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The Hydrogen Atom Model as a Conceptual Bridge: Photon–Electron Interaction in Perovskite Solar Cells and Its Implications for Physics Education

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Abstract: Perovskite solar cells (PSCs) exemplify the application of quantum principles in renewable energy technologies, with their operation rooted in photon–electron interactions analogous to the Bohr model of the hydrogen atom. To date, no systematic critical review has explicitly mapped this conceptual continuity for pedagogical purposes. This systematic review (n=14) employs qualitative thematic synthesis to (1) describe how the hydrogen atom model informs electron excitation in perovskites, (2) synthesize recent literature on energy transitions, and (3) analyze its relevance to physics education. Findings demonstrate that the quantized energy transition principle extends from atomic systems to solid-state band structures, establishing a novel conceptual bridge that simplifies complex quantum phenomena for secondary learners. Despite differences in scale and exciton binding energy, the conceptual continuity provides a powerful analogy for teaching quantum mechanics. Integrating PSCs into STEM or project-based learning offers an authentic context to enhance quantum literacy, linking foundational theory with real-world innovation. This approach aligns with modern curricula such as Indonesia's Merdeka Curriculum, particularly in themes of Critical Reasoning and Global Diversity.

Keywords: Energy transition, Hydrogen atom model, Perovskite, Photon–electron interaction, Physics

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Introduction

The advancement of renewable energy technologies has positioned perovskite solar cells (PSCs) as one of the most promising solutions for a sustainable energy transition. The power conversion efficiency of perovskite solar cells has increased dramatically from approximately 3% to over 25% within less than a decade, marking extraordinary progress in photovoltaic technology (Green et al., 2023). This improvement is driven by the perovskite material's exceptional ability to absorb sunlight and generate electron–hole pairs through photon–electron interaction. The fundamental mechanism involves the excitation of electrons from the valence band to the conduction band upon absorption of photons with sufficient energy.

Although perovskite systems are formally described using band theory in solid-state physics, the fundamental principle, that only photons with energy exceeding a specific threshold can excite electrons finds its conceptual origin in early quantum models, particularly the Bohr model of the hydrogen atom. The notion that electron excitation depends on the resonance between photon energy and the material's band gap represents a direct logical extension of the energy quantization principle inherent in the hydrogen atom model.

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The teaching of quantum concepts at the secondary education level tends to be abstract and disconnected from real-world technological applications, contributing to low levels of student quantum literacy. Students' difficulties in developing adequate quantum literacy constitute a primary challenge in modern physics education. Perovskite solar cells, with their elegant working mechanism and broad socio-ecological impact, offer an authentic context ideal for bridging foundational quantum theory with cutting-edge technological innovation.

However, despite the growing body of research on perovskite photovoltaics and quantum physics education, these fields remain largely disconnected. Existing literature predominantly focuses on material synthesis, device engineering, and stability optimization, while educational studies rarely anchor abstract band theory to foundational atomic models. Consequently, there has been no previous critical review that systematically maps the conceptual continuity between the hydrogen atom model and photon–electron interactions in perovskite solar cells for pedagogical purposes. This disciplinary gap limits the development of coherent teaching frameworks that could make quantum principles more accessible and contextually meaningful for secondary learners.

To address this gap, this review systematically examines 14 peer-reviewed studies using qualitative thematic synthesis based on conceptual categories. The primary novelty lies in formalizing a *conceptual bridge* that links discrete atomic quantization to solid-state band excitation in perovskites. Specifically, this study aims to: (1) elucidate how the hydrogen atom model informs electron excitation mechanisms, (2) synthesize current literature on energy transition principles, and (3) evaluate the pedagogical implications for modern physics instruction. By mapping this conceptual continuity, the review provides educators with a theoretically grounded,technology-integrated approach to teaching quantum phenomena.

Method

This review employs a Systematic Literature Review (SLR) approach, adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility in the literature selection process. The literature search was conducted systematically using the Publish or Perish software as a tool to identify scholarly publications from three primary academic databases: Google Scholar (n= 300), ScienceDirect (n= 280) and Taylor & Francis Online (70). The search strategy employed a combination of keywords connected by Boolean operators: ("hydrogen atom model" OR "Bohr model") AND ("perovskite solar cell" OR "halide perovskite") AND ("photon-electron interaction" OR "energy transition") AND ("physics education" OR "quantum literacy" OR "STEM education").

The selection of studies followed predefined inclusion and exclusion criteria to ensure methodological rigor and topic relevance (see Table 1). Screening began with the titles and abstracts, followed by a full-text review of eligible articles. The inclusion and exclusion criteria are shown in Table 1.

Table 1. Inclusion And Exclusion Criteria for Article Selection

Criteria	Inclusion	Exclusion
Document Type	Peer-reviewed and indexed journal articles	Non-scientific opinions, popular blogs and magazines, unpublished theses/dissertations, documents without peer review
Year of Publication	2015-2025	Outside this range
Language	English	Languages other than English
Topic Focus	The hydrogen atom model as the basis for the photon–electron concept, photon–electron interactions in perovskite, band structure and exciton dynamics, the use of quantum concepts for learning	General solar cell article without discussion of photons and electrons, atomic model article without reference to perovskite or education
Content Focus	Photon–electron interactions in perovskite, the relationship between the hydrogen atom model and quantum processes in solar cells, the integration of quantum concepts in physics education, pedagogical approaches related to photon–electron concepts	Technical content on perovskite materials without atomic or educational context, pure chemistry or engineering content without quantum physics aspects, educational articles without concepts of atoms/photons/solar cells

Data were analyzed using thematic synthesis based on conceptual categories, focusing on quantum foundations, solid-state parallels, exciton dynamics, and pedagogical integration. To ensure coding reliability, data extraction and quality assessment were conducted independently by two reviewers. Inter-rater reliability was calculated using **Cohen's kappa** (κ = 0.84), indicating strong agreement. Any discrepancies in coding or eligibility decisions were resolved through consensus discussion. A total of 650 records were initially identified. After systematic screening and eligibility assessment, 14 peer-reviewed articles were selected as the primary sources for this review. The complete selection process is visualized in the PRISMA 2020 flow diagram below.

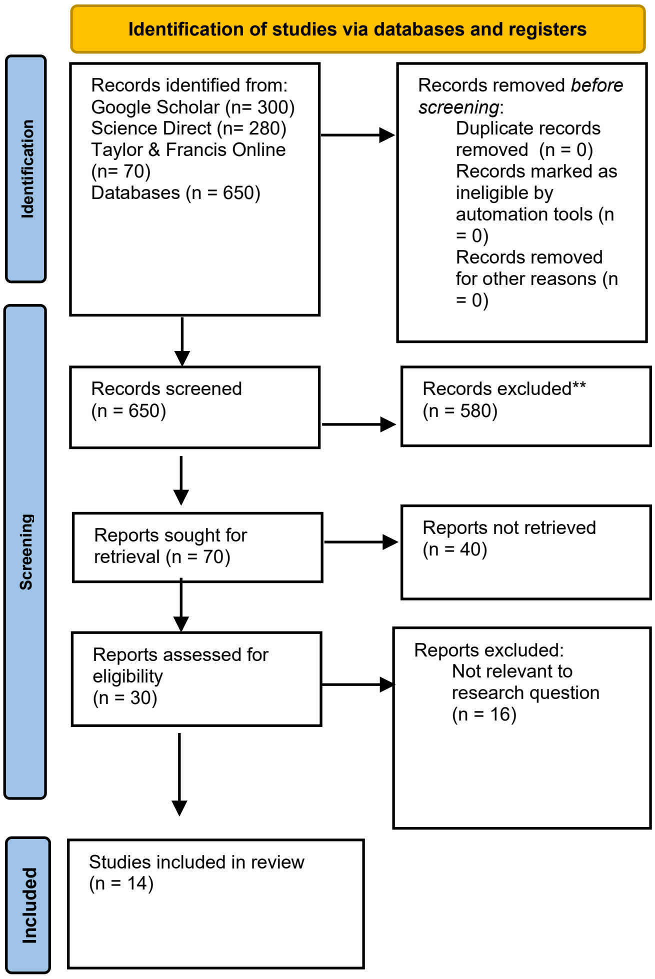


Figure 1. PRISMA 2020 Flow Diagram

Result and Discussion

Hydrogen Atom Model: Quantum Foundation of Energy Transitions

The energy levels in an atom represent the discrete quantum states that an electron may occupy. According to the Bohr model of the hydrogen atom, each electron possesses a specific energy determined by its principal quantum number (n), and these energies are quantized, expressed by the equation:

$$E_n = -\frac{13.6}{n^2}\ \text{eV}$$

The negative sign indicates that the electron is bound to the nucleus, and as the principal quantum number (n) increases, the energy level rises and the binding force to the nucleus weakens (Griffiths & Schroeter, 2018). When the electron absorbs external energy, such as from a photon, it can be excited to a higher energy level or, if the absorbed energy exceeds the binding energy, it may be completely liberated from the nucleus (ionization).

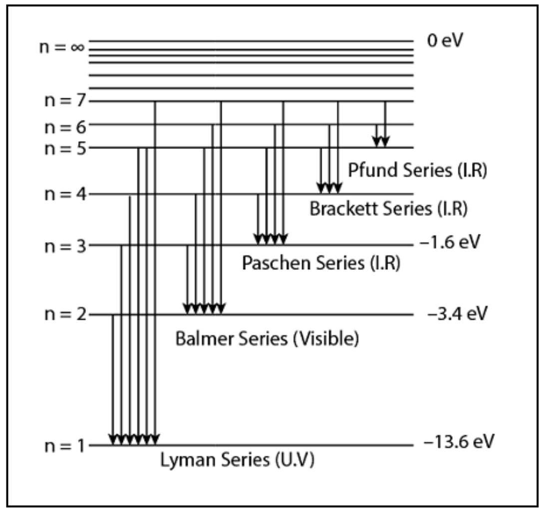


Figure 2. Energy level diagram for the hydrogen atom. Source: ***Nanni, L. (2015)***

The process of electron excitation occurs when a photon with energy

$$\Delta E = hv$$

is absorbed by the atom, causing the electron to transition from a lower energy level to a higher one. Conversely, when the electron returns to its original state, a photon of identical energy is emitted. This mechanism underlies the formation of atomic emission and absorption spectra, which for the hydrogen atom manifest as distinct spectral series, Lyman, Balmer, and Paschen. This phenomenon provides direct experimental evidence that electron energy is quantized rather than continuous, and that each energy transition corresponds precisely to a specific wavelength of light (Olszewski, 2019).

This concept of energy levels and electron excitation is directly relevant to understanding the working mechanism of perovskite-based solar cells. In perovskite materials, the electronic band structure replaces discrete atomic energy levels, where electrons can be excited from the valence band to the conduction band upon absorbing a photon with energy equal to or greater than the material's bandgap. This process generates electron–hole pairs, which subsequently contribute to electrical current. The underlying principle is identical to electron transitions in the hydrogen atom, except that in perovskites, the transition occurs across a continuous energy band rather than discrete levels (Kirchartz, 2019). Electron–phonon interactions in perovskites govern the efficiency of excitation and charge carrier mobility, making them a key factor in the development of modern photovoltaic materials (Yamada & Kanemitsu, 2022).

In the context of physics education, understanding energy levels and electron excitation serves as a conceptual bridge between microscopic quantum principles and their applications in renewable energy technologies. Through simple experiments or simulations such as observing the hydrogen emission spectrum and modeling band transitions in semiconductors, students can grasp the relationship between photon energy, electron transitions, and electricity generation. This approach integrates fundamental quantum concepts with real-world phenomena, thereby strengthening scientific literacy and enhancing the relevance of physics education to technological advancement (Csernovszky & Horváth, 2018).

Photon absorption is a fundamental process linking atomic energy levels to electron excitation in photovoltaic materials. In the hydrogen atom model, photons act as carriers of quantized energy and can be absorbed only when their energy precisely matches the difference between two discrete electron energy levels,

$$\Delta E = hv$$

Photons with energies mismatched to these transitions are neither absorbed nor converted, but instead transmitted or reflected. This energy-selective absorption underlies the discrete absorption spectra observed in hydrogen, where each spectral line corresponds to a specific electronic transition between quantized states. The selective nature of photon absorption provides direct empirical evidence for energy quantization and the quantum interaction between electromagnetic radiation and matter.

Although photon absorption in solid-state materials such as halide perovskites exhibits greater complexity, it remains fundamentally grounded in the same quantum principles. When a photon with energy equal to or exceeding the bandgap is absorbed, an electron is excited from the valence band to the conduction band, generating either an exciton or free charge carriers. The intensity of photon absorption is strongly influenced by the material's band structure, density of states (DOS), and electron–phonon coupling. Organic–inorganic perovskites such as $CH_3NH_3PbI_3$ exhibit a high optical absorption coefficient and low exciton binding energy, enabling nearly every absorbed photon to efficiently generate free charge carriers (Saliba et al., 2023).

Photon absorption is also intrinsically linked to the power conversion efficiency of perovskite solar cells. Following absorption, the excited electrons must undergo relaxation to the lower edge of the conduction band and be extracted prior to recombination. The phenomenon of photon recycling, where emitted photons are reabsorbed by the material, has been shown to enhance net photon absorption and extend charge carrier lifetimes. By understanding the interplay between photon energy, electron energy levels, and absorption efficiency, researchers can optimize the composition and structure of perovskites to maximize the utilization of the solar spectrum.

Mechanism of Photon-Electron Interaction in Perovskite Solar Cells

The interaction between photons and electrons is central to the process of converting light energy into electrical energy in perovskite solar cells. This mechanism begins when photons with energy equal to or greater than the material's bandgap (E_g) are absorbed by the perovskite active layer, exciting electrons from the valence band (VB) to the conduction band (CB). This transition generates electron–hole pairs ($e^- - h^+$), which serve as the primary charge carriers in the solar cell (T. Wang et al., 2016).

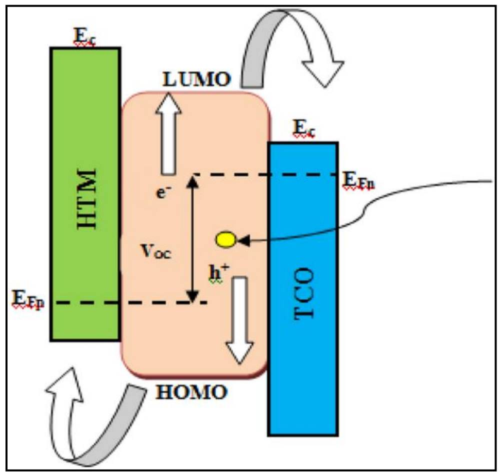


Figure 3. Schematic of the working principle of a perovskite solar cell
Source: Adapted from Bahtiar & Sartika (2019)

This process constitutes a direct application of the principle of energy quantization as described in the hydrogen atom model. In the hydrogen atom, a photon can be absorbed only if its energy exactly matches the difference between two discrete electron energy levels ($\Delta E = hv$). By analogy, in perovskites, the photon energy determines whether an electron can be excited from the valence band to the conduction band (J. Wang et al., 2024). Thus, photon absorption in perovskites represents collective electron excitation within a solid-state quantum band structure, rather than transitions occurring in an isolated atom (Kharintsev et al., 2025).

After the electron–hole pairs are generated, these charge carriers must be efficiently separated and extracted prior to recombination. The typical device structure consists of a perovskite absorber layer sandwiched between an electron transport layer (ETL) and a hole transport layer (HTL), where electrons migrate toward the cathode through the ETL and holes transport toward the anode via the HTL.

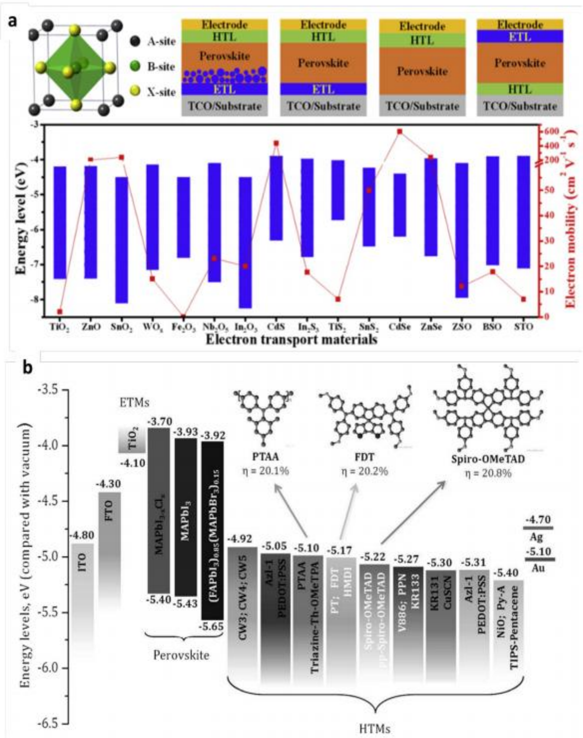
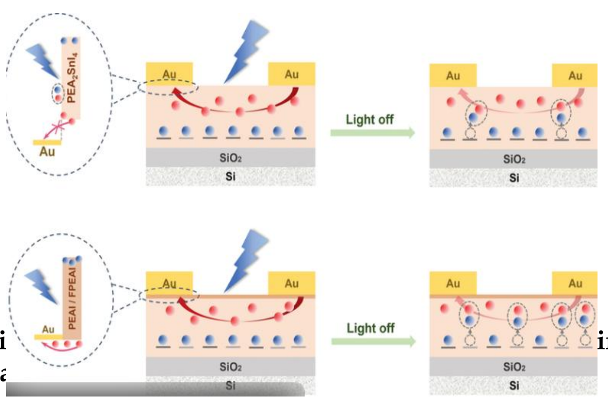


Figure 4. Crystal and band structure of perovskites
Source: Adapted from Elsevier (2020) and Wiley (2016)

Following absorption, the excited electrons undergo energy relaxation through electron–phonon coupling. This mechanism critically influences energy transfer efficiency and charge carrier lifetime. The unique band structure of perovskites, illustrated in Figure 4, enables both relaxation and charge transport to occur with minimal energy loss (S. Wang et al., 2022).



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Source: Yamada & Kanemitsu (2022)

To generate electrical current, the electron–hole pairs must be efficiently separated by the internal electric field at the interface between the perovskite layer and the charge transport layers (ETL and HTL). Electrons migrate toward the cathode through the ETL, while holes move toward the anode via the HTL. This layered structure (see Figure 5) ensures unidirectional charge flow and minimizes recombination. Furthermore, perovskites exhibit a high optical absorption coefficient and support the phenomenon of photon recycling, the reabsorption of photons emitted from radiative recombination, which enhances the open-circuit voltage and overall cell efficiency (Kirchartz, 2019).

To systematically map the mechanistic and pedagogical contributions of the selected literature, Table 2 presents a thematic synthesis of all 14 included studies. Each entry highlights the specific insight provided by the study regarding photon–electron interactions and its utility for physics instruction.

Table 2. Thematic Synthesis of Included Studies (n=14) and Conceptual Contributions

Author (s)	Focus Area	Key Contribution to Mechanism	Pedagogical Value
Nanni (2015)	H–atom energy levels	Foundational quantization equations & spectral evidence	Baseline for atomic-to-solid-state analogy
Griffiths & Schroeter (2018)	Quantum theory	Clarifies bound-state transitions & ionization thresholds	Theoretical grounding for secondary instruction
Olszewski (2019)	Transition intervals	Quantifies discrete jump durations	Reinforces discrete vs. continuous paradigms
Kirchartz (2019)	Photon management	Demonstrates photon recycling & absorption efficiency	Links quantum absorption to PV efficiency
Saliba et al. (2023)	Charge dynamics	Highlights high absorption coefficient & low exciton binding	Explains spontaneous e^-–h^+ dissociation
Yamada & Kanemitsu (2022)	e–phonon coupling	Details relaxation pathways & mobility	Bridges microscopic interaction to macroscopic current

T. Wang et al. (2016)	Device architecture	Maps ETL/HTL charge separation pathways	Visualizes unidirectional flow for modeling
J. Wang et al. (2024)	Defect passivation	Shows structural stability preserves quantum response	Connects material engineering to consistent excitation
S. Wang et al. (2022)	Compositional tuning	Correlates bandgap shifts with A/X site modifications	Enables inquiry-based material design experiments
Kharintsev et al. (2025)	Disordered perovskites	Explores extreme photon–e⁻ interactions in non-ideal lattices	Advanced extension for tertiary/gifted learners
Adjogri & Meyer (2020)	Lead-free alternatives	Compares bandgap tunability across compositions	Supports sustainability & critical reasoning themes
Miah et al. (2025)	Degradation mechanisms	Identifies environmental factors affecting exciton stability	Promotes systems-thinking & eco-literacy
Csernovszky & Horvath (2018)	PV in education	Proposes context-based modules linking PV to atomic models	Empirical basis for STEM integration
Xia et al. (2020)	Heterojunction optimization	Demonstrates interface-driven charge extraction	Illustrates real-world application of threshold principles

Conceptual Relationship: Hydrogen Atom Model versus Electron Excitation in Perovskites

The fundamental principle of the Bohr hydrogen atom model, despite being developed over a century ago, remains relevant in explaining photon–electron interactions in modern materials such as perovskites. The primary distinction lies in the scale of the system: the hydrogen atom is a bound system with discrete energy levels, whereas perovskites are solid-state materials characterized by continuous energy bands. Nevertheless, both systems share the same quantum foundation: electron excitation occurs only when the photon energy meets or exceeds a minimum threshold.

In the Bohr model, electron transitions require a photon with energy exactly matching the energy difference between levels:

$$hv = E_{nf} - E_{ni}$$

(Nanni, 2015). In perovskites, this principle is modified such that a photon can excite an electron from the valence band to the conduction band only if $hv \geq E_g$, where E_g is the material's bandgap typically around 1.5–1.6 eV for $CH_3NH_3PbI_3$-based perovskites (Adjogri & Meyer, 2020).

Another key distinction lies in the exciton binding energy. In the hydrogen atom, the exciton (electron–hole pair) possesses a large binding energy (~13.6 eV), rendering it stable. In contrast, in perovskites, the exciton binding energy is extremely low (a few meV), causing the electron–hole pair to spontaneously dissociate into free charge carriers without requiring an external electric field a feature that significantly enhances solar cell efficiency (Miah et al., 2025).

To clarify this analogy, Table 3 synthesizes the key concepts from both systems.

Table 3. Conceptual Guide: Hydrogen Atom Model and Perovskite Mechanism

Hydrogen Atom Model	**Perovskite Mechanism**	**Quantum Interpretation**
Discrete energy levels (E_n)	Valence band and conduction band	Quantization of energy in bound atomic systems versus continuous solid-state systems
Electron transition: $n_i \rightarrow n_f$	Excitation: $VB \rightarrow CB$	Energy conservation: $hv = \Delta E$
Photon energy must exactly	Photon energy ≥ bandgap (E_g)	Minimum energy threshold for excitation

match ΔE		
High exciton binding energy	Low exciton binding energy **(meV)**	Spontaneous dissociation of electron–hole pairs in perovskites

This visualization demonstrates that, despite perovskites being a far more complex system, the Bohr model remains a powerful conceptual analogy for understanding why only light of specific wavelengths can generate electrical current.

Relevance to Physics Education

This study provides a specific theoretical contribution to physics education by positioning the hydrogen atom model as a conceptual bridge to explain photon–electron interactions in perovskite solar cells. Within the Merdeka Curriculum framework, this topic can be implemented through a *Project-Based Learning* (PjBL) model with clearly defined syntax: (1) formulating an essential question that links the hydrogen atom model to the working mechanism of perovskite solar cells, (2) designing a project such as developing a simulation or conceptual model of photon–electron interactions, (3) organizing a project timeline, (4) monitoring and guiding the investigation process, (5) testing and presenting project outcomes, and (6) evaluating and reflecting on the learning process. This structured sequence enables students to engage with abstract quantum concepts through guided and meaningful learning experiences.

Empirical evidence supporting the effectiveness of Project-Based Learning in physics education is summarized in Table 4. As shown, multiple studies employing experimental, quasi-experimental, and systematic review approaches consistently report that PjBL enhances students' conceptual understanding, critical thinking, creativity, and problem-solving skills. Although most studies are conducted in general physics contexts, their findings are highly relevant to abstract topics such as atomic models and photon–electron interactions, which require strong conceptual visualization and active learning engagement.

Table 4. Empirical Evidence of Project-Based Learning (PjBL) in Physics Education

Author (s)	**Year**	**Research Type**	**Topic**	**Key Findings**
Farkhan et al.	2025	Bibliometric Review	Physics Education	PjBL is recognized as an effective approach to enhance conceptual understanding and 21st-century skills in physics learning
Al-Kamzari & Alias	2025	Systematic Literature Review	Secondary Physics	PjBL improves critical thinking, creativity, collaboration, and communication skills in physics education
Rusli et al.	2022	Sytematic Literature Review	STEM Physics	STEM-integrated PjBL shows effectiveness in improving learning outcomes across multiple physics topics
Zakirman	2022	Quasi-Experimental	Basic Physics	PjBL significantly improves students' understanding of physics applications compared to conventional

				methods
Usman et al.	2024	Development Study	Basic Physics	PjBL enhances students' critical thinking skills in physics learning contexts
Suwasono et al.	2024	Systematic Review	Physics Education	Most PjBL studies show improvement in creative thinking and higher-order thinking skills

Conclusion

This systematic review establishes that the hydrogen atom model remains a robust conceptual scaffold for explaining photon–electron interactions in perovskite solar cells. We formalize a direct logical continuity between discrete atomic quantization ($\Delta E = h\nu$) and solid-state band excitation ($h\nu \geq E_g$), demonstrating that the threshold principle of energy transitions remains invariant across scales. This conceptual bridge reconciles foundational quantum mechanics with modern solid-state physics without compromising scientific accuracy, offering a unified pedagogical framework previously absent in the literature.

The proposed integration of perovskite-based contexts into secondary physics education provides educators with a ready-to-implement, curriculum-aligned strategy. By embedding the hydrogen–perovskite analogy within Project-Based Learning or STEM modules, teachers can transform abstract quantum concepts into inquiry-driven, technology-contextualized experiences. This approach directly addresses low quantum literacy by reducing cognitive overload, mitigating common misconceptions about photon energy thresholds, and fostering socioscientific reasoning aligned with Indonesia's Merdeka Curriculum.

Future research should prioritize: (1) empirical classroom trials measuring conceptual gain using validated diagnostic instruments, (2) longitudinal studies assessing long-term retention of quantum principles, (3) cross-cultural adaptations to validate the model's transferability across diverse educational systems, and (4) the development of augmented reality simulations to visualize exciton dissociation and electron–phonon coupling in real time. Ultimately, perovskites function not only as a frontier renewable energy technology but also as a transformative pedagogical lens for democratizing quantum literacy in the 21st century.

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