


**TEACHING THE PHOTOELECTRIC EFFECT IN HIGH SCHOOL: AN INQUIRY-BASED APPROACH GROUNDED IN THE HISTORY AND PHILOSOPHY OF SCIENCE**

**O ENSINO DO EFEITO FOTOELÉTRICO NO ENSINO MÉDIO: UMA ABORDAGEM INVESTIGATIVA COM FUNDAMENTOS DA HISTÓRIA E FILOSOFIA DA CIÊNCIA**

**LA ENSEÑANZA DEL EFECTO FOTOELÉCTRICO EN LA EDUCACIÓN SECUNDARIA: UN ENFOQUE INVESTIGATIVO FUNDAMENTADO EN LA HISTORIA Y FILOSOFÍA DE LA CIENCIA**

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**ABSTRACT**

The persistence of traditional practices in Physics Education, still centered on content exposition and the mechanical application of formulas, has hindered students' conceptual understanding of Modern Physics topics in High School, including the Photoelectric Effect. Considering the guidelines of the Brazilian National Common Curricular Base and the need for approaches that promote problematization and scientific argumentation, this article aims to present an inquiry-based proposal for teaching the Photoelectric Effect articulated with elements of the History and Philosophy of Science. This is a theoretical-bibliographic and propositional study that systematizes a didactic organization structured around a contextualized problem situation involving light sensors. The proposal mobilizes prior knowledge, fosters hypothesis formulation and confrontation, and leads to the conceptual systematization of the quantum model of light, highlighting the limitations of the classical wave interpretation. The incorporation of historical episodes supports the understanding of transitions between explanatory models and of the nature of science. As a result, a didactic organization suitable for the school context is outlined, capable of promoting comprehension of radiation–matter interaction and the role of frequency in photoelectric emission. It is concluded that the inquiry-based approach, integrated with digital resources and formative

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assessment, is viable and pedagogically relevant for High School, contributing to more meaningful learning aligned with current curricular guidelines.

**Keywords:** Physics Education. Photoelectric Effect. High School. Inquiry-Based Approach. History and Philosophy of Science.

## RESUMO

A permanência de práticas tradicionais no Ensino de Física, ainda centradas na exposição de conteúdos e na aplicação mecânica de fórmulas, tem dificultado a compreensão conceitual de temas da Física Moderna no Ensino Médio, entre eles o Efeito Fotoelétrico. Considerando as orientações da Base Nacional Comum Curricular e a necessidade de abordagens que promovam problematização e argumentação científica, este artigo tem como objetivo apresentar uma proposta investigativa para o ensino do Efeito Fotoelétrico, articulada a elementos da História e Filosofia da Ciência. Trata-se de um estudo de natureza teórico-bibliográfica e propositiva que sistematiza uma organização didática estruturada a partir de uma situação-problema contextualizada envolvendo sensores crepusculares. A proposta mobiliza conhecimentos prévios, fomenta a formulação e o confronto de hipóteses e conduz à sistematização conceitual do modelo quântico da luz, evidenciando os limites da interpretação clássica ondulatória. A incorporação de episódios históricos favorece a compreensão da transição entre modelos explicativos e da natureza da ciência. Como resultado, delinea-se uma organização didática viável ao contexto escolar, a proposta de ensino pretendida, capaz de favorecer a compreensão da interação radiação–matéria e do papel da frequência na emissão fotoelétrica. Conclui-se que a abordagem investigativa, integrada a recursos digitais e avaliação formativa, contribui e é viável e pertinente para ensino médio para uma aprendizagem mais significativa e coerente com as diretrizes curriculares vigentes.

**Palavras-chave:** Ensino de Física. Efeito Fotoelétrico. Ensino Médio. Abordagem Investigativa. História e Filosofia da Ciência.

## RESUMEN

La permanencia de prácticas tradicionales en la Enseñanza de la Física, aún centradas en la exposición de contenidos y en la aplicación mecánica de fórmulas, ha dificultado la comprensión conceptual de temas de la Física Moderna en la Educación Secundaria, entre ellos el Efecto Fotoeléctrico. Considerando las orientaciones de la Base Nacional Común Curricular de Brasil y la necesidad de enfoques que promuevan la problematización y la argumentación científica, este artículo tiene como objetivo presentar una propuesta investigativa para la enseñanza del Efecto Fotoeléctrico, articulada con elementos de la Historia y Filosofía de la Ciencia. Se trata de un estudio de carácter teórico-bibliográfico y propositivo que sistematiza una organización didáctica estructurada a partir de una situación-problema contextualizada relacionada con sensores crepusculares. La propuesta moviliza conocimientos previos, fomenta la formulación y confrontación de hipótesis y conduce a la sistematización conceptual del modelo cuántico de la luz, evidenciando los límites de la interpretación clásica ondulatoria. La incorporación de episodios históricos favorece la comprensión de la transición entre modelos explicativos y de la naturaleza de la ciencia. Como resultado, se delinea una organización didáctica viable para el contexto escolar, capaz de favorecer la comprensión de la interacción radiación–materia y del papel de la frecuencia en la emisión fotoeléctrica. Se concluye que el enfoque investigativo, integrado con recursos digitales y evaluación formativa, es viable y pertinente para la Educación Secundaria, contribuyendo a un aprendizaje más significativo y coherente con las directrices curriculares vigentes.



**Palabras clave:** Enseñanza de la Física. Efecto Fotoeléctrico. Educación Secundaria. Enfoque Investigativo. Historia y Filosofía de la Ciencia.



## 1 INTRODUCTION

The contents of Modern Physics occupy a strategic place in High School because they enable the understanding of phenomena that underlie technologies widely present in everyday life. However, their classroom approach does not always favor a consistent conceptual understanding. In many cases, these themes are presented in a synthetic way, excessively formal or disconnected from the scientific problems that gave rise to them, tending to transform them into fragmented and insignificant content for students (Nardi, 2001).

Among these contents, the Photoelectric Effect stands out for marking the transition between classical Physics and Modern Physics. The phenomenon highlights the limits of the wave model of light by demonstrating that the emission of electrons by certain materials depends on the frequency of the incident radiation and not only on its intensity, as predicted by the classical interpretation (Nussenzweig, 1997). This conceptual rupture goes beyond the technical sphere and opens space for epistemological discussions about the construction of scientific knowledge.

In the school context, the problematizing dimension of this historical-scientific episode is not always explored. The Photoelectric Effect is usually presented as a direct application of equations without investigating the experimental evidence that challenged classical physics and motivated new interpretations. By disregarding this historical and conceptual path, the opportunity to discuss science as a dynamic activity, built from debates, tensions and theoretical reformulations is lost (Delizoicov; Angotti; Pernambuco, 2002).

Brazilian curriculum guidelines, especially the National Common Curricular Base (BNCC), emphasize the development of skills related to the investigation of phenomena, evidence-based argumentation, and critical analysis of technological applications (Brasil, 2018). In this horizon, the teaching of the Photoelectric Effect can contribute significantly to articulate Science, Technology, Society and Environment (CTSA) by enabling the analysis of devices such as optical sensors and photovoltaic cells and other devices present in the daily lives of students.

The incorporation of elements from the History and Philosophy of Science (HFC) enhances this approach by showing that scientific models are provisional constructions, formulated in specific contexts and subject to revision in the face of new experimental data (Gil-Pérez, 1993; Cachapuz et al., 2005). Such a perspective favors a less dogmatic understanding of science and more coherent with its historical nature, contributing to the formation of an investigative and critical posture.

In view of these considerations, this article starts from the following research question:

how can an investigative proposal, articulated with elements of HFC, the contextualization of the relations between CTSA and the insertion of Digital Information and Communication Technologies (DICTs), favor the conceptual understanding of the Photoelectric Effect in High School from a contextualized problem-situation?

From this perspective, it is considered that the incorporation of DICTs can expand the possibilities of visualization, simulation and analysis of this phenomenon, as long as it is guided by clear pedagogical intentional objectives that are coherent with the construction of scientific meanings.

In line with this issue, the objective of this work is to present and systematize an investigative proposal for the teaching of the Photoelectric Effect in High School, structured around a problem-situation involving twilight sensors and guided by the problematization, formulation and confrontation of hypotheses and subsequent conceptual systematization of the quantum model of light. It is intended to show how this didactic organization can contribute to the understanding of the role of frequency in photoelectric emission, to the identification of the limits of the classical wave interpretation and to the analysis of technological applications associated with the interaction between radiation and matter, in line with the current curricular guidelines.

## **2 THEORETICAL FRAMEWORK**

### **2.1 TEACHING MODERN PHYSICS IN HIGH SCHOOL AND THE CHALLENGE OF THE PHOTOELECTRIC EFFECT**

The insertion of Modern Physics themes in High School has been defended as part of a scientific education consistent with contemporary demands, especially when linked to the understanding of technologies present in everyday life. The national curriculum guidelines, especially the BNCC, reinforce the centrality of practices that favor investigation, evidence-based argumentation, and critical reading of natural and technological phenomena, shifting teaching from a strictly transmissive logic to learning experiences with meaning and significance (Brasil, 2018).

In this scenario, the Photoelectric Effect acquires relevance because it marks the transition between classical and quantum physical models and allows the interpretation of applications such as sensors, optoelectronic devices, photovoltaic cells, among others.

Despite this relevance, the educational literature and school experience highlight a recurring problem: the Photoelectric Effect is usually presented as a "ready-made episode" of Modern Physics, often reduced to the exposition of the statement and the equation, with little exploration of the conceptual conflicts that make it meaningful.

In this way of teaching, the student tends to memorize relationships without understanding the central point of the phenomenon: the existence of a minimum frequency (or cutoff frequency) and the distinction between the role of frequency in the occurrence of emission and the role of intensity in the amount of electrons emitted. When this is not made explicit through problematization and consistent didactic mediation, intuitive interpretations persist (for example, the belief that "more intensity always guarantees emission"), which clash with the behavior observed in experiments and applications (Nussenzveig, 1997).

Thus, sustaining a proposal for teaching the Photoelectric Effect for High School requires recognizing that the obstacle is not only mathematical: it is epistemological. The theme becomes potent when the student realizes that the classical model, although successful in many contexts, does not explain certain experimental results that the change of model is not a "theoretical whim", but a response to evidence. It is precisely this passage (from the classical wave explanation to a quantum description) that needs to appear didactically as a construction and not as a simple exchange of formulas.

## 2.2 LEARNING AS CONSTRUCTION OF MEANINGS AND THE ROLE OF PROBLEMATIZATION

Overcoming school practices centered on the mechanical transmission of content remains a historical challenge of education. In educational criticism, Freire (1968) characterizes banking education as a form of teaching that reduces the student to the reception of information, weakening dialogue and problematization.

In another key, Rubem Alves (2010) points out that excessively rigid school models can limit student curiosity, creativity and engagement. This criticism gains even more sensitive contours in topics such as the Photoelectric Effect, because learning depends on the student attributing meaning to the "why" of the change in model and not only to the "how" to calculate a quantity.

From the psychological and pedagogical point of view, conceptual understanding can be favored when teaching is organized in such a way as to relate new information to existing structures, allowing the student to rework his ideas. Ausubel (1985) points out that learning gains meaning when new knowledge is anchored, in a non-arbitrary way, in what the student already knows.

Piaget (1998) contributes by situating cognitive conflict as an engine of conceptual reorganization through movements of imbalance and rebalancing. Vygotsky (1987), in turn, emphasizes social and linguistic mediation, emphasizing that conceptual advancement does



not occur in isolation, but in interaction (for example, teacher and student or between students in group discussion), especially in the Zone of Proximal Development (ZDP).

In curricular terms, this set of contributions converges with the requirement for learning that articulates understanding, argumentation, and critical application of knowledge rather than the reproduction of procedures (Brasil, 2018).

In this sense, the Photoelectric Effect becomes an especially fertile content for work with the construction of meanings, because it can be taught as a point of tension between competing explanations, mobilizing hypotheses and confronting predictions with evidence, instead of being presented as a definitive conclusion from the beginning, since learning implies constructing meanings and establishing relationships (Resnick, 1983).

### 2.3 TEACHING BY INQUIRY, HFC AND CTSA AND TDICs articulations

One of the most consistent ways to operationalize this change in perspective is teaching by inquiry. Gil-Pérez (1993) and Cachapuz et al. (2005) defend models centered on problem-situations that mobilize previous knowledge, stimulate the formulation of hypotheses and promote argumentative confrontation until the systematization of knowledge. In this approach, the problem-situation does not function as an "applied exercise", but as a trigger for real questions, capable of making initial conceptions explicit and creating conditions for their reconstruction.

In the case of the Photoelectric Effect, the work with HFC elements further strengthens the investigative structure because it helps the student to realize that science is not limited to ready-made truths: it involves debates, limits of theories, decisive experiments and conceptual changes. Historical episodes, when integrated with didactic intentionality, favor the understanding of the nature of science, the transition between explanatory models and the role of evidence in the development of knowledge (Cachapuz et al., 2005). In addition, the problematization can be enriched by links between STSA relationships by placing the phenomenon in dialogue with technologies and social choices that depend on the radiation-matter interaction, bringing the content closer to the student's concrete experience (Brasil, 2018).

The use of DICTs can also broaden the visualization and exploration of the phenomenon, as long as it does not become a substitute for conceptual reasoning. Simulations and digital resources tend to be productive when they come in as instruments to test hypotheses, facilitate the dynamics and visualization of the phenomenon in question, compare predictions and interpret results, maintaining the centrality of argumentation and teacher mediation. In other words, HFC, CTSA and TDIC do not appear as "decorative



additions", but as devices that help to sustain the investigative path and to make the phenomenon understandable at the level of high school schooling.

## 2.4 FORMATIVE ASSESSMENT, DIDACTIC TRANSPOSITION AND INCLUSION

Consistent with teaching by inquiry, evaluation cannot be limited to the final verification of correct answers. Campos and Nigro (1999) advocate an integrated evaluation of the process, capable of monitoring advances and difficulties and accurately guiding pedagogical interventions. Pozo (2009) reinforces this idea by proposing continuous and multidimensional evaluation strategies that allow observing how the student reorganizes his explanations and what obstacles persist. In the Photoelectric Effect, this is particularly important because many difficulties appear at the explanatory level: the student can even repeat the equation, but continue to interpret the phenomenon under a classical logic of "continuous energy" dependent only on intensity.

In addition, teaching Modern Physics in High School requires attention to didactic transposition. It is not a matter of "simplifying" university physics, but of reorganizing scientific knowledge into school knowledge, preserving its coherence and explanatory power in accessible language aligned with the curriculum (Delizoicov; Angotti; Pernambuco, 2002). From this perspective, materials such as those of the Group for the Reelaboration of Physics Teaching (GREF, 1993) and guidelines of the National Book and Didactic Material Program (PNLD) 2024, already articulate, in some cases, investigative strategies to everyday situations and to elements of HFC, CTSA and TDICs, supporting the teacher in the selection and organization of content in order to avoid mathematical formalism as an end in itself.

Finally, an investigative proposal consistent with the BNCC must consider the inclusive dimension of teaching. The organization of group activities, the use of multiple languages (text, debate, simulation, records), the progressive explanation of concepts and formative monitoring favor equitable participation, as long as the teacher plans interventions that recognize different rhythms, specificities and ways of learning of students (Brasil, 2018).

Thus, the theoretical framework systematized here sustains a proposal for teaching the Photoelectric Effect that seeks to produce conceptual understanding through problematization, investigation, mediation and historical-epistemological sense instead of the mechanical transmission of formulas.

## 3 METHODOLOGY

This study is presented as a propositional investigation, developed from a qualitative approach and based on theoretical-bibliographic research. By proposing a didactic

organization for the teaching of the Photoelectric Effect in High School, the article is not based on direct empirical application, but on the critical analysis of consolidated references in the field of Physics Teaching and Science Teaching.

Bibliographic research, as Gil (2010) points out, makes it possible to examine and articulate productions already prepared, such as books, scientific articles and normative documents, allowing the systematization of theoretical foundations pertinent to the problem in question. The option for the qualitative approach stems from the interest in understanding pedagogical implications, conceptual meanings and possibilities of didactic reorganization of the content, prioritizing interpretation rather than quantification of data.

Lüdke and André (2013) emphasize that investigations of this nature seek to apprehend meanings and relationships present in the analyzed references, while Bogdan and Biklen (1994) highlight that the focus falls on the contextualized understanding of the phenomenon studied. Although it does not involve subjects or data collection in the field, the present work shares this orientation by critically examining how the Photoelectric Effect is approached in the school environment and which alternatives can favor its conceptual understanding.

The methodological development started from the delimitation of a specific didactic problem: the recurrent presentation of the Photoelectric Effect as an isolated algebraic application, disconnected from the conceptual conflicts that marked the transition between the classical and the quantum interpretation of light.

From this delimitation, the following axes were analyzed: contributions of HFC elements to the teaching of Modern Physics, fundamentals of teaching by investigation, CTSA articulations, pedagogical use of TDICs and national curriculum guidelines with emphasis on the BNCC. We sought to identify theoretical convergences and gaps in the school treatment of the theme, especially with regard to the distinction between intensity and frequency of incident radiation.

In view of this, the investigative proposal presented in the article was elaborated. The didactic organization was structured around a contextualized problem-situation involving twilight sensors, contemplating the survey of previous knowledge, formulation and confrontation of hypotheses, guided insertion of historical episodes and conceptual systematization of the quantum model of light. Mathematical formalization was maintained at the level compatible with high school, preserving the scientific coherence of the phenomenon without reducing teaching to operational procedures.

As a limitation, it is recognized that the proposal was not empirically validated in the scope of this work, configuring itself as a didactic organization based on specialized literature



and open to future investigations of application and analysis in a school context. As this is a theoretical and purposeful study, there was no participation of students or collection of empirical data, dispensing with ethical procedures related to research with human beings.

## 4 RESULTS AND DISCUSSIONS

The critical examination of the literature selected throughout this work made it possible to outline a didactic organization focused on the teaching of the Photoelectric Effect in High School, conceived from the articulation between the survey of the students' initial conceptions, problematization anchored in a concrete technological context and progressive construction of the scientific model with teacher mediation and support from HFC elements, CTSA and TDICs relationships.

Considering that it is a theoretical-bibliographic and propositional study, the results presented focus on the explanation of this pedagogical organization and the analysis of its formative contributions discussed in the light of academic productions in the area.

### 4.1 ORGANIZATION OF THE DIDACTIC PROPOSAL

The proposal is organized in sequential and interdependent stages, designed to favor the conceptual reconstruction of the Photoelectric Effect based on a concrete problem. The starting point consists of the survey of the students' initial conceptions about light, energy, light intensity and frequency. This mapping can be carried out through a brief diagnostic pre-test or by guided reading of a short text that explores notions of this theme. The objective is not to classify answers, but to make visible previous ideas, often anchored in the conception that greater luminous intensity implies greater energy transferred.

The proposed problem situation is as follows: poles with twilight sensors turn on at dusk and turn off at dawn, responding differently to LED and incandescent lamps. The question then arises: does the operation of the sensor depend only on the intensity of the incident light or does the frequency of the radiation and the material of the sensor also influence the process?

Organized in small groups, students discuss the proposed situation and record their explanatory hypotheses. Interpretations based exclusively on the intensity of the light often emerge, evidencing an intuitive understanding close to the classic wave model. This conception refers to Maxwell's formulation, in 1865, which unified electricity and magnetism by demonstrating that disturbances in the electric and magnetic fields propagate in a vacuum with speed:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \quad (1)$$

whose numerical value is close to  $3.0 \times 10^8$  m/s, coinciding with the speed of light in a vacuum. From this correspondence, Maxwell concluded that light was an electromagnetic wave, and, in this theoretical framework, the energy carried by radiation was continuously related to its intensity (Nussenzvieg, 1997).

It is at this point that teacher mediation becomes decisive and necessary. The professor asks the groups to explain their justifications, promotes the confrontation between arguments and leads the reflection beyond the classical explanation, opening space for the introduction of experimental impasses that challenged the wave model and boosted the emergence of Modern Physics.

Conceptual systematization is conducted by articulating the problem-situation to historical episodes. In 1887, Hertz observed that the incidence of ultraviolet light radiation facilitated electrical discharges between metal electrodes. The phenomenon, later investigated by Lenard in 1902, revealed two results incompatible with Classical Physics: the existence of a minimum potential and frequency below which no electron emission occurs, and the dependence of the kinetic energy of electrons on the frequency of light and not on intensity. These results explain the limit of the classical wave model (GREF, 1993).

The conceptual rupture gains greater clarity with the introduction of Planck's hypothesis in 1900, according to which energy (J) is quantized and expressed by:

$$E = hf \quad (2)$$

where  $h$  is Planck's constant ( $6.63 \times 10^{-34}$  J·s) and  $f$  is the frequency (Hz) of the radiation.

In 1905, Einstein, based on the law of conservation of energy, applied this idea of Planck's to the photoelectric phenomenon, proposing that light is composed of photons (particles associated with discrete amounts of energy) and formulating the equation of the Photoelectric Effect:

$$E = \phi + K_{\max} \quad (3)$$

where  $\phi$  (J) represents the work function of the material, characterized by the electronic structure of the material and  $K_{\max}$  (J) the maximum kinetic energy of the ejected electron. Hence the condition of issuance:



$$hf \geq \varphi \quad (4)$$

defining the cut-off frequency  $f_0 = \varphi/h$  (Nussenzvieg, 1997).

For  $f < f_0$ , there is no emission, even in bright light; For  $f \geq F_0$ , electrons are ejected and the sensor is triggered. This shows that the color of the light, associated with its  $f$ , is decisive for the operation of the sensor, explaining why some lamps are more effective than others.

Once the condition  $f \geq f_0$  is satisfied, the intensity of the light starts to act in the process, because its increase leads to the number of incident photons per unit of time, resulting in greater emission of electrons and, therefore, in greater photoelectric current. Thus, the intensity controls the amount of electrons emitted, while the occurrence of the effect depends on the  $f$ . As  $\varphi$  is characteristic of the material, different sensors have different  $f_0$ , the higher  $\varphi$ , the higher the  $f_0$  and vice versa.

From the energy point of view, in photoelectric emission, the energy of the incident photon is divided into two parts: one to overcome that of the material and the other converted into the maximum kinetic energy of the emitted electron  $K_{max}$  (J), where  $K_{max} = eV_0$  (4). This energy balance is expressed by Einstein's equation for the Photoelectric Effect,  $E = \varphi + K_{max}$  (3), putting (2) in (3), becomes:

$$hf = \varphi + K_{max} \quad (5)$$

Thus, it is evident that the energy of electrons depends on the  $f$  of light and not on its intensity, in contrast to classical physics.

Although this corpuscular explanation adequately describes the Photoelectric Effect, it does not explain wave-like phenomena of light, such as diffraction and interference, observed in Young's experiment (1801), evidencing the wave-particle duality of light as an electromagnetic wave.

Thus, the discussion expands by problematizing the wave-particle duality. Young's experiment in 1801 demonstrated light interference, confirming the wave-like character of light. Later, Compton, in 1923, reinforced the corpuscular character by observing the scattering of X-rays by electrons, evidenced by the increase in wavelength dependent on the angle, interpreted as a collision between particles, where the photon transfers energy and momentum through:

$$\Delta\lambda = \lambda' - \lambda = (h/mec)(1 - \cos\theta) \quad (6)$$



Thus, for the first time, the understanding that light cannot be described exclusively as a wave or as a particle was consolidated. In interactions with matter, as in the Photoelectric Effect, it manifests corpuscular behavior, according to Einstein's interpretation; in propagation phenomena, such as interference and diffraction, it shows a wave nature, as demonstrated in Young's experiment (1801). This tension between models does not represent a contradiction, but rather an expansion of the explanatory framework of Physics (GREF, 1993).

The wave-particle duality was extended beyond radiation by De Broglie in 1924, when he proposed that dual behavior is not restricted to light, but applies to all matter. According to his hypothesis, each particle with a quantity of motion is associated with a wavelength given by:

$$\lambda = h/p \quad (7)$$

where  $\lambda$  represents the wavelength (m) and  $h$  the Planck constant (J·s). For non-relativistic particles, such as electrons in various experiments, linear momentum can be expressed by:

$$p = mv \quad (8)$$

where  $m$  is the mass (kg) and  $v$  is the velocity (m/s). Substituting (8) in (7) obtains:

$$\lambda = h/mv \quad (9)$$

This relationship shows that the greater the amount of particle motion, the shorter the associated wavelength, making its wavelike character less noticeable. However, for light particles and moderate velocities, such as electrons, the wavelength can be comparable to atomic dimensions, enabling the experimental observation of electron diffraction in the experiment by Davisson and Germer, in 1927, empirically confirming De Broglie's hypothesis and consolidating the conceptual basis of Modern Physics.

The paradigmatic change underway was deepened by Heisenberg, also in 1927, when he formulated the Uncertainty Principle, expressed by:

$$\Delta x \cdot \Delta p \geq h/4\pi \quad (10)$$

This relationship establishes fundamental limits to the simultaneous determination of the position ( $x$ ) and momentum ( $p$ ) of a particle, indicating that the very act of measuring



interferes with the observed system. The following year, Bohr synthesized this new understanding by proposing the Principle of Complementarity (1928), according to which wave and corpuscular descriptions are mutually necessary for the complete explanation of quantum phenomena, although they cannot be observed simultaneously in the same experimental arrangement (Nussenzweig, 1997).

Within the scope of the didactic proposal, the historical path is not presented as a mere chronological sequence of discoveries, but as a resource to understand the conceptual conflict faced by science itself. By returning to the problem situation of twilight sensors, students begin to recognize that the activation of the device depends on the energy of the incident photon, the work function ( $\phi$ ) characteristic of the material and the frequency of the radiation. The luminous intensity, although it influences the current generated after emission, does not determine its occurrence if condition (4) is not satisfied.  $hf \geq \phi$

This articulation between concrete problem, historical tension and progressive formalization of the scientific model makes visible the limits of the classical interpretation, according to which it would be enough to increase the intensity of light to increase the energy transferred. By showing that there is no emission when the frequency is lower than the cutoff frequency, even under intense radiation, the proposal introduces in a conceptually consistent way the foundations of Modern Physics.  $f_0$

Thus, the resolution of the problem-situation explains that the Photoelectric Effect depends on three interrelated factors: the frequency of the radiation that conditions the occurrence of the emission, the intensity that regulates the amount of electrons ejected, and the material of the sensor that defines the work function and, consequently, the cut-off frequency. The phenomenon is no longer presented as an isolated application of an equation and exemplifies the transition between different explanatory models.

In light of the BNCC guidelines, this approach favors the understanding of the nature of science and the relationships between CTSA when analyzing devices such as optical sensors, automatic doors, alarms, photovoltaic cells, among many others. By exploring such applications, the student broadens the interpretation of the concept and constructs meanings beyond the school context, recognizing its presence in everyday technologies.

To consolidate learning, the use of TDICs such as the interactive simulations of Physics Education Technology (PhET), allows you to dynamically observe the interaction between radiation and matter, manipulating the frequency, intensity and material of the metal. In these activities, students relate  $E$ ,  $f$ , and  $\phi$ , strengthening conceptual understanding, preventing mathematics from being reduced to a decontextualized algorithmic procedure.  $fE\phi f_0$



With this, the organization of the didactic proposal ends, which integrates problematization, conceptual mediation, HFC elements, CTSA articulations and intentional use of DICTs, paving the way for the discussion of its pedagogical implications in the following subsection.

#### 4.2 DISCUSSION OF THE RESULTS IN THE LIGHT OF THE LITERATURE

The systematized didactic organization converges with constructivist assumptions by mobilizing previous knowledge and promoting cognitive conflict, favoring progressive conceptual reorganization. The initial problematization proves to be fundamental to make alternative conceptions explicit, allowing mathematical formalization to emerge as a response to an explanatory impasse and not as an external imposition.

The incorporation of elements of HFC broadens the understanding of the nature of scientific knowledge. By highlighting the conflicts between classical and quantum interpretations, the proposal contributes to overcoming dogmatic views of science as a set of finished truths. This perspective is aligned with curricular guidelines that emphasize argumentation, critical analysis and contextualization.

Teacher mediation is decisive to maintain the balance between conceptual rigor and student participation. Mathematics is not eliminated, but reintegrated as an explanatory tool. Equations are no longer formulas to be applied mechanically and express interpretable physical relationships.

The articulation with digital resources and technological applications expands the formative reach of the content, reinforcing its relevance in the contemporary context. However, as it is a theoretical systematization, the proposal still lacks empirical validation in a specific school context, presenting itself as a possibility for future investigations.

In general, the results discussed indicate that the problematized teaching of the Photoelectric Effect, articulated with HFC, CTSA relations and the intentional use of DICTs, constitutes a consistent alternative to introduce fundamentals of Modern Physics in High School. By highlighting the limits of Classical Physics and explaining the conflicts that gave rise to the quantum description, the proposal favors a conceptually more solid, critical and contextualized understanding of the phenomenon.

#### 5 CONCLUSION

This article aimed to present and systematize an investigative proposal for the teaching of the Photoelectric Effect in High School, articulated with elements of HFC, CTSA relations and TDICs. From a theoretical-bibliographic and propositional research, a didactic



proposal was outlined centered on a problem-situation contextualized in the activation of twilight sensors as a strategy to mobilize initial conceptions, favor problematization and lead to the progressive construction of the quantum model of light.

The results discussed indicate that the proposal makes it possible to treat the Photoelectric Effect beyond the isolated use of equations, making visible the conceptual core of the phenomenon: the emission condition associated with the cut-off frequency, the work function of the material and the distinction between the role of frequency (occurrence of the effect) and intensity (amount of electrons emitted after the condition is satisfied).

By integrating historical episodes, from Young through Maxwell, Hertz, Panck, Lenard, Einstein, Compton, De Brogli, Davisson and German, Heisenberg and Bohr, with the explicitness of the tensions between classical and modern explanations, the sequence favors a less dogmatic understanding of science and closer to its real dynamics, marked by experimental impasses, dispute of interpretations, paradigm shifts, theoretical reformulations.

From the pedagogical point of view, the proposal is feasible to be applied in the school context because it brings together objective positive points: it starts from a technological problem close to everyday life, organizes clear stages (diagnosis, hypotheses, argumentative confrontation and systematization), preserves mathematical formalization compatible with High School without reducing the theme to algorithmic procedures and opens space for formative evaluation throughout the process through records, syntheses and justifications.

The use of interactive simulations such as PhET, when guided by questions and conceptual goals, tends to broaden the visualization of the phenomenon and support the interpretation of the relationships between frequency, energy, and material, reinforcing meaningful learning.

In summary, the proposal presented constitutes a consistent alternative to introduce fundamentals of Modern Physics in High School in line with the guidelines of the BNCC, by promoting investigation, argumentation and critical reading of phenomena and technological applications.

As a limitation, as it is a purposeful study, the didactic organization was not empirically tested in the scope of this work, pointing to the need for future investigations that implement the sequence in the classroom and analyze evidence of learning and challenges of teacher mediation. Even so, the systematization carried out offers a reasoned and replicable didactic path for the Photoelectric Effect to be taught as a significant conceptual construction and not as a mere application of formulas.



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## REFERENCES

- Alves, R. (2010). *Conversas com quem gosta de ensinar* (13<sup>a</sup> ed.). Papirus.
- Ausubel, D. P. (1985). *Aquisição e retenção de conhecimentos: Uma perspectiva cognitiva*. Plátano.
- Bogdan, R., & Biklen, S. (1994). *Investigação qualitativa em educação: Uma introdução à teoria e aos métodos*. Porto Editora.
- Brasil. Ministério da Educação. (2018). *Base Nacional Comum Curricular*. MEC.
- Cachapuz, A., et al. (2005). *A necessária renovação do ensino de ciências*. Cortez.
- Campos, M. C., & Nigro, R. G. (1999). *Didática de ciências: O ensino-aprendizagem como investigação*. FTD.
- Delizoicov, D., Angotti, J. A., & Pernambuco, M. M. (2002). *Ensino de ciências: Fundamentos e métodos*. Cortez.
- Freire, P. (1968). *Pedagogia do oprimido*. Paz e Terra.
- Gil, A. C. (2010). *Métodos e técnicas de pesquisa social* (6<sup>a</sup> ed.). Atlas.
- Gil-Pérez, D. (1993). Contribución de la historia y de la filosofía de las ciencias al desarrollo de un modelo de enseñanza/aprendizaje como investigación. *Enseñanza de las Ciencias*, 11(2), 197–212.
- Grupo de Reelaboração do Ensino de Física. (1993). *Física* (Vols. 1–3). EDUSP.
- Halliday, D., & Resnick, R. (1983). *Fundamentos de física* (3<sup>a</sup> ed.). LTC.
- Lüdke, M., & André, M. E. D. A. (2013). *Pesquisa em educação: Abordagens qualitativas* (2<sup>a</sup> ed.). EPU.
- Nussenzveig, H. M. (1997). *Curso de física básica: Ótica, relatividade e física quântica* (Vol. 4, 1<sup>a</sup> ed.). Edgard Blücher.
- Nardi, R. (Org.). (2001). *Pesquisas em ensino de Física*. Escrituras.
- Piaget, J. (1998). *A formação do símbolo na criança*. LTC.
- Pozo, J. I. (2009). *Aprendizes e mestres: A nova cultura da aprendizagem*. Artmed.
- Vygotsky, L. S. (1987). *A formação social da mente*. Martins Fontes.