ORIGINAL ARTICLE

INTERNATIONAL JOURNAL OF ARTIFICIAL INTELLIGENCE

ISSN: 2692-5206, Impact Factor: 12,23
American Academic publishers, volume 05, issue 05,2025

Journal: https://www.academicpublishers.org/journals/index.php/ijai

INTEGRATING ELEMENTS OF QUANTUM PHYSICS INTO PHYSICS EDUCATION IN ACADEMIC LYCEUMS

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Annotation: This article is dedicated to studying quantum mechanics topics such as blackbody radiation, the Compton effect, Bohr's theory, de Broglie waves, wave-particle duality, and Heisenberg's uncertainty relations within academic lyceums and higher educational institutions. These topics are explored based on the principle of consistency. Introducing probabilistic-statistical concepts enables the identification of the probabilistic-statistical nature of each topic, facilitating a deeper and faster understanding of core concepts by students and learners. A consistent, structured approach to these quantum physics topics significantly improves the quality of physics education.

Keywords: Principle of consistency, blackbody radiation, Rayleigh–Jeans and Wien's laws, photoelectric and Compton effects, Bohr's theory, de Broglie wave, wave-particle duality, Heisenberg uncertainty relations.

INTRODUCTION

Educational institutions that are part of the continuous education system—including general secondary schools, academic lyceums, and higher education institutions—attach special importance to the study of quantum physics within the physics curriculum.

One of the main challenges in the current continuous education system is the lack of adequate attention to the application of the didactic principle of consistency in teaching physics at different levels. While general physics, theoretical physics, and methods of teaching physics are studied in higher education, this principle is often overlooked in lower stages of education. As a result, a unified and coherent system that ensures methodological and content consistency in teaching physics in academic lyceums and universities has yet to be developed [23, p. 8].

The principle of consistency, from a scientific standpoint, aligns with the principle of correspondence, and from a didactic perspective, involves the development of subject-specific requirements for educators. This is especially crucial when teaching the same subject at different educational levels, where content may be similar but the depth, complexity, and teaching methods differ. The principle of consistency plays a significant role in the development and analysis of quantum mechanical concepts [8, p. 56].

Each level of education—general secondary, academic lyceum, and higher education—has its own requirements for studying physics topics. However, the main goal is to ensure that at every educational stage, teaching is organized with a focus on continuity, taking into account

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American Academic publishers, volume 05, issue 05,2025

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students' level of knowledge, mathematical preparation, and logical thinking skills. This approach helps enhance students' interest and motivation in learning the fundamentals of physics, ultimately improving the quality of education and contributing to the training of qualified specialists.

In the introduction of the article, we aim to justify the main objective. The core purpose is to substantiate the need for developing the goals, objectives, and methodology for applying the principle of continuity in education across all levels of the continuous education system—particularly in general secondary education, academic lyceums, and higher education institutions.

MATERIALS AND METHODS

In writing this article, the current state of quantum mechanics instruction in general secondary schools, academic lyceums, and higher education institutions was studied. A comprehensive scientific analysis method was employed.

Max Planck's exploration of the laws of blackbody radiation demonstrated that classical physics theories are only fully valid in limiting cases where the physical quantities with the dimension of action are significantly greater than the value of the quantum of action.

Based on the idea that beyond the correspondence between classical and quantum theories in boundary conditions, there exists a deeper analogy, Niels Bohr formulated the principle of correspondence. This principle can also be viewed as a method for extending the boundaries of classical concepts in the development of new scientific knowledge [3, 4, pp. 23–56].

It is essential to ensure that students acquire a coherent understanding of quantum physics elements, which requires collaboration between physics and chemistry teachers to deliver uniform and meaningful content.

First and foremost, conclusions derived from teaching elements of quantum physics in the school physics curriculum should be used to qualitatively reconsider the methodology for studying electron states in atoms.

Teaching students the elements of quantum physics must be regarded as a modern educational priority, aimed at developing a contemporary understanding of the atom. Although the wave theory, which resolved many difficulties in Bohr's atomic model, has existed for over 70–80 years, Bohr's model is still widely used due to its simplicity in calculating the hydrogen atom's spectrum. However, given the tremendous scientific and technological advances humanity has achieved over time, students must now be familiar with the foundations of modern science.

To achieve this, quantum physics topics should be studied in depth, with particular attention to developing confidence in the wave nature of particles. If students are thoroughly introduced to key modern physics concepts—such as the idea of a "trajectory" for micro-particles and the "state" of micro-particles through probabilistic ideas and frameworks—the

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American Academic publishers, volume 05, issue 05,2025
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connections between various topics in quantum physics will become more coherent and integrated [10, p. 82].

RESULTS AND DISCUSSION

The principle of continuity is considered a more general concept compared to the correspondence principle. In education, continuity refers to the interconnected development of knowledge, skills, and competencies across different levels of the educational system. This implies a logical connection between the knowledge acquired at earlier stages and the assimilation of new knowledge at later stages, with the previous content being retained and integrated [3, p. 79].

In general secondary education, probabilistic and statistical concepts are introduced qualitatively. At the academic lyceum level, these ideas are developed both qualitatively and to some extent quantitatively. In higher education, while studying general and theoretical physics courses within a defined scope and mathematical framework, these concepts are developed not only qualitatively but also in full quantitative terms.

The introduction of probabilistic and statistical ideas initially forms a scientific worldview in students and enhances their statistical reasoning, which is essential for practical activities [3, p. 95].

In the academic lyceum physics curriculum, the content and scope of probabilistic-statistical concepts are expanded and developed compared to general secondary education. For instance, although the Rutherford scattering experiments are initially introduced at an elementary level, they are studied in greater depth in the lyceum, enriching students' understanding of randomness [3, 2, pp. 97–156].

Similarly, in the study of atomic structure and models, general concepts are introduced first. In subsequent stages, students explore the planetary model of the atom, its limitations, Bohr's postulates, and the specifics of Bohr's theory of the hydrogen atom in more detail. Bohr's investigation of atoms revealed that electron motion within atoms follows specific laws that reflect their true nature, which he discussed thoroughly. Bohr identified a key feature of atomic spectra: energy levels change only in discrete amounts. He used this observation to construct his theory, which was based on two fundamental postulates.

Although Bohr's theory is studied in some detail at the lyceum level, it is explored even more deeply in higher education.

In higher education, particularly in the atomic physics section of the general physics course, students acquire a more profound and mathematically rigorous understanding of atomic models and Bohr's postulates compared to the academic lyceum.

In the quantum mechanics course, Bohr's theory of the hydrogen atom is studied by aligning the physical meaning and mathematical framework with the study of particle motion in a centrally symmetric potential field. This involves the application of partial differential

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equation methods and their analysis, thereby deepening both the physical and mathematical content. Quantum mechanics intensifies the depth of both conceptual and mathematical understanding in this context.

Furthermore, it is emphasized that Bohr's theory has a limited scope and is applicable primarily to hydrogen-like atoms. In this context, the formula for the energy of an electron located on a discrete orbital in hydrogen-like atoms is analyzed, and the understanding of quantum numbers is further developed. Although numerous sources repeatedly emphasize the limitations of Bohr's theory and its applicability only to hydrogen-like atoms, its connection to the general ideas regarding the distribution of electrons in atomic shells underlines its continued relevance. Therefore, the process of forming physical concepts and laws in the minds of students and learners must follow a clear and systematic framework. Based on this, the meaning and essence of probabilistic-statistical concepts are also comprehensively studied. At both the academic lyceum and higher education levels, it is advisable to focus on the most essential quantum mechanical concepts that are appropriate for the required scope of quantum physics education at these stages. In the quantum physics section of the academic lyceum physics curriculum, it is recommended to study the foundational topics of quantum mechanics in the following sequence: blackbody radiation, Stefan–Boltzmann law, Rayleigh–Jeans and Wien's formulas, quantum of energy, Planck's formula, photoelectric effect, Compton effect, wave-particle duality, De Broglie hypothesis and wave, physical interpretation of De Broglie waves, wave function and its physical meaning, atomic models, planetary model of the atom, Bohr's theory for the hydrogen atom, atomic spectra, spectral series, and Heisenberg's uncertainty principle. Studying these topics in the suggested order is expected to yield the desired educational outcomes. In the academic lyceum, the focus is primarily on the conceptual content rather than the mathematical derivation of formulas. Emphasis is placed on deepening students' understanding of the laws governing the microworld and presenting the material in a simple and comprehensible manner. Planck's introduction of the photon energy quanta—i.e., the concept of energy quantization—marked the beginning of a conceptual shift from continuous to discrete quantities. This served as the basis for developing the concept of quantization. In academic lyceums, this topic is taught through experimental observations and explanations of formula meanings, while in higher education, mathematical derivations of the Stefan–Boltzmann law, Rayleigh–Jeans and Wien's formulas, and Planck's formula are presented (reference: [2, p. 102]). As a result, the sequential and logical study of these topics is ensured. Specifically, the Planck formula is statistically proven using the probability coefficients introduced by Einstein, thereby deepening the statistical interpretation of probabilistic-statistical concepts. In academic lyceums, the photoelectric and Compton effects are also studied. While exploring these topics, students are introduced to the concept of photon momentum, which is theoretically and experimentally confirmed based on the corpuscular nature of light. The formula describing the change in photon wavelength is analyzed, and the Compton experiment is studied (reference: [3, p. 146]). In higher education, when studying quantum mechanics topics, Einstein's ideas and formulas serve as the foundation for introducing the concept of "probability" in the interaction process between photons and electrons:

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$$\Delta\lambda = 2\,\Lambda Sin^2\frac{\theta}{2}. \quad (1)$$

This reveals the statistical nature of such interactions.

In the Compton effect, the formula for the change in the photon's wavelength is derived and analyzed based on the laws of conservation of energy and momentum. The scattering process of the photon is analyzed using a probabilistic-statistical approach. In both academic lyceums and higher education, while studying the Compton effect, it is methodologically appropriate to emphasize that this effect is applicable not only to the scattering of light by electrons but also to its scattering by neutrons and protons. Moreover, solving problems related to calculating the Compton wavelength for protons and neutrons during practical lessons would be beneficial. To engage academic lyceum students, the topics of the photoelectric and Compton effects are analyzed based on learning outcomes and on experimental results that confirm the corpuscular and wave properties of radiation. Studying the wave-particle duality of photons in academic lyceums sets the stage for exploring De Broglie's hypothesis and wave. Students are introduced to the idea that De Broglie's hypothesis reflects the universality of wave-particle duality for all microscopic particles in nature. Experiments that demonstrate the wave properties of microparticles are explained to students, and their understanding is deepened through simple questions and problems. Through this process, the meaning of De Broglie waves $\psi(r,t) = Ce^{i(Et-\vec{p}\vec{r})}$ (2)

(2) is clarified, and students' knowledge is expanded. The physical meaning of De Broglie waves is revealed through the introduction of the concept of probability. In higher education, the De Broglie phase and group velocities of microparticles are introduced, and the relationship between De Broglie wavelength and the kinetic energy of microparticles is derived and analyzed separately for particles moving at relativistic, ultrarelativistic, and non-relativistic speeds. The relationship between the De Broglie wavelength and the Compton wavelength of microparticles is determined for electrons, and the nature of this relationship is analyzed [4, 5, pp. 124–256].

In academic lyceums, the statistical or physical meaning of the De Broglie wavelength is explained through simple examples, and its deeper understanding is developed based on the interpretation of quantum mechanics by M. Born. M. Born's interpretation connects the corpuscular properties of microparticles with wave phenomena when explaining the statistical meaning of the De Broglie wavelength. The intensity of the De Broglie wavelength at any point in space is proportional to the probability of finding the particle at that location. In this case, the ratio of intensities at different locations in space is important. Therefore, De Broglie waves provide a statistical description of the motion of microparticles. The probability of a microparticle's location determines the intensity of the wave, and the De Broglie wavelength is expressed in general as a complex function of coordinates and time, called the wave function. The statistical meaning of the De Broglie wavelength, or the probability of the microparticle's position, is expressed as shown in equation

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$$dW(x,y,z,t) = |\psi(x,y,z,t)|^2 dV \qquad (3).$$

The Heisenberg uncertainty principle (4) is taught in a simplified form in academic lyceums and is deepened in higher education while maintaining conceptual consistency.

$$\overline{(\Delta p_x)^2}\ \overline{(\Delta x)^2} \quad \frac{\hbar^2}{4} \qquad (4)$$

The principle that it is impossible to simultaneously determine the coordinates and momentum of a microparticle is one of the fundamental laws of nature. When analyzing the uncertainty principle, it is crucial to always consider that microparticles differ fundamentally from macroparticles. Classical mechanics, which assumes that a particle has both a precise position and momentum at any given moment, is radically different from quantum mechanics. It is important to emphasize this distinction when teaching the relevant parts of physics to students, as it plays a critical role in shaping their understanding. Thus, based on the above, quantum theory fully realizes the essence of Heisenberg's uncertainty principle from both a physical and mathematical perspective, fundamentally denying the possibility of simultaneously determining both position and momentum in classical mechanics. The Heisenberg uncertainty principle, which is based on the wave-particle duality of microparticles, should be emphasized in academic lyceums during the study of quantum mechanics. It requires deep philosophical reflection and physical knowledge from the teachers. Based on the above, the Heisenberg uncertainty principle limits the application of classical concepts to microscopic objects. In classical mechanics, to fully determine the motion of an object at all times, the initial conditions of its position and velocity must be given. However, according to the uncertainty principle, this is impossible. Therefore, in the microcosm, the concept of a particle's trajectory has no meaning. Only the probability of finding a particle at a specific point in space can be discussed. It should be emphasized that the impossibility of simultaneously determining both position and momentum is not due to technical difficulties but is inherently connected to the fundamental laws of nature, as confirmed by experiments. This idea should be deeply ingrained in students' and learners' minds. The Heisenberg uncertainty principle is associated with the Planck constant, which has the units of action, and this makes the principle have a limiting character. It is important to clarify that the uncertainty principle only applies to microscopic phenomena and reflects the physical essence of quantum mechanics, which differs significantly from classical concepts. Using the uncertainty principle, one can determine the smallest volume element in phase space and the surface area of a phase cell in phase space. In conclusion, based on the above topics, teaching in academic lyceums and higher education systems with an emphasis on consistency helps deepen students' knowledge and reduces the time spent on studying topics. In all educational levels, seminar classes on the radiation laws of absolute black bodies and their teaching have a significant role. A special methodology for organizing seminar classes on this topic should be developed for these two levels of education. Organizing seminar classes in academic lyceums and higher education institutions on the topic of the radiation laws of absolute black bodies is of great importance. The methodology for organizing seminar classes on this topic needs to be developed. It is advisable to start

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seminar classes with the study of the photoelectric effect. Below, we present the seminar class plan.

Seminar Plan for Studying the Photoelectric Effect in the Physics Course at Academic Lyceums

1. Laws of the Photoelectric Effect: Experimental results of studying the photoelectric effect.
2. Stolietov's Laws and Their Essence.
3. Einstein's Formula for the Photoelectric Effect and Its Significance.
4. Proving the Laws of the Photoelectric Effect Based on Einstein's Formula.
5. Applications of the Photoelectric Effect in Modern Technology.

Seminar Plan for Studying the Compton Effect in the Physics Course at Academic Lyceums

1. Deriving the Compton Formula Using the Law of Conservation of Energy and Momentum in the Compton Effect.
2. Proving the Compton Formula for Neutrons and Protons and Explaining How It Was Verified in Experiments.
3. Studying the Essence of Compton's Experiment and Modeling It on a Computer.

Organizing such seminars in the final years of academic lyceums will allow students to gain a deeper understanding of the essence of the effect and serve as a foundation for learning how to derive the Compton formula, study the collision phenomenon that lies at the core of this process, and model collisions on a computer.

Similar seminars are also advisable in undergraduate physics programs. It is considered appropriate to organize seminar sessions on quantum mechanics at the higher education level.

Conclusion

In conclusion, organizing seminars in academic lyceums and higher education institutions for the physics course, and partially in secondary education, would be appropriate as it helps to deepen the understanding of probabilistic-statistical concepts and ideas, and the essence of randomness. Organizing seminars on the photoelectric effect and deriving the Compton formula in academic lyceums will lay the foundation for understanding the collision phenomenon and its modeling on computers.

At the higher education level, including topics such as "De-Broglie Waves, Wave-Particle Duality" and "Heisenberg's Uncertainty Principle and Its Physical and Philosophical Implications" is also deemed appropriate. When these topics are taught experimentally in academic lyceums, with an emphasis on understanding the content of formulas, they can be expanded at the higher education level to include mathematical expressions for Stefan-Boltzmann's law, Rayleigh-Jeans, and Wien's laws, as well as Planck's formula.

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Teaching quantum physics at both academic lyceums and higher education institutions in a comparative way, while ensuring consistency in the discussion of formulas, will significantly improve the quality of education at both levels and contribute to the future enhancement of teaching quality.

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