(WIP) Building the Quantum Pipeline in Middle School: A Curriculum Design and Implementation Study

Ms. Jiwon Lai Kim, Purdue University – West Lafayette (College of Engineering)

Jiwon Kim is a Ph.D. student at the School of Engineering Education, Purdue University. She earned her M.Sc. in Informatics (emphasis in Human-Computer Interaction) and B.Sc. in Earth Science Education, both from Seoul National University. Her research interests include engineering/science education, integrated STEM education, and engineering for K-12 students. Currently participating in the IQ-PARC project with Dr. Muhsin Menekse, she focuses on developing and evaluating quantum science curricula for middle school students by actively collaborating with teachers.

Dr. Muhsin Menekse, Purdue University – West Lafayette (College of Engineering)

Muhsin Menekse is an Associate Professor at Purdue University with a joint appointment in the School of Engineering Education and the Department of Curriculum & Instruction. Dr. Menekse's primary research focuses on exploring K-16 students' engagement and learning of engineering and science concepts by creating innovative instructional resources and conducting interdisciplinary quasi-experimental research studies in and out of classroom environments. Dr. Menekse is the recipient of the 2014 William Elgin Wickenden Award by the American Society for Engineering Education. He is also selected as an NSF SIARM fellow for the advanced research methods for STEM education research. Dr. Menekse received four Seed-for-Success Awards (in 2017, 2018, 2019, and 2021) from Purdue University's Excellence in Research Awards programs in recognition of obtaining four external grants of $1 million or more during each year. His research has been generously funded by grants from the Institute of Education Sciences (IES), the U.S. Department of Defense (DoD), Purdue Research Foundation (PRF), and the National Science Foundation (NSF).

Building the Quantum Education Pipeline in Middle School: A Curriculum Design and Implementation Study (Work-In-Progress)

Abstract

The increasing relevance of quantum science in modern engineering fields, such as quantum computing and information processing, has prompted national calls to produce a quantum-ready workforce. While many U.S. universities have offered undergraduate quantum courses and acknowledged the importance of quantum education, efforts to build a robust educational pipeline have largely overlooked K-12 education. To explore the potential of a quantum education pipeline, this work-in-progress paper presents an exploratory study of the design and implementation of a science curriculum that introduces foundational quantum concepts to 6th-grade students. The curriculum integrates two core quantum topics (i.e., wave-particle duality and energy quantization) into the existing 6th-grade academic standards. The curriculum consists of three modules that guide students from an exploration of the classical properties of light to an understanding of its particle and wave nature, ultimately leading to the concept of wave-particle duality. The curriculum was implemented by two middle school teachers in their classrooms in the Midwestern United States with a total of 201 students. To evaluate the curriculum's impact on student learning, we employed a pre-test/post-test research design. We designed an assessment consisting of 9 items to measure learning outcomes in both the targeted quantum concepts and the related physical science topics covered in the standard curriculum. A paired-samples t-test showed that students' total scores significantly increased from pre-test (M = 2.015) to post-test (M = 3.445), $t(199) = 11.876$, $p < .001$. This result provides early evidence for the feasibility of introducing foundational quantum science in middle school and suggests that quantum concepts can be integrated into existing science instruction without disrupting core content.

1. Introduction

Quantum mechanics is the description of the behavior of matter and light in all its details and, in particular, of the happenings on an atomic scale [1]. Quantum science underpins modern physics, chemistry, and materials science and thus serves as the foundation of emerging technologies, including quantum computing, secure communication, and advanced sensing [2-5]. Reflecting its growing importance in modern society, national initiatives, such as the National Quantum Initiative Act [6] and NSF priorities [7], emphasize the need to build quantum education capacity. In light of such initiatives, many U.S. universities have introduced introductory quantum courses for undergraduates [8]. However, quantum concepts remain largely absent from U.S. K-12 science academic standards, particularly at the middle school level. Such an absence is contradictory to increasing calls to introduce core, modern STEM topics earlier to support long-term STEM engagement and conceptual coherence among K-12 students [9-10].

A major barrier to the earlier introduction of quantum science is that quantum concepts are widely considered counterintuitive and difficult to teach without advanced mathematics [11]. Additional challenges include interpreting non-classical phenomena, shifting from deterministic to probabilistic reasoning, and using language to describe quantum behavior [11]. As a result, in the United States, K-12 STEM curricula often defer quantum topics until high school or college, limiting opportunities to scaffold learning and contributing to a lack of coherent conceptual progression between students' early learning about light and waves in middle school and their later formal instruction in quantum physics [12]. In contrast, several European countries have incorporated foundational quantum topics into secondary curricula to better align K-12 school science with contemporary scientific and engineering practices [13]. Motivated by such a contrast, the present study designs and evaluates a middle school science curriculum that introduces basic quantum concepts, particularly those related to light, while remaining aligned with the core science curriculum in the U.S. context.

2. Related Works and Research Question

The quantum topics commonly addressed in secondary education tend to emphasize foundational ideas that support later learning about quantum technologies. For example, the European Competence Framework for Quantum Technologies highlights essential background knowledge in domains such as "Concepts and Foundations" and "Physical Foundations of Quantum Technologies." It includes topics like superposition, interference, quantization, measurement, complementarity, and entanglement [14-15]. Prior research also shows that although broad frameworks include advanced concepts (e.g., decoherence and non-locality), national curricula typically focus on more accessible topics such as quantization and atomic models [15]. A cross-national curriculum analysis across 15 countries by [12] identified a shared core set of widely taught quantum topics, including discrete energy levels, light-matter interaction, wave-particle duality, Heisenberg's uncertainty principle, and the probabilistic nature of quantum physics. In addition, recent work on high school teacher professional development proposes a vertical progression that begins with classical wave behavior (e.g., diffraction and polarization) and builds toward quantum concepts such as superposition, qubits, entanglement, and quantum information applications, while also supporting teachers in developing standards-aligned lessons [16].

While such studies emphasize the importance of teaching foundational quantum knowledge to K-12 students, another vein of research consistently shows that students experience substantial difficulty understanding quantum concepts. Several reasons are that they often blend classical and quantum ideas, rely on concrete mental models, and struggle with abstract representations and the role of scientific models. For example, [17] reports that pre-university students find quantum phenomena highly counterintuitive and recommends instructional approaches that avoid reinforcing classical misconceptions. Similarly, [18] found challenges in teaching wave-particle duality due to differing interpretations of duality and unclear distinctions between prediction rules and physical reality. Furthermore, studies on students' atomic and molecular models further show that learners frequently confuse models with reality and encounter language-based misunderstandings [19]. Comparative work also suggests that even older students rarely use wave-function-based explanations when interpreting uncertainty and wave behavior [20]. To support successful conceptual development of quantum knowledge, several researchers (e.g., [21]) emphasize learning progressions and conceptual trajectories that describe how students move from basic to more sophisticated explanations of matter and duality. They further argue that carefully sequenced instruction, including simulations and hands-on activities, can promote deeper understanding.

Recent K-12 quantum education studies suggest that effective curriculum design draws on familiar STEM education strategies, including balancing cognitive challenge with instructional scaffolding, incorporating hands-on inquiry, and using carefully managed analogies. For example, a quantum key distribution module designed by Weissman et al. [22] demonstrates that introducing demanding core principles (e.g., entanglement and secure communication) can promote student engagement when paired with supportive explanations and real-world contexts. Hands-on experiments and guided simulations have also been shown to help students make sense of abstract ideas such as wave–particle duality and quantum computing concepts [23]. In addition, instructional interventions using analogies and physical models, such as the Einstein-First project and musical analogies for atomic structure, can improve student interest and understanding; however, researchers caution that analogies must be used carefully to avoid reinforcing misconceptions [13], [24]. Finally, teacher-focused research indicates that professional development can strengthen teachers' knowledge of quantum science and pedagogical readiness, particularly when it emphasizes discourse, perspective-taking, and lesson integration aligned with instructional goals [16], [25].

Inspired by the abovementioned literature on teaching quantum topics to K-12 students, our work-in-progress research aims to explore how basic quantum concepts can be effectively taught by embedding them into the existing middle school curriculum. To achieve such a goal, we set our research question as follows: "Does participation in the Basic Quantum Science Curriculum improve Grade 6 students' learning outcomes in quantum science concepts and related traditional science concepts?"

3. Curriculum

The curriculum consists of three parts: Part 1 introduces fundamental characteristics of light, Part 2 emphasizes the particle nature of light, and Part 3 focuses on wave behavior and wave-particle duality. Each part follows the 5E instructional design model [26]. Part 1 focuses on foundational ideas about light and its observable properties before learning quantum knowledge.

- Lesson 1a: Students use spectrum glasses to observe and compare visible light spectra from different sources (e.g., classroom lights, candlelight, and LED flashlights).
- Lesson 1b: A teacher explains core concepts, including energy, wavelength, and the electromagnetic spectrum.
- Lesson 1c: Students explore the wave-like behavior of light through a double-slit activity using lasers and a flashlight.

Part 2 introduces the concept of a photon, the particle nature of light, and the introductory understanding of energy quantization.

- Lesson 2a: Students use UV-reactive beads to explore how higher-energy light (UV) can cause observable changes, supporting the idea that light can transfer energy in discrete amounts. The term 'photon' is actively used in the explanation.
- Lesson 2b: Students learn how spectrometry provides element-specific spectral patterns and connect these observations to energy quantization in introductory quantum explanations.
- Lesson 2c: Students observe emission spectra from spectrum tubes and use spectrum analysis tools to compare spectral lines across different gases. A teacher explains that excited atoms emit energy as discrete packets called photons.

Part 3 focuses on light interference as evidence of light's wave-particle duality.

- Lesson 3a: Students use an interference simulation and teacher-guided explanation to examine how constructive and destructive interference produce bright and dark regions.
- Lesson 3b: Students compare diffraction and slit-interference patterns across different wavelengths using simulations. The primary focus is that wave behavior is necessary to explain interference. Combining this with the previous understanding of light as particles

(i.e., photons), the lesson ultimately supports an introductory and conceptual understanding of wave-particle duality.

4. Method

Table 1.
A Summary of Post-Test Questions

No	Primary learning focus	Relevant learning goals that include foundational quantum topics (Students should be able to…)
Q1	Continuous vs. discrete light spectra	Establish the baseline understanding of light spectrum that later support reasoning about emission spectrum.
Q2	Relationship between wavelength and energy	Relate photon's wavelength with its energy in visible and UV lights. Through explicit usage of photons, build up the notion that light not only exhibits wave-properties but also consists of photons.
Q3	Color-wavelength correspondence in visible light	
Q4	Energy transfer by UV light	
Q5	Element-specific emission spectrum and photon emission	Explain the principle of emission spectra: photons (or light) are emitted when an excited atom becomes an unexcited atom. Conceptually understand why each element has spectral lines.
Q6	Identification of elements using emission spectra	
Q7	Constructive and destructive wave interference (sound)	Reason how and why wave-interference patterns are created and apply it to light wave-interference. Identify the interference pattern as evidence of wave properties of light.
Q8	Interference as evidence of light's wave behavior	
Q9	Integration of interference and photon-based evidence	Identify light as showing both particle and wave wave-particle duality of light by integrating prior findings. Explain wave-particle duality of light using some of the experiments in the lessons.

We conducted a one-group pretest-posttest research design. Participants included two middle school science teachers and 201 students from two public schools in the Midwestern United States. Both teachers volunteered to integrate quantum science into their instruction, participated in a professional development workshop, and were recruited following IRB approval. Each teacher received $1,000 for participation. The study procedure included curriculum development, a teacher workshop, curriculum revision, and classroom implementation. The curriculum focused on three foundational quantum ideas: wave properties, particle properties (photon), and wave-particle duality of light. We selected them for alignment with Grade 6 learning goals about light and the electromagnetic spectrum. After the workshop's lectures, demonstrations, and feedback sessions, the team revised curriculum materials and assessments, and teachers implemented the unit over approximately three weeks, using a pre-test, an instruction period, and a post-test, with minor pacing differences across schools. Table 1 summarizes nine questions that comprise the post-test. The pre-test consists of the same questions, with minor sentence adjustments.

5. Results

To examine whether students' overall performance improved after the curriculum, we compared students' total pre-test and post-test scores across the assessment items using a one-tailed paired-samples t-test (hypothesis: post-test > pre-test). The statistical tests used $\alpha = .05$. On average, students scored higher on the post-test (M = 3.445) than on the pre-test (M = 2.015). This increase was statistically significant, $t(199) = 11.876$, $p = 3.07 \times 10^{-25}$ (one-tailed). The magnitude of the improvement was large, with Cohen's $d^z = 0.84$, indicating a substantial improvement in students' performance following the curriculum.

6. Discussion

The results suggest that the curriculum supported students' learning of introductory quantum ideas alongside existing science content, extending prior work that identified common school-level quantum topics and typical instructional sequences [14]. By centering foundational concepts such as wave-particle duality, this study provides a middle-school example from the U.S., where quantum topics are rarely emphasized in standards, and complements international trends toward integrating quantum physics in secondary education [12, 14]. However, the average post-test score was 3.445 out of 9, which corresponds to an accuracy rate of 38 %. Contrary to our expectation that students would answer at least 50 % of the items correctly, these results suggest that there is still room to strengthen students' mastery of quantum topics, although the initial gains were meaningful for a first implementation with students who had no prior exposure.

Future work should first conduct item-level analyses to identify which misconceptions (i.e., distractor options in multiple-choice questions) most frequently led students astray. We should also explore alternative instructional sequences, such as introducing wave behavior before particle behavior, to better align with Grade 6 topics on wavelengths and the electromagnetic spectrum. In addition, we can incorporate teachers' feedback more systematically and invite teachers to co-design the curriculum more proactively, so that sequencing decisions better match instructional goals and improve conceptual accessibility, drawing on discussions of sequencing approaches in quantum education for students older than middle school students [27].

References

[1] R. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics, Vol. III*. California Institute of Technology, 1963/2013.

[2] A. S. Dzurak *et al.*, "Development of an undergraduate quantum engineering degree," *IEEE Trans. Quantum Eng.*, vol. 3, pp. 1–10, 2022.

[3] F. Greinert *et al.*, "Future quantum workforce: Competences, requirements, and forecasts," *Phys. Rev. Phys. Educ. Res.*, vol. 19, no. 1, 2023.

[4] Authors, "Anonymized Citation," 2025a.

[5] Authors, "Anonymized Citation," 2025b.

[6] National Quantum Coordination Office, "National Quantum Initiative Act," 2018.

[7] National Science Foundation, "Dear Colleague Letter: Advancing Quantum Education and Workforce Development (NSF 21-033)," 2020.

[8] C. Hughes *et al.*, "Assessing the needs of the quantum industry," *IEEE Trans. Educ.*, vol. 65, no. 4, pp. 592–601, 2022.

[9] Authors, "Anonymized Citation," 2024.

[10] C. Stambaugh, "A Quantum Leap Forward: How Tiny Particles Can Bring Us Exciting New Tech," *NIST*, 2025.

[11] T. Bouchée *et al.*, "Conceptual difficulties in introductory quantum physics," *Stud. Sci. Educ.*, vol. 58, no. 2, pp. 183–202, 2022.

[12] H. K. E. Stadermann, E. van den Berg, and M. J. Goedhart, "Analysis of secondary school quantum physics curricula," *Phys. Rev. Phys. Educ. Res.*, vol. 15, no. 1, 2019.

[13] T. Kaur *et al.*, "Teaching Einsteinian physics at schools," *Phys. Educ.*, vol. 52, no. 6, 2017.

[14] F. Greinert and R. Müller, "European competence framework for quantum technologies," *Zenodo*, 2024.

[15] A. Merzel *et al.*, "The core of secondary level quantum education," *EPJ Quantum Technol.*, vol. 11, no. 1, 2024.

[16] T. R. Kelly *et al.*, "Vertical progression for quantum education," 2024.

[17] G. Ireson, "The quantum understanding of pre-university students," *Phys. Educ.*, vol. 35, no. 1, pp. 15–21, 2000.

[18] Y. W. Cheong and J. Song, "Meanings of wave-particle duality," *Sci. Educ.*, vol. 23, no. 5, pp. 1011–1030, 2014.

[19] A. G. Harrison and D. F. Treagust, "Students' mental models of atoms," *Sci. Educ.*, vol. 80, no. 5, pp. 509–534, 1996.

[20] M. V. Bøe and S. Viefers, "Descriptions of quantum uncertainty," *Sci. Educ.*, vol. 32, no. 2, pp. 297–326, 2023.

[21] J. C. Hadenfeldt *et al.*, "Students' progression in understanding matter," *J. Res. Sci. Teach.*, vol. 53, no. 5, pp. 683–708, 2016.

[22] E. Y. Weissman *et al.*, "Teaching quantum key distribution," *EPJ Quantum Technol.*, vol. 11, no. 1, 2024.

[23] P. P. Angara *et al.*, "Teaching quantum computing to high-school-aged youth," *IEEE Trans. Quantum Eng.*, vol. 3, 2022.
[24] H. Vieira and C. Morais, "Musical analogies for quantum models," *J. Chem. Educ.*, vol. 99, no. 8, pp. 2972–2980, 2022.
[25] N. Balta *et al.*, "Professional development for Einsteinian physics," *Teacher Dev.*, vol. 26, no. 2, pp. 166–188, 2022.
[26] R. W. Bybee *et al.*, *The BSCS 5E Instructional Model*. BSCS, 2006.
[27] A. Buzzell, T. J. Atherton, and R. Barthelemy, "Quantum mechanics curriculum in the U.S.," *Phys. Rev. Phys. Educ. Res.*, vol. 21, no. 1, 2025.