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DEVELOPING STUDENTS' SCIENTIFIC THINKING IN THE STUDY OF QUANTUM MECHANICS

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Abstract: This paper examines methodological approaches to developing students' scientific thinking while they study quantum mechanics. Scientific thinking is interpreted as the ability to formulate and test hypotheses, connect theoretical models with physical phenomena, apply probabilistic reasoning, analyse evidence, and justify conclusions. A structured teaching sequence is proposed that combines problem situations, thought experiments, multiple representations, interactive simulations, evidence-based discussion, and reflective assessment. The approach helps students move beyond the mechanical use of formulas toward a conceptual and reasoned understanding of quantum phenomena.

Keywords: *quantum mechanics, scientific thinking, physics education, probabilistic reasoning, problem-based learning, interactive simulation, thought experiment.*

Introduction:

Modern physics education should not be limited to the transmission of established knowledge. It must also develop students' ability to reason scientifically, evaluate explanations, interpret evidence, and construct justified conclusions. This task becomes particularly important in quantum mechanics because its principles differ significantly from the intuitive concepts developed through everyday experience and the study of classical physics.

Concepts such as the wave function, superposition, probability density, quantum measurement, uncertainty, and wave-particle duality cannot be mastered through the memorisation of definitions and formulas alone. Research on university quantum

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mechanics has shown that students may successfully perform mathematical procedures while still experiencing difficulty in interpreting the physical meaning of their results or applying quantum principles in unfamiliar situations [1]. Reviews of introductory quantum education likewise emphasise the need for teaching approaches that connect formalism with conceptual reasoning and observable phenomena [4]. Therefore, instruction should deliberately foster evidence-based reasoning, model construction, and reflection on the limits of classical explanations.

The purpose of this paper is to identify methodological conditions and teaching techniques that can support the development of students' scientific thinking in the study of quantum mechanics. The methods used include analysis of physics education research, comparison of traditional and active-learning approaches, pedagogical modelling, and synthesis of research-based practices in quantum education.

Main part:

In the context of quantum mechanics, scientific thinking may be understood as a combination of conceptual, procedural, argumentative, and reflective abilities. A student who thinks scientifically should be able to:

- identify a physical problem and formulate a research question;
- propose hypotheses and evaluate their consistency with physical principles;
- distinguish between classical and quantum models of a phenomenon;
- connect mathematical expressions with their physical interpretation;
- use probabilistic reasoning to analyse quantum processes;
- interpret observations, experimental data, graphs, and computer models;
- justify conclusions and recognise the limits of an applied model;
- critically examine and revise their own reasoning.

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In a predominantly lecture-based approach, students often receive the conclusions of quantum theory in a ready-made form. Consequently, quantum mechanics may be perceived as a collection of difficult formulas that must be applied according to a fixed algorithm. To develop scientific thinking, the learning process should instead allow students to pass through the principal stages of scientific inquiry: identifying a problem, proposing an explanation, testing predictions, interpreting results, and refining a model. Research indicates that tentative reasoning can be productive because it enables students to compare competing conceptual structures and gradually build more coherent explanations [2].

The proposed methodology consists of five interconnected stages:

Problem situation. The instructor presents a phenomenon that cannot be adequately explained by classical ideas. Examples include single-particle interference, the photoelectric effect, quantum tunnelling, or spin measurement. Students formulate the problem and explain why a familiar classical model is insufficient.

Hypothesis generation. Students propose possible explanations, discuss them in pairs or groups, and predict the observations that would follow if each hypothesis were correct. The teacher does not immediately classify every answer as correct or incorrect but asks students to support their claims with physical arguments.

Construction of a quantum model. The necessary concepts and mathematical expressions are introduced together with their physical interpretation. For example, when discussing the wave function, students should distinguish the function $\psi(x,t)$ from the probability density $|\psi(x,t)|^2$ and examine how each representation changes with time. Symbolic, graphical, verbal, and experimental representations should be explicitly connected.

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Virtual or thought experiment. Students predict an outcome, vary the parameters of a model, and compare their predictions with a simulation or a logically constructed thought experiment. Visualisation is particularly useful for wave-packet evolution, potential wells, tunnelling, and particle interference. A combined simulation-tutorial has been shown to support students' visual understanding of the time evolution of quantum systems [3]. A broader synthesis of research-based quantum teaching strategies also confirms the value of guided inquiry, active engagement, and carefully designed representations [5].

Interpretation and reflection. Students determine which hypothesis is best supported, identify the evidence behind their conclusion, explain why a classical account is inadequate, and define the limits of the model used. This stage shifts attention from obtaining a formal answer to understanding and justifying the solution process. Evidence-based sensemaking has been found to be especially productive when learners integrate abstract quantum concepts [6].

The double-slit experiment provides a useful example of this sequence. Students first predict the distribution that will appear on a detection screen. After discussing classical particle and wave models, they observe how an interference pattern gradually emerges when particles pass through the apparatus one at a time. They then explain why the position of an individual detection event cannot be predicted with certainty, although the probability distribution of many events can be calculated. Finally, they analyse how obtaining which-path information changes the observed pattern. The activity promotes probabilistic reasoning and reveals the role of measurement in quantum mechanics.

The wording of instructional questions is also important. Questions such as “Which formula should be used?” or “What is the numerical answer?” mainly test reproduction and procedural fluency. To develop scientific thinking, students should regularly address questions such as:

- Which physical principles support this conclusion?
- How will the result change if the experimental conditions are modified?
- Which classical assumption is no longer applicable in this situation?
- What evidence could confirm or reject the proposed hypothesis?
- What is the physical meaning of the mathematical result?
- What are the limitations of the model being used?

Tasks that coordinate multiple representations are especially useful. A single quantum phenomenon may be represented through an equation, a graph, an experimental scheme, a verbal explanation, and a dynamic simulation. Students should learn not only to read each representation but also to translate between them and recognise what information each one provides. At the same time, the limitations of analogies must be discussed explicitly, because an uncritical transfer of classical images to quantum objects can reinforce misconceptions.

Assessment should also reflect the goal of developing scientific thinking. In addition to the correctness of a final answer, evaluation should consider the logical structure of the reasoning, the justification of a hypothesis, the interpretation of mathematical results, the use of evidence, and the ability to identify and correct errors. Suitable instruments include conceptual questions, open-ended problems, analysis of incorrect solutions, short written explanations, comparison tasks, and reflective reports.

The effectiveness of the proposed approach may be evaluated through four criteria. The cognitive criterion reflects understanding of fundamental quantum concepts; the operational criterion reflects the ability to apply knowledge in a new context; the argumentative criterion reflects the ability to justify conclusions using

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physical principles and evidence; and the reflective criterion reflects the ability to analyse and improve one's own solution. These criteria allow assessment to focus on the quality of thinking rather than on formula reproduction alone.

Conclusion:

Developing students' scientific thinking in quantum mechanics requires a transition from the presentation of ready-made knowledge to the organisation of inquiry-oriented learning. Problem situations, hypothesis generation, thought experiments, interactive simulations, multiple representations, evidence-based discussion, and reflection make abstract quantum concepts more meaningful. Through such activities, students learn not only to use the mathematical formalism of quantum mechanics but also to interpret results, test assumptions, revise models, and construct scientifically justified explanations. These abilities form an essential component of the professional competence of future physicists and physics teachers.

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