Quantum information science and technology professional learning for secondary science, technology, engineering, and mathematics teachers

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[This paper is part of the Focused Collection in Investigating and Improving Quantum Education through Research.] There is a growing need in the United States for a workforce trained in quantum information science and technology (QIST), a disciplinary topic that is rarely addressed in precollege science, mathematics, and computer science curricula. University quantum physics and physics education researchers designed and initiated a 4-week, 12-h QIST professional development workshop for $N = 51$ preservice and in-service secondary school science, mathematics, and computer science educators. A STEM integration framework guided the workshop structure, which incorporated a situated cognition model for learning quantum concepts and computing, identifying recent advances in quantum technologies, planning curricula, and differentiating among QIST subfields including quantum communication, quantum computation, quantum simulation, and quantum metrology and sensing. The pre-/post-research design employed a newly developed teacher attitude survey, *Teacher Self-Efficacy in Quantum Information Science and Technology Scale (TSE-QIST)*. Exploratory factor analysis identified three latent constructs in teachers' self-efficacy, including (i) knowledge about QIST academic pathways and careers; (ii) QIST pedagogical fluency and STEM integration; and (iii) facilitating QIST learning. Parametric comparisons of means indicated that teacher participants showed significant gains overall and in all latent constructs with medium to large effect sizes ($p < 0.001$). This professional learning model shows promise in strengthening teachers' self-confidence in pedagogical content knowledge of quantum ideas so they may facilitate student engagement in quantum information science, a field that involves conceptual change and is often considered abstract, counterintuitive, inaccessible, and suitable only for the academically elite. Implications for policy and practice are discussed.

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I. INTRODUCTION

The United Nations' recent declaration of the *International Year of Quantum Science and Technology* in 2025 has highlighted the need to strengthen global capacity for promoting public awareness and interest in quantum-related education and technological advancement [1]. Quantum information science and technology (QIST) is a rapidly emerging discipline that has surpassed the availability of a qualified workforce for the development of new technologies and theories [2–4]. Workers in QIST fields typically have backgrounds in quantum mechanics and computer science, yet only 41% of U.S. high school graduates have taken a physics course and 25% have taken computer science [5,6]. It is important to broaden and

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improve precollege QIST-related education to inspire and prepare students to pursue these careers.

To meet the growing need for students educated in these evolving disciplines, QIST workforce development has become both a national and international priority. The *QIST National Workforce Strategic Development Plan*, issued by the U.S. National Quantum Initiative, emphasized the importance of fostering QIST interest before students enter college and have already chosen their academic and career pathways [4,7]. The precollege pipeline is essential for meeting the national mission of educating a broad range of students in QIST disciplines, as stated in the plan: "The United States should develop a diverse, inclusive, and sustainable workforce that possesses the broad range of skills needed by industry, academia, and the U.S. government, while being able to scale and adapt as the QIST landscape evolves" [4] (p. 4).

Research has suggested that early exposure to QIST and its applications promotes workforce readiness to meet the expanding need for professionals in QIST fields [2,8]. However, QIST topics are typically not taught before upper-level undergraduate or graduate courses, which may be too late to inspire students toward QIST careers [9]. Therefore, preparing secondary teachers to provide QIST content and skills in their classrooms is an important strategy for increasing interest and engagement.

This study examined the outcomes of a QIST professional learning intervention for middle and high school teachers (with students of approximate ages 12–18) in science, technology, engineering, and mathematics (STEM) fields. The four-session, 12-h *EduQation* workshop was developed and taught by university physics and physics education faculty in both a university setting and an urban informal science institution. Teacher outcomes were measured in terms of self-efficacy, or one's perception of competence in teaching tasks and facilitating student learning [10], which has been shown to increase and improve classroom practices that incorporate STEM integration [11]. The research questions that guided the study of this replicable model for QIST professional learning were

1. How might secondary STEM teachers' self-efficacy in QIST-related instructional factors be measured?
2. What QIST-related self-efficacy subscales might be identified through exploratory factor analysis?
3. How has teachers' self-efficacy in QIST-related instructional factors changed during their participation in a professional learning workshop?

II. LITERATURE REVIEW

Despite the recent push to include QIST topics in precollege STEM education [4], there has been little research on best practices for providing teachers with professional learning on implementing QIST instruction in their classrooms. A literature search for publications about QIST precollege teacher professional learning interventions yielded only five papers [12–16], fewer of which analyzed teacher outcomes with descriptive data, teacher artifacts, interviews, and/or survey open-ended responses. This suggests the need for more in-depth inferential analysis of precollege teacher outcomes from QIST professional learning interventions.

Even with only a few empirical works, there were overlapping strategies and results that have been utilized when developing QIST professional learning programs. These considerations and strategies, some of which have been supported by other research, generally fall into three categories: (i) addressing conceptual challenges for teachers and their students when teaching and learning QIST; (ii) adopting best practices for teaching QIST concepts; and (iii) resolving the challenges of implementing QIST in standards-aligned curricula, particularly in the physical sciences.

A. Conceptual QIST learning challenges

According to QIST educational experts, teachers preparing students for QIST postsecondary study must be able to teach about the wave-particle duality of light, the probabilities associated with wave functions, and the complexities of atomic structure and behavior, some of which is covered in high school chemistry and AP Physics [17,18]. However, further knowledge is often required, such as the concept of de Broglie waves, Heisenberg's uncertainty principle, and wave functions [18]. Once this foundation has been established, teachers may then introduce QIST concepts and skills, such as quantum states and their measurement, the quantum bit or qubit, entanglement, coherence, quantum gate operations, quantum computing, quantum communication, and quantum sensing [19].

For students to learn about foundational QIST topics, there are several major challenges that teachers may encounter regarding the conceptual difficulty of the topics. For example, they must overcome a lack of directly observable phenomena, as well as content that is abstract in nature [20–22]. They must be guided in understanding the language used by experts in the field, as it may be confusing, especially for younger students [20]. Quantum phenomena are often described with a combination of words (spoken and written), mathematical expressions, and visual representations, and educators may jump among these forms with little to no transition [20,23].

Students may also have difficulty resolving cognitive conflicts between classical physics and quantum physics [20]. For example, students should describe light with aspects of both the particle model and the wave model simultaneously, while only being introduced to light as either a particle or a wave by their teachers [24,25]. They may struggle with the abstract nature of quantum concepts and how to relate the mathematical formalism of quantum mechanics to physical systems. Furthermore, students may find the probabilistic nature of quantum mechanics at odds with the determinism that characterizes much of classical physics [20]. Because of these difficulties, teachers have expressed concerns about their students' ability to learn these complex topics with the existing standards-based concepts typically taught in secondary classes [13].

B. Best practices to increase QIST understanding

To address student difficulties in learning QIST concepts and skills, STEM teacher professional learning should be taught using strategies similar to those that teachers can use with their own students. This *situated learning model* [26] has shown promise in collaborative professional learning since teachers have the opportunity to mimic their students' learning processes, recognize and resolve conceptual challenges, and anticipate timing issues [27]. Several studies of QIST professional learning workshops reported positive outcomes when hands-on activities and physical or computational representations of abstract phenomena were used [12–16]. This was also evident in QIST programs designed for precollege students, which have often used activities similar to those in teacher workshops [13,28,29]. For example, in the student program described in Angara *et al.* [30], students played with toy doughnuts to represent the potential states of a qubit, in which the sides with and without frosting represent the $|0\rangle$ and $|1\rangle$ basis states and spinning the doughnut up on its side represents superposition. In other programs for both students and teachers, there were interactive computer simulation activities that increased understanding of abstract topics [13,31–33].

C. Challenges in teaching QIST with standards-aligned instruction

Despite these promising teaching strategies, there is still the challenge that science teachers must follow existing curricula, often based on the *Next Generation Science Standards* (NGSS [34]) while teaching with limited time in which to cover the content [12,14]. This is problematic since NGSS only includes the word "quantum" to identify the term as a part of a topic that should not be tested, and only some advanced high school science courses, such as AP Physics 2, include quantum physics topics [34,35]. However, enrollment in such courses is low, for example, AP Physics 2 enrolled 21 835 students out of 15.3 million high school students in the United States in 2020 [36,37]. Furthermore, access and performance in this course are inequitable, with intersectional groups traditionally underrepresented in STEM enrolling at lower rates and earning lower scores [38].

Another issue for teachers including QIST in their instruction is that even after training, teachers may still lack self-efficacy in their ability to teach these topics [12,14]. Sutrini *et al.* [14] found that teachers who had attended their workshops were requesting help after the program to prepare QIST content for their classrooms. According to Holincheck *et al.* [12], the level of teacher confidence was lower for their 2-h workshop than in their 5-h workshop, consistent with other research suggesting that teachers tend to gain self-efficacy in their ability to teach QIST from a longer exposure to professional learning [15,16]. This is consequential since research has shown that increased teacher self-efficacy improves their willingness to integrate science across disciplinary boundaries [11] as well as student achievement [39]. However, other research has shown that improved self-efficacy does not necessarily correspond with increased content knowledge and reformed teaching practices [11,40], and it may correlate to overconfidence and diminished outcomes [41]. More research is needed to understand potential relationships among teacher self-efficacy, instructional practices, and student outcomes.

D. Theoretical framework

The theoretical framework for *EduQation* professional learning utilized the *STEM integration framework*, which suggests that integrated STEM requires a complex interconnectedness of pedagogical strategies from respective disciplines [42]. QIST instruction is inherently multidisciplinary, with key concepts and skills drawn from physics, chemistry, mathematics, and computer science. STEM integration often emphasizes the coverage of content without providing students with opportunities for developing a deeper understanding or drawing connections between learning in different contexts [43].

The STEM integration approach to fostering cognition suggests that quantum literacy and related 21st-century scientific habits of mind may be fostered through integrating disciplinary QIST knowledge with practical computing applications that apply to real-world challenges in QIST research and development. Since research has indicated that effective professional development models facilitate innovative teaching practices through situated cognition and collaboration [26], it is logical to use the STEM integration framework to guide both classroom and professional development experiences [42]. The professional learning structure in the present study facilitated the preparation of STEM teachers to integrate QIST principles in disciplinary content and curricula; this required the development of teachers' content knowledge and pedagogical content knowledge in quantum principles and computing. Furthermore, teachers in the present study were trained to include potential applications of quantum computing as anchoring phenomena in their instruction—this is consistent with research suggesting that integrated STEM learning should be authentic and focused on real-world technological problems [44].

The framework for the teachers' professional development was also derived from psychosocial theory that characterizes students' academic and career choices and actions, and how science teachers might interact with students to influence STEM understanding, interest, and career aspirations. Bandura suggested that the self-efficacy of learners (in the case of the present study—teachers) may be improved through situated learning, social persuasion by experts, and social modeling [45]. Teachers may facilitate students' knowledge and self-efficacy through their own disciplinary mastery and pedagogical content knowledge [46], with attention toward the counterintuitive, abstract nature of quantum ideas [47] and cognitive load reduction [48]. This is particularly important in the field of quantum computing since secondary students often do not have an understanding of quantum principles, consequently, they may be unable to conceptualize the relevance of quantum computing in solving problems that classical computers cannot [49]. When confident teachers advance student understanding through effective STEM integration, students may gain an appreciation for quantum computing, strengthen their knowledge of the physical sciences, and identify academic coursework that will prepare them for related careers.

III. METHODS

A. Research design and context

The QIST professional learning intervention, *EduQation,* included $N = 51$ self-selected secondary teachers from both urban and suburban school districts in New York, New Jersey, and Connecticut. This study explored the outcomes of the *EduQation* intervention for secondary teachers using a pretest or post-test design [50]. The main goal of the intervention was to improve teachers' QIST knowledge and skills, pedagogical self-efficacy, and awareness of QIST careers and academic pathways. The NSF-funded program consisted of four sessions (12 contact hours) offered once per week in the evenings. The intervention was run 3 times in 2023–24, twice at a research university in a suburban location and once at an informal science institution in an urban location. By utilizing both locations, the researchers recruited participants from a diverse group of secondary schools.

The participants in *EduQation* professional learning included 51 middle and high school teachers from the southeast region of New York State. Of these 51 teachers, 38 were in-service STEM teachers, 10 were preservice physics teachers, 2 were retired, and 1 was a district-level STEM administrator. The in-service teachers collectively taught approximately 2900 students annually. The majority of teachers (76%, $n = 39$) taught or were training to teach physics, while others taught STEM subjects including chemistry, Earth science, biology, mathematics, computer science, and general science.

The teachers were recruited from 35 high schools in the Southeast New York metropolitan region; two-thirds of these schools enrolled more than 30% of students who qualified for free and reduced lunch, an indicator of low socioeconomic status. The mean teaching experience among the in-service teachers was 15.5 years. More than half of them (61%) reported learning about some aspects of quantum science in their preservice coursework. When asked whether their schools supported the integration of quantum concepts into existing STEM curricula, 50% agreed, 33% were neutral, and 17% reported their schools were not supportive.

Of the 51 participants, 40 completed both the pre- and post-self-efficacy surveys, although a sample of 48 teachers was used to calculate postsurvey reliability and perform exploratory factor analysis. The survey had been piloted with 17 STEM teachers who participated in focus group sessions to test instructional strategies before the start of the formal *EduQation* program.

B. Professional learning structure

The *EduQation* program developers or instructors included a theoretical quantum physicist, an experimental quantum physicist, and a physics education researcher. Their combined expertise contributed to programmatic elements connected to their work in classical and quantum physics, experimental quantum simulations with ultracold atoms, quantum computation and condensed matter physics, and research on programmatic outcomes of educational interventions.

The four-session themes included: (i) Building Blocks of Classical and Quantum Physics; (ii) Quantum Ideas: From Superposition to Entanglement; (iii) Quantum Computing Fundamentals; and (iv) QIST Pedagogy, Curriculum Development, and Career Awareness. Instructors introduced QIST topics and provided strategies for including these topics in science, mathematics, and computer science classrooms, focusing on methods to help students overcome the challenges of learning QIST and providing ample collaborative time for teachers to determine how QIST topics may be included in their existing curricula. The conceptual approach to topics was organized through a vertical progression illustrated in Fig. 1. Teachers first learned about classical wave behavior (diffraction and polarization) as a precursor to quantum concepts such as single-particle superposition, photon polarization states, and quantum bits (qubits). They then progressed to waveplates and quantum gates, basic quantum circuits, entanglement, Bell's inequality, and quantum key distribution. Once they had a foundation in classical and quantum concepts and skills, they worked on developing lessons that could apply these ideas in their standards-based curricula.

The *EduQation* workshop included a combination of lectures, demonstrations, and hands-on experiences that provided a foundation in classical and quantum physics, superposition, entanglement, and quantum computing and measurement. These topics were introduced using strategies described in the literature review as successful in increasing understanding of QIST [12–14,31–33]. Hands-on activities included experiments and simulations with

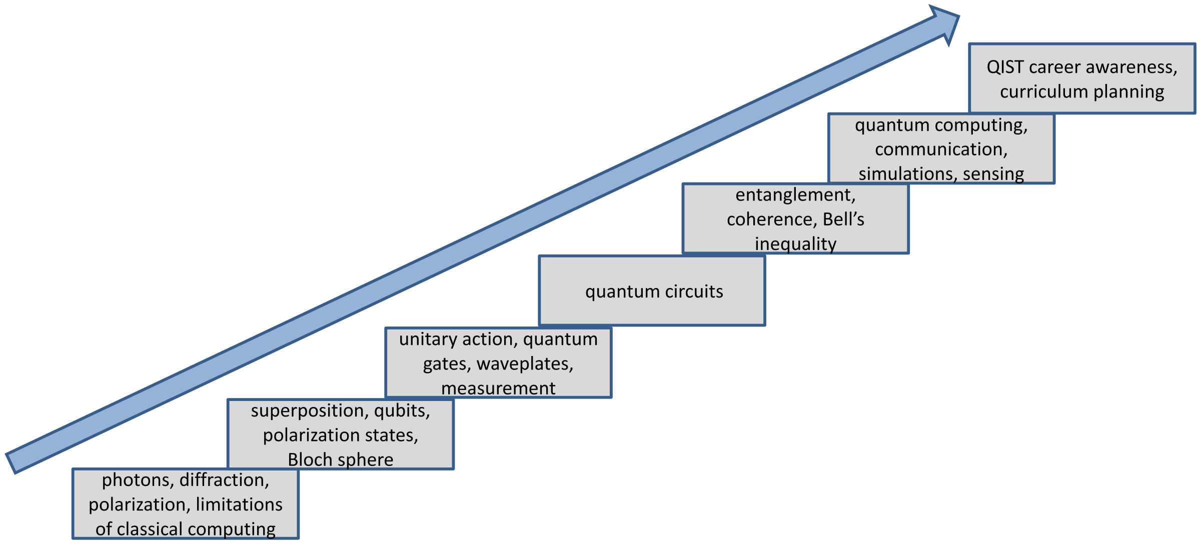

FIG. 1. Vertical progression of QIST concepts, skills, a curriculum planning.

diffraction, interference, and Malus's law, demonstrations with a Mach-Zehnder interferometer, building Bloch sphere models, and manipulating qubit representations with *Wolfram Mathematica* [51]. Teachers solved problems with classical gates, vectors and matrices, and quantum key distribution. They played games to illustrate quantum gates before building quantum circuits with IBM Composer (for more detailed descriptions of these activities, see Ref. [28]).

Connections with NGSS [34] were highlighted throughout the program using K-12 curricular frameworks developed by the National Q-12 Partnership for physics, chemistry, computer science, and middle school STEM [52]. The three-dimensional approach outlined in NGSS was applied to QIST concepts as teachers were prompted to consider how these ideas could be implemented in their instruction. For example, when introducing the qubit, teachers considered learning outcomes from the Q-12 frameworks with respect to computer science and quantum information science, as shown in Fig. 2. The example below uses middle school learning outcomes since some participating teachers taught both middle and high school.

These outcomes were mapped to NGSS standards and the three-dimensional learning strands of disciplinary core ideas, crosscutting concepts, and science and engineering practices, as shown in Fig. 3. Students learn that encoded qubits may include photons, atoms, electrons, and trapped ions while considering the crosscutting concept of light carrying energy as electromagnetic radiation. They might demonstrate these concepts through building models or performing experiments with polarization filters and birefringent materials.

Teachers spent time in content-based teams to develop QIST lessons that utilized an anchoring phenomenon, or a sensemaking event, related to potential QIST applications —examples might include cryptography, solar capture, and traffic control. They considered the experiments, simulations, and activities from the program to develop instructional plans appropriate for their students, along with assessments to set benchmarks for content and skills mastery. Figure 4 illustrates sample activities and anchoring phenomena.

C. Quantitative data collection and analysis

Teacher self-efficacy outcomes were measured by quantitative survey data analyzed via descriptive and inferential statistics. The *Teacher Self-Efficacy in Quantum Information Science and Technology Scale (TSE-QIST)* (Table I) was used to assess teachers' familiarity with and confidence in teaching QIST principles and skills prior to the workshop and

Middle School STEM Standard 4.1 (QIS Key Concepts for Middle School)	
Computer Science Learning Outcome	**QIS Learning Outcome**
"Students will describe how, in information technology, information must be stored in a collection of physical systems, each with two possible states" (p.18).	"Students will describe how systems which obey the laws of quantum mechanics can store information as quantum bits" (p.18).

FIG. 2. Middle school learning outcomes for storing information as qubits [52].

Alignment with NGSS and QIS Learning Frameworks
Disciplinary Core Ideas in the *Physical Sciences*: QIS MS – Key Concept 4 (Qubits): “The quantum bit, or qubit, is the fundamental unit of quantum information, and is encoded in a physical system, such as polarization states of light, energy states of an atom, or spin states of electrons” (p.16).
Crosscutting Concepts related to *Energy and Waves*: QIS MS 4.3 – Description: “Light carries energy as electromagnetic radiation” (p.19).
Science and Engineering Practices including *Competing Designs*: QIS MS 4.3 – Possible Activities: “Students can develop a communication system that uses the polarization of light to encode 0’s and 1’s, which can be measured with polarizers or sunglasses. Students can demonstrate how polarization is manipulated and controlled using birefringent materials such as clear tape” (p.19).
Supporting Standards: NGSS MS-PS4-3: “Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.” NGSS MS-ETS1-2: “Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.” NGSS-PS4-1: “Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to energy in a wave.” NGSS-PS4-2: “Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.”

FIG. 3. Three-dimensional NGSS alignment for introducing the qubit [34,52].

again at the close of the workshop. Because there were no existing instruments to assess this topic, a survey was designed and piloted by modifying questions from three surveys that measure engineering familiarity and self-efficacy—the *Master Teacher Engineering Professional Development Survey* [53], the *Teaching Engineering Self-Efficacy Scale* [54], and the *Familiarity with Design, Engineering, and Technology (DET) Survey* [55]—along with several questions created by the researchers to address self-efficacy in providing information about QIST academic pathways and careers. Content validity was established by three experts in physics education, quantum computing, and experimental quantum physics.

The survey was administered electronically with additional questions to collect background information about the teachers’ certifications, teaching experience, and prior quantum coursework. The teachers responded to each of the 23 items by selecting from Likert-scale choices 1 (strongly disagree) to 5 (strongly agree). The pre- and postsurveys had high internal consistency (Cronbach’s $\alpha = 0.95$ for presurvey, $\alpha = 0.91$ for postsurvey) [56]. Eight items were removed from the original 31-item survey due to low factor loadings or cross loadings among multiple factors.

The dimensionality of the 23 remaining survey items was analyzed using exploratory factor analysis with an oblique

Building Blocks of Classical Waves and Quantum Physics	Quantum Ideas	Quantum Computing Fundamentals
Single slit vs double slit interference	Bloch sphere model	Qubits & quantum gates
PhET simulations	Visualizing quantum states	Qubit Touchdown game
Diffraction gratings	Mathematica code simulation	Two-qubit states
Polarization and light intensity	Single-photon interference	Two-qubit entangling gates
Mach-Zehnder interferometer	Thought experiments (entanglement)	IBM Quantum Composer circuits
Waveplate demonstrations	Lab tour: Simulating quantum systems	Quantum key distribution (QKD)

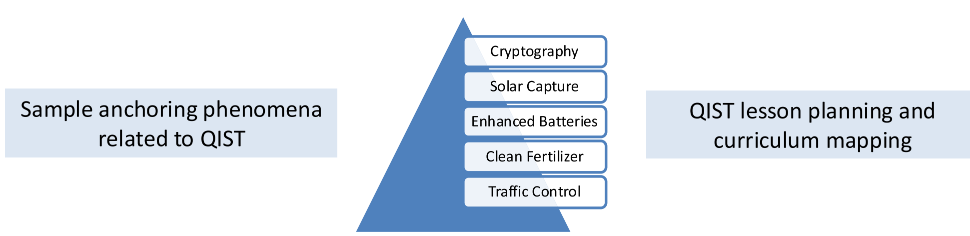

FIG. 4. QIST concepts, activities, and anchoring phenomena for inclusion in NGSS-based lesson planning.

TABLE I. Factor analysis of teachers' QIST attitudes. The bold values in table indicate the primary factor loadings for each survey item.

Items	Factor loadings		
Self-efficacy in knowledge about QIST academic pathways and careers			
1. I am able to stay current in my knowledge of quantum science and computing [54].	**0.740**	0.582	0.485
2. I am able to recommend relevant high school STEM courses to students interested in pursuing a quantum information science and technology (QIST) career [53].	**0.797**	0.596	0.511
3. I am able to differentiate among QIST careers [53].	**0.808**	0.486	0.677
4. I am familiar with the prerequisite knowledge necessary for students to pursue QIST-related majors in college.	**0.861**	0.479	0.496
5. I am able to connect students with experts in QIST.	**0.800**	0.210	0.520
6. I am aware of the opportunities for high school students to gain exposure and experience in QIST.	**0.689**	0.143	0.491
7. I am able to discuss how quantum computers can solve modern day technological challenges [54].	**0.748**	0.566	0.489
8. I can identify fundamental differences between classical and quantum computing.	**0.782**	0.453	0.166
9. I am able to spend the time necessary to plan quantum science lessons for my class	**0.604**	0.412	0.411
Self-efficacy in facilitating QIST learning			
10. I am able to increase students' interest in learning about quantum science and computing [53].	0.500	**0.673**	0.560
11. I am able to discuss how quantum concepts are connected to everyday life [54].	0.313	**0.773**	0.384
12. I am able to encourage my students to think creatively during quantum science activities and lessons [53].	0.360	**0.819**	0.657
13. I am able to encourage my students to think critically during quantum science activities and lessons [53].	0.398	**0.756**	0.608
14. I am able to encourage my students to interact with each other when participating in quantum science activities.	0.449	**0.821**	0.587
15. I am able to motivate students who show low interest in learning about quantum science and computing [54].	0.294	**0.538**	0.271
16. I am familiar with basic quantum concepts.	0.388	**0.700**	0.320
17. I am able to recognize and appreciate quantum concepts in my subject area [53].	0.523	**0.753**	0.365
Self-efficacy in QIST pedagogical fluency and STEM integration			
18. I am able to integrate quantum science activities into my classroom instruction.	0.523	0.485	**0.873**
19. I am able to teach quantum concepts as well as I do other STEM concepts in my curriculum [54].	0.287	0.426	**0.783**
20. I am able to create quantum science activities at the appropriate level for my students.	0.673	0.471	**0.883**
21. I am able to select appropriate materials for quantum science activities.	0.572	0.510	**0.906**
22. I am able to develop relevant assessment questions about quantum science for my students [54].	0.598	0.543	**0.895**
23. I am able to measure student comprehension of quantum concepts that I have taught [54].	0.493	0.596	**0.723**

Promax rotation. This method was chosen to allow for correlations among the factors. Composite scores were compiled for the survey as a whole and for each of the factors identified via factor analysis. Pre-/postsurvey composites were analyzed using paired sample t-tests, for which *a priori* power analysis indicated the sample size was adequate to detect a medium effect in means comparisons with 80% power [57].

IV. RESULTS

A. Factor analysis of teacher attitudes

Exploratory factor analysis was run with a three-factor solution to maximize explained variance while identifying latent factors with foundations in prior STEM education research. This solution was chosen after first examining the scree plot, which indicated a two- to four-factor solution might be appropriate (Fig. 5). Subsequent analyses indicated that the two-factor solution explained less variance than the three-factor solution (58.92% vs 64.97%), while the four-factor solution had at least four cross-loaded items (defined as "items that give high loading on more than one factor and where the difference between these loadings is less than 0.10" [58] (p. 176)). Items were removed individually until a stable matrix was observed with no cross-loaded items and maximal variance.

The *TSE-QIST* survey with three subconstructs explained 64.97% of the variance in teachers' self-efficacy responses. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.76, which is above the 0.6 minimum threshold [59], and the Bartlett's test of sphericity was significant ($\chi^2(253) = 698.02$, $p < 0.001$). All primary factor loadings exceeded the recommended threshold of 0.4 [60], with a minimum of 0.5. The sample size for this factor analysis ($N = 48$) falls within the recommended range of $N = 45$ to $N = 55$ for a three-factor solution with an item-to-factor ratio of 7 to 8 with wide communality (for the present study, 0.47–0.85), although there has been disagreement on this point [61]. Also, relatively few secondary teachers have engaged in QIST professional learning interventions. Consequently, this

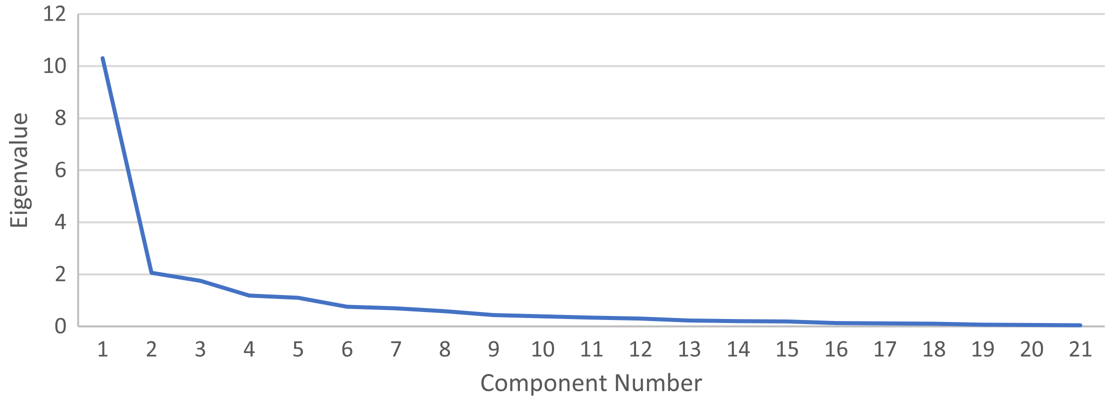

FIG. 5. Exploratory factor analysis scree plot.

analysis should be considered preliminary with future confirmatory factor analysis to provide more robust results with larger samples.

Although *a priori* factors were not specifically identified, the survey was developed with items that reflected the intended workshop outcomes for teachers. Within-factor items exhibited shared conceptual meaning and theoretical consistency with each other. These factors were aligned with the goals of the professional learning program, which included improved self-assessment of QIST knowledge and skills (for the purpose of effective teaching and student learning), as well as awareness of QIST career opportunities and academic preparation. The researchers examined the item distribution and three factors were characterized, each with at least six items: (i) self-efficacy in knowledge about QIST academic pathways and careers, which accounted for 22.63% of the item variance ($a = 0.90$); (ii) self-efficacy in QIST pedagogical fluency and STEM integration (21.18% of item variance, $a = 0.93$); and (iii) self-efficacy in facilitating QIST learning (21.16% of item variance, $a = 0.88$).

To confirm the validity of the Promax rotation method, bivariate Spearman correlations were measured among the postsurvey factors. Each factor had a strong correlation with the other two ($r > 0.60$), suggesting an oblique method was appropriate:

- Self-efficacy in knowledge about QIST academic pathways and careers was correlated with self-efficacy in QIST pedagogical fluency and STEM integration [$r(49) = 0.74$, $p < 0.001$].
- Self-efficacy in knowledge about QIST academic pathways and careers was correlated with self-efficacy in facilitating QIST learning [$r(49) = 0.66$, $p < 0.001$].
- Self-efficacy in QIST pedagogical fluency and STEM integration was correlated with self-efficacy in facilitating QIST learning [$r(50) = 0.61$, $p < 0.001$].

The nine questions in factor 1 (*self-efficacy in knowledge about QIST academic pathways and careers*) focused on the level of teacher preparedness for encouraging students to further their QIST studies and/or explore QIST career options. These questions included knowledge of coursework to best prepare themselves for postsecondary QIST study, as well as knowledge of the four general areas of QIST workforce development (i.e., quantum sensing and metrology, quantum computing, quantum communication, and quantum simulations) [62].

Factor 2 (*self-efficacy in QIST pedagogical fluency and STEM integration*) consisted of eight questions that described the teachers' confidence in their ability to teach QIST concepts through appropriate planning, activities, and assessment. Questions also addressed teachers' self-efficacy in finding ways to implement QIST concepts and skills in their specific STEM disciplines.

The final construct, factor 3 (*self-efficacy in facilitating QIST learning*) consisted of six questions that related to teachers' self-assessed effectiveness to guide their students to think creatively and critically in collaborative QIST learning environments. Survey items and their accompanying factor loadings are given in Table I.

B. Comparisons of means of teachers' attitudes

A paired samples t test was performed on the attitude survey results as a whole and on each factor of the pre- and postsurvey to determine changes related to participation in *EduQation*. Missing data were deleted listwise. The paired samples t test for the entire survey showed significant improvement among the teachers ($t=9.84$, d.o.f. $=35$, $p<0.001$, 95%CI[22.58,34.31]) from presurvey ($M=69.22$, SD $=17.33$) to postsurvey ($M = 97.67$, SD $= 9.41$), with a large effect size (Cohen's $d = 1.64$).

When broken down by factor, *self-efficacy in knowledge about QIST academic pathways and careers* showed significant improvement ($t = 12.53$, d.o.f. $= 38$, $p < 0.001$, 95%CI[11.82, 16.38]) from presurvey ($M = 24.59$, SD $=$ 7.55) to postsurvey ($M = 38.69$, SD $= 4.07$), with a large effect size ($d = 2.01$). The second factor, *self-efficacy in facilitating QIST learning,* improved ($t = 6.87$, d.o.f. $=$ 39, $p < 0.001$, 95%CI[4.68, 8.57]) from presurvey ($M =$ 28.38, SD $= 5.60$) to postsurvey ($M = 35.00$, $SD = 3.00$),

TABLE II. Paired samples t-test results.

Self-efficacy factor[a]		M	SD	t	Cohen's d
I. Knowledge about QIST academic pathways and careers	Pre	24.59	7.55	12.53	2.01
	Post	38.69	4.07		
II. Facilitating QIST learning	Pre	28.38	5.60	6.87	1.09
	Post	35.00	3.00		
III. QIST pedagogical fluency and STEM integration	Pre	16.77	6.15	7.79	1.25
	Post	24.13	3.32		
Overall composite[a]	Pre	69.22	17.33	9.84	1.64
	Post	97.67	9.41		

[a] $p < 0.001$ for composite and all factors.

with a large effect size ($d = 1.09$). Finally, *self-efficacy in QIST pedagogical fluency and STEM integration,* improved ($t = 7.79, \mathrm{d.o.f.} = 38, p < 0.001, 95\%\mathrm{CI}[5.45, 9.27]$) from presurvey ($M = 16.77, \mathrm{SD} = 6.15$) to postsurvey ($M = 24.13$, $\mathrm{SD} = 3.32$), with a large effect size ($d = 1.25$). The t-test results are summarized in Table II.

V. DISCUSSION

Integrating QIST knowledge and skills into existing curricula is a crucial step in building the QIST workforce of the future, as these topics are not often covered before advanced undergraduate courses, after which many students have already chosen their career paths [9]. The *EduQation* professional learning intervention significantly increased teachers' self-efficacy in QIST instruction, providing them with the tools to increase the number of students exposed to QIST topics and workforce options before they develop career aspirations. This work expands the research base in precollege QIST teacher professional learning, building upon limited prior literature [12–16] by providing a valid, reliable survey instrument for measuring teacher self-efficacy (the *TSE-QIST Scale*) and performing inferential analyses of teacher outcomes. These analyses were viewed through a STEM integration framework [42,43], in which teachers were given strategies for addressing the interdisciplinary curricular demands inherent in QIST instruction [17,62].

The first and second research questions explored the development of an instrument to measure affective teacher outcomes in QIST professional learning. This is consequential since many QIST professional learning programs are in the early stages and robust measures of secondary teacher outcomes have been limited [29]. Teacher self-efficacy has been linked to increased job satisfaction and the implementation of STEM integration and inquiry-based learning [11,39], however, the relationship between teacher self-efficacy and student achievement has been inconclusive [41,63]. The *TSE-QIST Scale*, modified from previous self-efficacy scales in STEM fields [53–55], was designed to measure STEM teacher self-efficacy in teaching QIST principles and skills, knowledge of QIST advancements and potential relevance, impact on student learning in QIST, and capacity to advise on QIST career pathways, including precollege STEM coursetaking postsecondary study, and differentiating jobs in the field. The *TSE-QIST Scale* demonstrated excellent fit and reliability while differentiating subdimensions of QIST self-efficacy. This instrument shows promise for use in QIST professional learning programs to assess affective outcomes, which are often predictive of classroom practices and student learning [11,39,63]. However, more research is needed to explore these secondary outcomes as formal QIST instruction is expanded in secondary classrooms.

The third research question examined whether teachers improved their QIST self-efficacy after participating in the *EduQation* workshop. Teachers improved their QIST self-efficacy with large effect sizes in the overall composite and the three subconstructs: *knowledge of QIST academic pathways and careers, facilitating QIST learning,* and *QIST pedagogical fluency and STEM integration*. Programmatic elements that may have contributed to this outcome included participation in hands-on experiences and demonstrations [12–14], modeling complex quantum phenomena such as cryptography and quantum erasure [15], use of computational tools and games to understand quantum gates [13,14], and spending time talking with QIST students and faculty experts and exploring their laboratories [13]. Teachers also benefited from learning about QIST conceptual learning progressions and career expectations [15]. Their situated experiences contributed to increases in self-efficacy, which may facilitate the implementation of QIST concepts in their standards-based STEM curricula [17,20,21,39], although more research is needed to examine how this affects student learning. Although the teachers experienced situated learning and social persuasion by faculty experts, which has been shown to improve behaviors associated with positive outcomes [45], they may need to experience the QIST teaching process first hand to demonstrate their ability to teach these concepts well while facilitating student engagement and learning.

The participants in the *EduQation* intervention represented a variety of secondary educators in multiple STEM disciplines (majority physics), many of whom taught in schools with 30% of students of low socioeconomic status. It is essential to develop QIST teacher training that reaches teachers in schools with large numbers of traditionally underserved students in STEM. A diverse, inclusive workforce is necessary to meet the demands of the rapid expansion of QIST employment opportunities [2,4,7,9,64]. Therefore, QIST professional learning should also include information on academic and career preparation for QIST jobs. Many students of color and students of low socioeconomic status do not have equitable access to physics, computer science, and advanced mathematics [5,6,65], so it is important that teachers communicate with students about these opportunities in the absence of more formalized advisement [53,66].

The results of this study provide a replicable model for creating future teacher professional learning workshops. Although QIST expertise at the university level is not readily available for secondary STEM teachers in U.S. schools, this informal learning model is a first step toward identifying effective programmatic elements that may be translated into formal preservice teacher education. This is essential to promote QIST instruction in precollege classrooms to increase student exposure and workforce development in the field [4].

A. Implications

Professional development has shown promise in strengthening teachers' self-efficacy so they may facilitate student engagement in QIST, a field that involves conceptual change and is often considered abstract, counterintuitive, inaccessible, and suitable only for the academically elite [67,68].

Providing teachers with professional learning presents a unique opportunity for expanding the reach of a workshop from only 50 teachers to thousands of students annually. It is also important that within these types of workshops, there is access to both QIST and science education experts because this provides content and strategies for teaching QIST to a younger audience.

The design of a research instrument (*TSE-QIST Scale*) to measure self-efficacy is an initial step in assessing teacher outcomes and facilitating future research in this area. Although research has suggested that increased self-efficacy is related to a greater incidence of reformed STEM classroom practices [11,39], this affective construct may be an invalid proxy for student outcomes [41,69]. In the present study, it is unclear whether QIST pedagogical self-efficacy and awareness translated to students' QIST learning and career aspiration formation. However, novel professional learning models that promote both QIST learning and academic or career advisement may be promising for preparing teachers to incorporate rapidly emerging technologies in their courses. Self-efficacy may be a precursor to shifting their beliefs and pedagogy. More empirical work is needed to explore the relationships among teachers' QIST self-efficacy, beliefs, practices, and student performance. This might include longitudinal studies with implementation meetings, which have been shown to improve teacher and student outcomes [70].

These findings are of interest to precollege STEM educators and policymakers because research suggests that early intervention is key in increasing workforce readiness and diversity in QIST [2,8,71]. Training physics teachers to discuss potential careers in the field has been implemented in the American Physical Society's STEP-UP Program [72], and the *EduQation* model adopted a similar approach to career aspiration formation. If teachers and school personnel are more confident in discussing modern-day career options, they may be more likely to share this information with their students [53,66,73].

Research universities with teacher certification programs are ideal locations for designing and implementing QIST professional learning, as they can provide expertise in both QIST and preservice teacher education. However, this will limit accessibility for many U.S. teachers. *EduQation's* partnership with an urban informal science institution expanded the project's reach to more STEM teachers in high need schools. Future professional learning models might consider online and/or hybrid instruction to reach a large group of precollege teachers, however, this would have to be carefully curated to incorporate social interaction among teachers and sustained teacher networks.

B. Limitations

This study was limited by a small sample size, which will be addressed by repeating the above analyses after new cohorts complete the *EduQation* workshop with approximately 30 additional teachers each year. Larger sample sizes will allow for confirmatory factor analysis to evaluate the *a priori* exploratory factor structure and strengthen validity [61]. The teacher-participants were recruited from schools in the New York—New Jersey—Connecticut tristate region, and their self-reported attitudes may not be generalizable to teachers in other regions of the United States and internationally. Recruiting control group teachers would strengthen empirical findings by comparing the self-selected teacher participants to the general population of STEM teachers. Furthermore, qualitative analysis in the form of teacher interviews, focus groups, and examination of teacher artifacts would provide more nuanced findings of effective programmatic elements.

This study was further limited by not reporting teachers' QIST knowledge and skills acquisition. Future research will examine these variables and examine potential correlations to self-efficacy and student engagement and learning. A final limitation was a long-term follow-up to observe changes in teachers' practices. A more formalized QIST teacher network is in the planning stages for teachers to share lesson plans, QIST activities, and assessments that are aligned with NGSS and state-level learning standards.

C. Conclusions

The results of this pilot study indicate that a professional learning workshop designed and delivered by experts in QIST and physics education is effective in improving secondary teachers' self-efficacy in their ability to teach QIST topics, communicate the relevance of QIST discoveries and applications, and introduce students to QIST careers and academic pathways. This experience was both rigorous and accessible, providing teachers with the depth of knowledge required to teach QIST concepts and skills while increasing their confidence in their knowledge and abilities. This is a first step toward changing teachers' beliefs about QIST as well as their instructional practices.

There is a limited amount of research on secondary QIST education despite the global imperative for more well-trained individuals to enter QIST-related fields [29]. Further research on this topic is necessary to determine the best ways to increase exposure to QIST for all K-12 students.

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