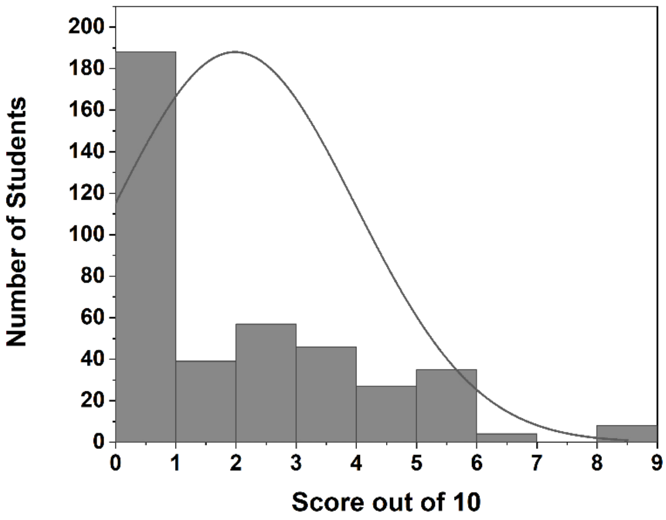

Figure 9. Number of students as a function of score out of 10

3-9- *Grades according to the Learning Style of the Student*

In Figure 10, students with an accommodating learning style, characterized by a preference for learning through movement, experiments, and the creation of original proposals, obtained a mean grade of 1.94 (SD = 2.26). The median grade was 0.83, with a minimum of 0 and a maximum of 8.33. Those who identified themselves as having an assimilating learning style, which entails reflective learning and a tendency to organize and systematize content, achieved a mean grade of 1.71 (SD = 1.82). The median grade was 0.83, ranging from 0 to 6.66. Students with a diverging learning style, characterized by a preference for learning through observation, attention to detail, and emotional engagement, obtained a mean grade of 2.52 (SD = 2.08). The median grade was 2.50, with a minimum of 0 and a maximum of 8.33.

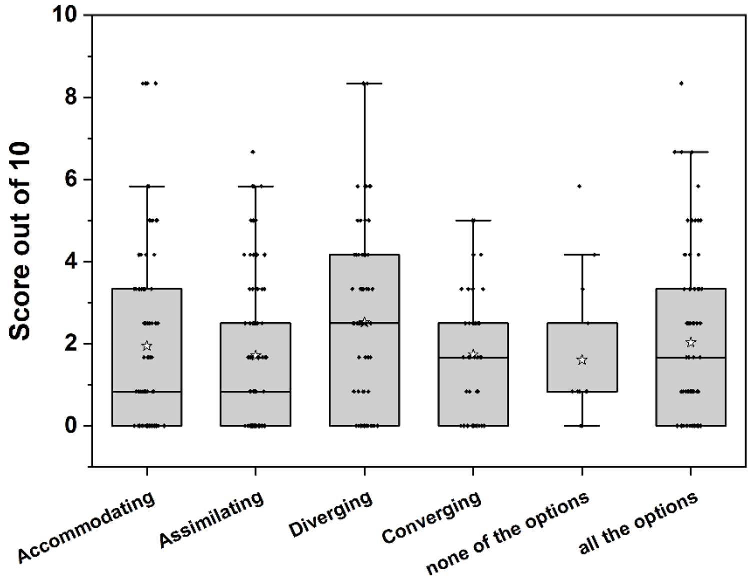

Figure 10. Score out of 10 as a function of the different learning styles

Those who identified themselves as having a converging learning style, involving a preference for practical experiences, problem-solving, and the application of theory, achieved a mean grade of 1.73 (SD = 1.48). The median grade was 1.66, ranging from 0 to 5.00. For students who chose "none of the options" and did not identify with any particular learning style, the mean grade obtained was 1.60 (SD = 1.81). The median grade was 0.83, with a minimum of 0 and a maximum of 5.83. Students who selected "all the options" and identified with multiple learning styles obtained a mean grade of 2.02 (SD = 2.03). The median grade was 1.66, ranging from 0 to 8.33.

A Kruskal-Wallis H test was conducted to examine the differences in grades obtained among the different learning styles ($\chi 2(2) = 8.44$, $p = 0.14$). The mean rank scores were 192.86 for accommodating, 188.25 for diverging, 233.46 for converging, 187.88 for none of the options, and 206.11 for all the options. The results indicate that the grade obtained in the survey did not vary significantly based on the different learning styles.

3-10-Grades according to University Type

In Figure 11, for students attending private universities, the mean grade obtained is 2.89 (SD = 2.16). The median grade is 2.5, with a range from 0 to 8.33. In contrast, students enrolled in public universities achieved a mean grade of 1.67 (SD = 1.85). The median grade was 0.83, ranging from 0 to 8.33. A Kruskal-Wallis H test, using the Nonparametric Tests > K Independent Samples procedure in SPSS Statistics, demonstrated a statistically significant difference in the grades obtained based on the type of university ($\chi^2(2) = 28.60$, $p = 8.8E-08$). The mean rank score was 254.85 for private universities and 184.82 for public universities. These results indicate a significant distinction in the grades obtained between the two types of universities.

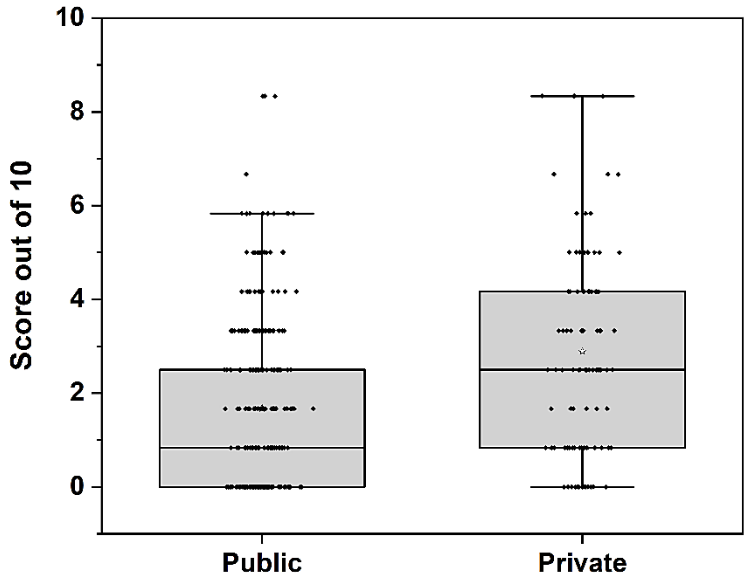

Figure 11. Score out of 10 as a function of the different university types

3-11-Grades according to the Area of the Residence of the Student

In Figure 12, for students residing in rural areas, the mean grade obtained is 1.91 (SD = 1.94). The median grade is 1.25, with a range from 0 to 8.33. On the other hand, students living in urban areas obtained a mean grade of 1.99 (SD = 2.02). The median grade was 1.66, ranging from 0 to 8.33. A Kruskal-Wallis H test, using the Nonparametric Tests > K Independent Samples procedure in SPSS Statistics, revealed no statistically significant difference in the grades obtained based on the student's area of residence ($\chi^2(2) = 0.009$, $p = 0.92$). The mean rank score was 201.09 for students in rural areas and 202.72 for those in urban areas. Thus, the grades obtained in the survey do not significantly differ based on the student's area of residence in the topics analyzed along the survey.

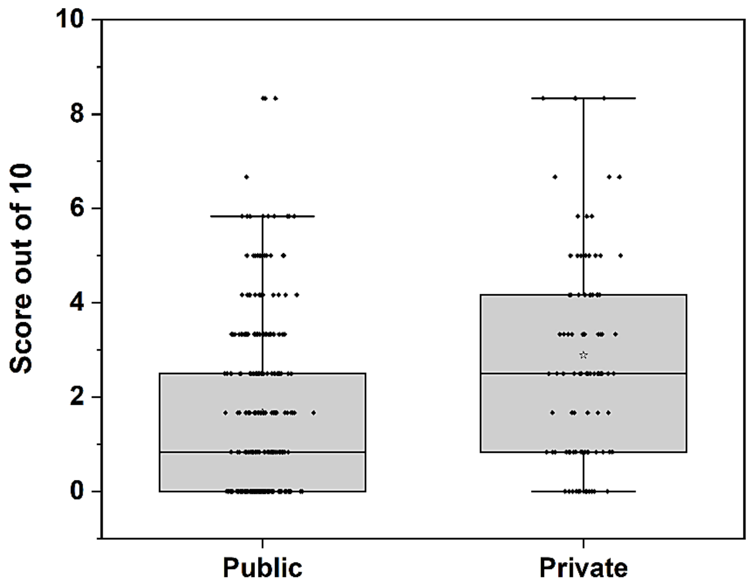

Figure 12. Score out of 10 as a function of the students residing area

3-12-Grades according to the Academic Level

Figure 13 presents the grade distribution for different academic level of students. Students in the pre-college level obtained a mean grade of 0.15 (SD = 0.37), with a median grade of 0. The minimum grade was 0, while the maximum grade reached 1.66. For students in the first to third level, the mean grade obtained was 2.19 (SD = 2.00), with a median grade of 1.66. The grade distribution ranged from 0 to 8.33. Students in the fourth to seventh level achieved a mean grade of 2.81 (SD = 2.10), with a median grade of 2.50. The minimum grade recorded was 0, while the maximum grade was 8.33. Those in the eighth to tenth level obtained a mean grade of 1.83 (SD = 1.36), with a median grade of 1.66. The grade range varied from 0 to 5.

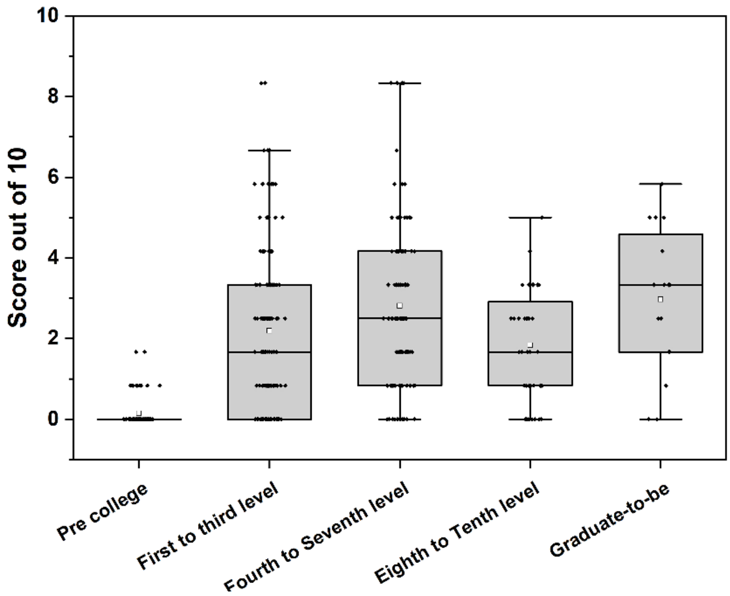

Figure 13. Score out of 10 as a function of the different levels of students

Undergraduate students obtained the highest mean grade of 2.96 (SD = 1.79), with a median grade of 3.33. The minimum grade recorded was 0, while the maximum grade reached 5.83. A Kruskal-Wallis H test was conducted to assess the differences in grades among the academic levels of students ($\chi^2(2) = 113.12$, $p = 1.58E\text{-}23$). The mean rank scores were 80.30 for precollege, 216.48 for the first to third level, 251.85 for the fourth to seventh level, 207.71 for the eighth to tenth level, and 267.66 for undergraduates. These results indicate a statistically significant difference in the grades obtained across the different levels of students. Thus, the grade obtained in the survey significantly varies based on the academic level of the student.

4- Conclusions

The pre-test presented here is a tool to assess knowledge about domains of modern physics related to the constituent and stability of the nucleus, quantum behavior of the nucleus, nuclear models, radioactive decay, and natural radioactive sources. Our results highlight deficiencies in knowledge about basic aspects such as the atomic structure, distinguishing between isotopes other than hydrogen isotopes, and the notion of binding energy. Significant ambiguity is also observed in student understanding of the concept of the quantum properties inherent in the nucleus, the meaning of the nuclear shell model, and the process of beta-minus decay. In addition, there are misconceptions among students about the natural radioactivity that humans are exposed to and the natural radionuclides that originated on Earth. This outcome reaffirms the inferences articulated by [30–32], whose studies have previously reported a lack of attainment in learning outcomes within the domain of physics.

About the total grades, there is a clear distinction between the performance of a few students who scored high and the majority of students who scored lower. The students' learning styles (self-identified by the students) did not show a significant association with the grades obtained in the pre-test. Regardless of their learning style preference, students achieved high performance levels.

There is a significant difference in the grade’s students earn based on the type of college they attend. Students from private universities usually have higher grades compared to students from public universities. It is important to note that while these results indicate a significant difference, individual variations within each university type should be considered. There may be students in public universities who achieve high grades and students in private universities who achieve lower grades. The observed distinction is based on the overall performance of the student population at each university type.

There is no significant difference in the grades obtained by students based on their area of residence. Students residing in rural and urban areas achieved similar scores. However, it is crucial to consider that other factors beyond the scope of this study may still contribute to variations in academic performance among students in different areas of residence. This conclusion is based on the specific context of the surveyed population and may not be generalized to all rural and urban areas.

The grade obtained in the survey significantly varies based on the academic level of the student. As students' progress through their academic journey, there is a general trend of improvement in performance, with undergraduate students achieving the highest mean grades. These findings emphasize the importance of considering the academic level when interpreting and comparing the grades obtained in the survey.

Our findings advocate for expeditious implementation of targeted educational interventions, encompassing the elucidation of misconceptions and the integration of support tools within the pedagogical framework. The adoption of inductive educational methodologies, including Team-Based Learning, Case Studies, Guided Discovery Learning, Past Learning in Problems, and similar approaches, in conjunction with technology applications such as virtual reality and immersive environments, emerges as indispensable. This integrated approach is imperative for the augmentation of student comprehension and the cultivation of a comprehensive knowledge foundation in the domain of modern physics.

5- Declarations

5-1- Author Contributions

Conceptualization, T.T. and S.B.; methodology, T.T.; validation, T.T, D.F.V.L, E.B-P., and M.B.; formal analysis, T.T. and C.V.G.; data curation, T.T.; writing—original draft preparation, T.T. and S.B.; writing—review and editing, T.T. and S.B.; project administration, T.T.; funding acquisition, T.T. and M.B. All authors have read and agreed to the published version of the manuscript.

5-2- Data Availability Statement

The data presented in this study are available in the article.

5-3- Funding

This work was supported by Corporación Ecuatoriana para el Desarrollo de la Investigación y Academia – CEDIA and Universidad Técnica Particular de Loja (UTPL).

5-4- Acknowledgements

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5-5- Institutional Review Board Statement

Not applicable.

5-6- Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

5-7- Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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