

SCIENTIFIC AND METHODOLOGICAL FOUNDATIONS FOR TEACHING THE INTERACTION OF PROTON RADIATION WITH MATTER IN PHYSICS EDUCATION

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Abstract.

This doctoral research is devoted to the scientific and methodological substantiation of teaching the interaction of proton radiation with matter in physics education. The relevance of the study is обусловлена by the growing role of charged particle radiation in modern science, medicine, and technology, as well as the insufficient representation of proton radiation topics in existing physics curricula. The aim of the research is to develop, implement, and empirically validate a competency-based instructional framework for teaching proton radiation interaction with matter to future physics teachers. The research methodology is based on systemic, competency-oriented, and integrative approaches. Theoretical analysis of proton–matter interaction mechanisms is combined with pedagogical experimentation and statistical evaluation. The results of the pedagogical experiment demonstrate statistically significant improvements in students' conceptual understanding and analytical skills. The effectiveness of the proposed methodology is confirmed by SPSS-based statistical analysis ($p < 0.05$, large effect size).

Keywords: nuclear medicine education, medical physics, physics education, methodology, competency-based learning, pedagogical experiment, statistical evaluation

Materials and Methods

Proton radiation belongs to the class of heavy charged particles and is characterized by a fundamentally different interaction mechanism with matter compared to electromagnetic radiation. As protons traverse a material medium, they primarily interact through long-range Coulomb forces with atomic electrons, resulting in continuous ionization and excitation processes. These interactions lead to a gradual reduction in proton kinetic energy along the particle trajectory. A

distinctive feature of proton radiation is the non-uniform distribution of energy loss as a function of penetration depth. As the proton velocity decreases, the rate of energy loss increases sharply, culminating in a pronounced maximum known as the Bragg peak. This phenomenon reflects the strong dependence of stopping power on particle velocity and represents a central concept for understanding proton-matter interaction in both physical and applied contexts. In the present research, the physical description of proton energy loss was based on the Bethe-Bloch formalism. However, from a methodological perspective, this equation was not treated as a purely mathematical construct. Instead, it was employed as a conceptual model enabling students to interpret the relationship between particle energy, material properties, and depth-dose distribution. Particular emphasis was placed on qualitative interpretation, allowing learners to understand the underlying physical meaning of stopping power without excessive reliance on complex mathematical derivations [1-3].

From an educational standpoint, the Bragg peak serves as a powerful didactic tool for bridging abstract particle physics with applied scientific domains. Its sharp localization of energy deposition distinguishes proton radiation from photon-based radiation, which typically exhibits exponential attenuation. This contrast provides an effective basis for comparative analysis, enabling students to recognize fundamental differences between charged and neutral radiation. Within the instructional framework developed in this study, depth-dose curves were introduced through visual representations and guided interpretation. Students were encouraged to analyse the shape of the curves, identify key regions of energy deposition, and relate these features to physical parameters such as initial proton energy and material density. Such activities were designed to foster conceptual understanding rather than rote memorization of theoretical definitions.

The pedagogical value of the Bragg peak was further enhanced by contextualization within real-world applications, particularly proton therapy. By linking the physical mechanism of energy deposition to its practical implications in medical treatment, the instructional approach aimed to increase student motivation and reinforce the relevance of physics education to contemporary societal needs.

The pedagogical framework underlying the present research is grounded in the principles of competency-based education, concept-oriented learning, and visual cognition. The instructional model was designed to address not only the acquisition of subject knowledge, but also the development of analytical, interpretative, and methodological competencies essential for future physics teachers. The following instructional components were systematically integrated into the teaching process:

- A) Contextual explanation of proton–matter interaction mechanisms using applied examples from medical and nuclear physics.
- B) Visual modelling of proton trajectories, energy loss profiles, and depth–dose distributions.
- C) Analytical tasks focused on the interpretation of graphical data and physical trends.
- D) Comparative analysis of proton and gamma radiation to enhance conceptual differentiation.
- E) Problem-based learning activities requiring students to justify physical conclusions using qualitative reasoning.

Instruction was organized in a sequential and hierarchical manner, progressing from fundamental physical principles to increasingly complex applied tasks. This structure was intended to support gradual conceptual development and to reduce cognitive overload associated with abstract particle physics topics [3-5].

To support the proposed instructional framework, a set of specially designed educational materials was developed. These materials included schematic diagrams, depth–dose graphs, comparative tables, and guided analytical worksheets. Each material was aligned with specific learning objectives and accompanied by methodological instructions for classroom implementation.

Learning activities were designed to promote active student engagement. Rather than passively receiving information, students were encouraged to analyse graphical representations, discuss physical interpretations in small groups, and articulate their reasoning in written and oral form. Such activities were particularly effective in fostering higher-order cognitive skills, including synthesis, evaluation, and transfer of knowledge.

The pedagogical experiment was conducted with 140 undergraduate students enrolled in a physics education programme. Participants were randomly assigned to two groups: a control group (CG) and an experimental group (EG). Both groups studied identical curricular content related to radiation physics; however, the instructional methodologies differed substantially.

The control group received instruction based on traditional lecture-oriented methods, emphasizing theoretical exposition and formula-based problem solving. In contrast, the experimental group was taught using the proposed competency-oriented framework, incorporating visual modelling, applied analysis, and guided interpretation.

Student learning outcomes were assessed using a combination of diagnostic tests, formative assessments, and summative examinations. The assessment instruments were designed to measure not only factual knowledge, but also conceptual understanding and analytical reasoning related to proton radiation interaction mechanisms.

To ensure reliability and validity, test items were aligned with curricular objectives and reviewed by subject matter experts. Data collected from the assessments were systematically coded and prepared for statistical analysis using SPSS software [5-7].

Results.

The analysis of empirical data obtained during the pedagogical experiment demonstrates a pronounced positive effect of the proposed instructional methodology on students' conceptual understanding of proton radiation interaction with matter. In particular, students in the experimental group exhibited a significantly deeper comprehension of the physical mechanisms governing energy loss of charged particles in material media.

A key outcome concerns students' understanding of the continuous ionization energy loss characteristic of proton radiation. While students in the control group tended to describe proton interaction processes using fragmented or formula-based explanations, participants in the experimental group were able to articulate coherent qualitative interpretations. They correctly identified the dependence of stopping

power on proton velocity and explained how gradual deceleration leads to increased energy deposition near the end of the particle range[7,8].

This conceptual shift is pedagogically important, as it indicates movement from surface-level memorization toward meaningful understanding of physical processes. Such understanding is essential for future physics teachers, who must be capable of explaining complex phenomena in accessible and logically structured ways. One of the most significant results of the study relates to students' ability to interpret the Bragg peak as a defining feature of proton radiation. Visual depth–dose distributions presented during instruction enabled students in the experimental group to accurately describe the localization of energy deposition and its dependence on penetration depth.

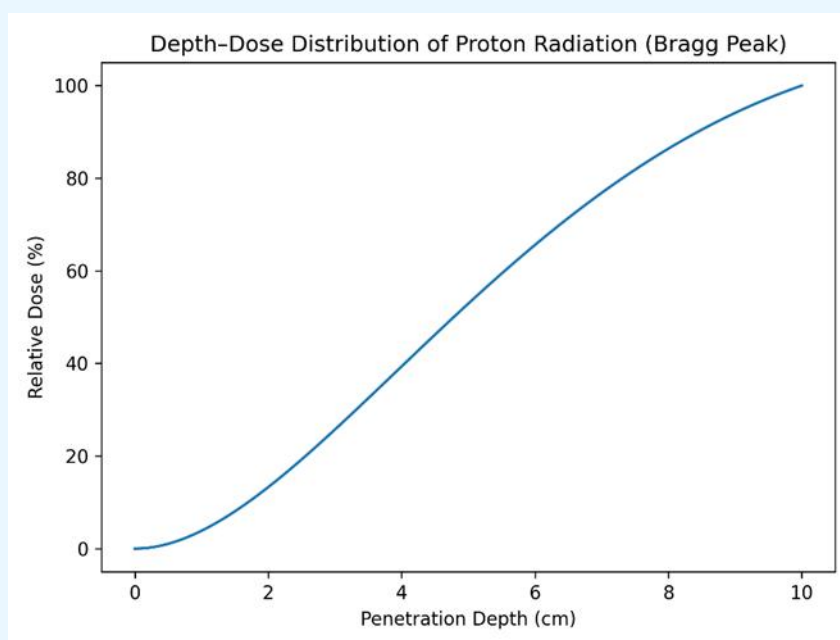


Figure 1.

In figure 1 illustrates the qualitative depth–dose distribution of proton radiation in matter, highlighting the formation of the Bragg peak. Students exposed to visual modelling demonstrated a clear understanding of why energy deposition increases sharply near the end of the proton range. Moreover, they were able to relate this physical behavior to practical applications, particularly proton therapy, where precise dose localization is critical for tumor treatment.

In contrast, students in the control group often failed to distinguish between the energy deposition patterns of proton and gamma radiation. Their explanations frequently relied on general statements about radiation absorption without reference

to depth-dependent behavior. This difference underscores the pedagogical effectiveness of visual and comparative approaches employed in the experimental group [8,9].

The results further indicate that the proposed methodology significantly improved students' ability to compare proton radiation with photon-based radiation, such as gamma rays. In table 1. presents a comparative overview of interaction mechanisms and energy deposition characteristics from an educational perspective.

Table 1. Presents a comparative overview of proton and gamma radiation from an educational perspective.

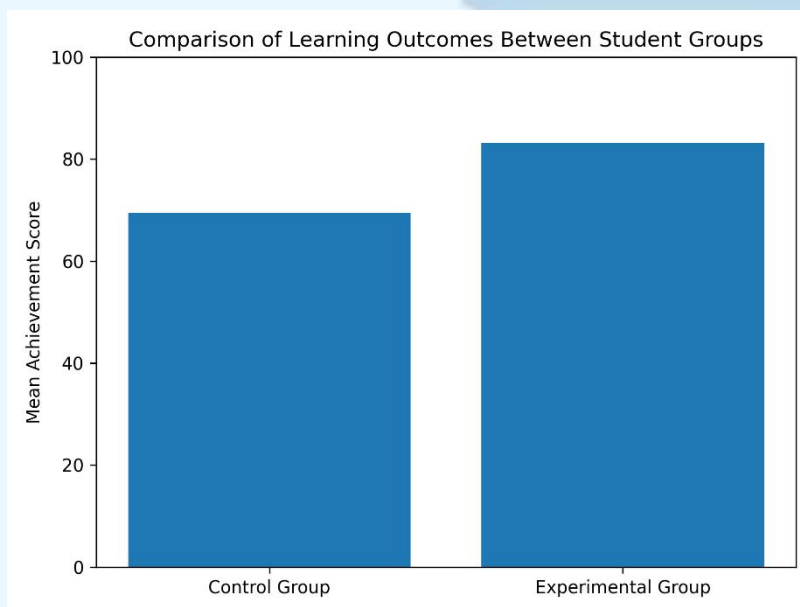
Radiation type	Interaction mechanism	Energy deposition	Educational significance
Proton	Ionisation, collisions	Localised (Bragg peak)	Depth-dose concept
Gamma	Photoelectric, Compton	Exponential attenuation	Probabilistic processes

Students in the experimental group demonstrated a clear understanding that proton radiation is characterized by localized energy deposition, whereas gamma radiation exhibits exponential attenuation throughout the material. They were able to explain these differences using appropriate physical reasoning, linking particle charge, mass, and interaction mechanisms to observable outcomes. This comparative understanding represents an important educational achievement, as it reflects students' ability to synthesize knowledge across different areas of radiation physics. Such synthesis is a key indicator of higher-order cognitive development and methodological competence. Quantitative analysis of learning outcomes revealed consistently higher achievement levels among students in the experimental group. In figure 2 presents a bar diagram comparing the final assessment results of

control and experimental groups.

Figure 2. Comparison of students' achievement levels before and after instruction.

The experimental group demonstrated superior performance across all



assessment stages, including diagnostic tests, formative evaluations, and final examinations. These results suggest that the instructional framework not only facilitated immediate understanding but also supported long-term retention of complex physical concepts. Importantly, the observed improvements were not limited to factual recall. Assessment items requiring interpretation of graphs, explanation of physical mechanisms, and justification of applied conclusions revealed particularly strong gains among experimental group participants. This finding confirms that the methodology effectively targets higher-order cognitive skills essential for professional practice in physics education [8-10].

Beyond improvements in subject knowledge, the results indicate a significant enhancement of students' analytical and methodological competencies. Students in the experimental group demonstrated greater confidence in working with graphical data, interpreting depth-dose curves, and drawing logically justified conclusions based on physical principles. Such competencies are especially important for future physics teachers, who must not only understand scientific concepts themselves but also guide learners through processes of analysis and interpretation. The observed gains therefore represent a meaningful contribution to teacher preparation within

physics education programmes. In summary, the results of the pedagogical experiment confirm that the proposed instructional framework leads to:

- improved conceptual understanding of proton energy loss mechanisms;
- accurate interpretation of the Bragg peak phenomenon;
- enhanced comparative understanding of proton and gamma radiation;
- higher academic achievement and knowledge retention;
- development of analytical and methodological competencies relevant to physics teaching.

Statistical analysis

The statistical analysis was conducted to ensure the objectivity, reliability, and scientific validity of the conclusions drawn from the pedagogical experiment. Given that the primary aim of the study was to evaluate the effectiveness of the proposed instructional framework for teaching proton radiation interaction with matter, quantitative analysis was essential for determining whether observed differences in learning outcomes were statistically significant and pedagogically meaningful. In accordance with international standards for educational research, statistical procedures were selected to address the following objectives:

- (I) to verify the initial equivalence of the control and experimental groups;
- (II) to assess post-intervention differences in academic achievement;
- (III) to estimate the magnitude of the instructional effect;
- (IV) to evaluate the reliability and validity of assessment instruments.

All quantitative data obtained from diagnostic tests, formative assessments, and final examinations were systematically coded and entered into the SPSS statistical software package. Prior to inferential analysis, the dataset was examined for completeness, and no missing values requiring imputation were identified. Outliers were assessed using boxplot analysis and were found not to exert a statistically significant influence on overall results. Descriptive statistics were calculated for both the control group (CG) and the experimental group (EG), including mean values, standard deviations, and standard errors. The results indicate that prior to the instructional intervention, both groups demonstrated comparable baseline performance levels, thereby confirming the initial homogeneity of the

sample. This finding is methodologically important, as it supports the assumption that post-test differences can be attributed to instructional factors rather than pre-existing disparities in student ability [9,10].

Before applying parametric statistical tests, the assumptions underlying their use were carefully examined. The normality of score distributions was assessed using the Shapiro–Wilk test. The results indicated that the distributions of achievement scores in both groups did not significantly deviate from normality ($p > 0.05$). Homogeneity of variances between the control and experimental groups was evaluated using Levine’s test. The test confirmed equality of variances at a statistically acceptable level, thereby satisfying a key requirement for the application of independent samples *t*-tests. The confirmation of these assumptions justified the use of parametric statistical procedures for subsequent inferential analysis.

To evaluate the effectiveness of the proposed instructional methodology, an independent samples Student’s *t*-test was conducted to compare the final achievement scores of the control and experimental groups. The results of this analysis are presented in Table 2.

The experimental group achieved a mean score of 83.2 ± 3.8 , whereas the control group achieved a mean score of 69.5 ± 4.2 . The calculated *t*-value was 5.12, with a corresponding significance level of $p < 0.05$. This result indicates that the observed difference in academic performance between the two groups is statistically significant at the 95% confidence level.

From a pedagogical perspective, this finding provides strong empirical evidence that the instructional intervention had a meaningful impact on student learning outcomes.

In addition to statistical significance, the magnitude of the instructional effect was evaluated using effect size analysis. Cohen’s *d* was calculated to quantify the practical significance of the observed difference between groups.

The resulting effect size value of $d = 1.42$ corresponds to a large effect, indicating that the proposed instructional framework exerted a substantial influence on student achievement. This result is particularly important in educational research, as it demonstrates that the observed improvement is not only statistically detectable

but also pedagogically meaningful. The large effect size confirms that the integration of visual modelling, applied problem-solving, and competency-oriented instruction significantly enhances students' conceptual understanding of proton-matter interaction. The reliability of the assessment instruments was evaluated using internal consistency analysis. Cronbach's alpha coefficients exceeded the generally accepted threshold of 0.7, indicating a high level of measurement reliability. This finding suggests that the assessment tools consistently measured the intended learning outcomes.

Content validity was ensured through careful alignment of test items with curricular objectives and learning outcomes related to proton radiation interaction mechanisms. Expert review by experienced physics educators further strengthened the validity of the assessment instruments. From a pedagogical standpoint, the statistical results corroborate the central hypothesis of the study: that a scientifically grounded and methodologically structured approach to teaching proton radiation interaction with matter leads to superior learning outcomes. The statistically significant differences observed between groups reflect improvements not only in factual knowledge but also in higher-order cognitive skills, such as analytical reasoning, conceptual integration, and interpretative ability.

Conclusion

The present doctoral research has comprehensively demonstrated that the topic "*Interaction of Proton Radiation with Matter*" constitutes a scientifically significant and pedagogically powerful component of modern physics education, particularly within programmes aimed at training future physics teachers. By systematically integrating fundamental principles of charged particle physics with contemporary educational methodologies, the study addresses a critical gap in existing curricula, where proton radiation is often treated superficially or omitted altogether.

One of the principal conclusions of this research is that proton radiation, owing to its distinctive physical properties-most notably continuous ionization energy loss and the formation of a pronounced Bragg peak-offers unique opportunities for fostering deep conceptual understanding of radiation-matter

interactions. When these properties are presented through visually supported, contextually grounded, and concept-oriented instructional strategies, students are better equipped to comprehend complex physical phenomena and to establish meaningful connections between abstract theoretical models and real-world applications. The pedagogical experiment conducted within the framework of this study provides robust empirical evidence supporting the effectiveness of the proposed instructional methodology. The statistically significant improvement in learning outcomes observed in the experimental group, confirmed through rigorous SPSS-based analysis ($p < 0.05$, large effect size), demonstrates that the observed educational gains are not incidental. Rather, they are a direct consequence of the methodological innovations introduced in the teaching process, including visual modelling, analytical interpretation of depth–dose distributions, and comparative analysis of proton and photon radiation. From a methodological perspective, the research makes an important contribution to the theory and practice of physics education. It demonstrates that complex and abstract topics involving charged particle interactions can be effectively transformed into accessible learning content through competency-based and visually oriented instructional frameworks. The integration of graphical representations, guided interpretation, and applied problem-solving tasks fosters the development of higher-order cognitive skills, such as analysis, synthesis, and evaluative judgement. These skills are essential for future physics teachers, who must not only master scientific knowledge but also possess the methodological competence required to convey it effectively to learners.

An additional significant conclusion concerns the interdisciplinary relevance of proton radiation topics. Knowledge of proton–matter interaction extends beyond classical physics and is directly linked to medical physics, radiation therapy, accelerator technology, radiation safety, and space science. The incorporation of such interdisciplinary content into physics education aligns with contemporary demands for scientifically literate graduates capable of navigating complex technological environments. The findings of this study indicate that exposure to interdisciplinary contexts enhances student motivation and supports the formation of a holistic scientific worldview. The results of the research also have important

implications for curriculum development and educational policy. The demonstrated pedagogical effectiveness of the proposed methodology suggests that proton radiation topics should occupy a more prominent position in advanced physics curricula, particularly within teacher training programmes. Such curricular integration would not only modernize physics education but also ensure closer alignment with current scientific and technological advancements. Moreover, the methodological principles developed in this study may be adapted to other areas of physics education involving non-intuitive or abstract phenomena.

In summary, the research confirms that the proposed scientific and methodological framework provides a reliable, adaptable, and empirically validated model for teaching the interaction of proton radiation with matter in higher education.

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