Student attitudes toward quantum information science and technology in a high school outreach program

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[This paper is part of the Focused Collection in Investigating and Improving Quantum Education through Research.] With the current growth in quantum information science and technology (QIST), there is an increasing need to prepare precollege students for postsecondary QIST study and careers. This mixed methods, explanatory sequential research focused on students' affective outcomes from a one-week, 25-h summer program for U.S. high school students in grades 10–12. The workshop structure was based upon psychosocial theories of self-determination and planned behavior, where QIST aspirations may be facilitated and viewed as achievable choices if students acquire disciplinary knowledge, self-efficacy, normative expectancy of their capacity in the field, and awareness of vocational roles. The program featured lectures, demonstrations, and hands-on experiences in classical and quantum physics and quantum computing. Students' attitudes toward QIST ($N = 77$)—including self-efficacy, self-concept, relevance, career aspirations, and perceptions of quantitative fluency—showed improvement with a medium effect size, even though treatment students entered the program with more positive QIST attitudes when compared with a control group of high school physics students ($N = 65$). Postprogram interviews with $n = 12$ participants identified several explanatory themes: (i) Students tended to comprehend classical and quantum topics taught through multiple representations, regardless of whether they had taken physics previously; (ii) students experienced some challenges with mathematics and science concepts that support quantum understanding, yet they revealed a willingness to learn new concepts outside of their comfort zone; (iii) students expressed motivation for pursuing science, technology, engineering, and mathematics and/or quantum-related careers in the future, as well as increased QIST self-concept, largely through understanding the relevance of QIST in solving technological problems; and (iv) students reported increased self-efficacy in understanding QIST topics and performing related tasks. This informal summer program showed promise in promoting positive student attitudes toward QIST, a critical emerging field in advancing technological solutions for global challenges.

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I. INTRODUCTION

With the current growth in quantum information science and technology (QIST), there is an increasing need to prepare precollege students for postsecondary QIST study and careers [1]. QIST is the synthesis of quantum mechanics and computer science to facilitate the development of theories and technologies that outperform classical

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computers [2]. There are many potential benefits of QIST to society in the areas of computing, communication, sensing, and foundational science [3]. However, there are also new risks that are evolving from the development of quantum computing technologies, especially in the field of cryptography, where conventional encryption schemes used to keep information protected by passwords and other authentication processes are at risk of being compromised [4,5]. Because of these potential risks and benefits, it is imperative to advance research in QIST disciplines and strengthen QIST career pipelines [6].

QIST fields are swiftly expanding beyond the available talent in all sectors, including industry, national laboratories, government agencies, and academia [6,7]. As recently as 2018, there were as few as 1000 people in the world performing leading research in quantum computing, and when considering growth in the field, there is still a significant shortage of talent [6,8]. There are many initiatives throughout the world that are investing heavily in the further development of QIST workforce development. As of 2023, an estimated $42 billion in public funding was dedicated to quantum technologies [9], with the global quantum technology market projected to reach $106 billion by 2040, the majority of which will be dedicated to quantum computing [10]. This will produce many jobs that require educational preparation in QIST-related disciplines and technologies. Despite all this investment and the resulting growth in technological development, the national workforce has been unable to keep up with the QIST employment demands. In 2022, one in two quantum jobs remained vacant due to a talent shortage [10].

To address this growing issue, the U.S. National Quantum Initiative issued the *QIST Workforce Development National Strategic Plan* in 2022, which stressed the importance of collaboration among government, academia, nonprofits, professional societies, and companies to create a diverse workforce that matches growth in the field. The plan also recommended fostering precollege interest in QIST as students develop career aspirations [6]. Despite this and other pushes for early, accessible QIST education that reaches diverse populations [11,12], there are still few options for U.S. students to learn about QIST principles and careers in high school.

The present mixed methods, explanatory sequential study examined the affective impacts of a high school QIST outreach program. This one-week program was developed and taught by university faculty to students in grades 10–12 (ages 15–18). By evaluating programmatic impacts, this research provides a replicable model with supported implications for precollege QIST educational policy and practice. The overarching research questions were the following:

1. How did participation in an informal summer program created by QIST and physics education experts affect high school students' QIST attitudes, including self-efficacy, self-concept, and perception of QIST relevance?
2. What programmatic elements contributed to shifts in students' attitudinal domains?

II. LITERATURE REVIEW

A. QIST education in the United States

To meet the growing need for QIST professionals, precollege and undergraduate students need to recognize QIST as a potential career as early as possible, as research has suggested that exposing students to science, technology, engineering, and mathematics (STEM) topics early and providing examples of their real-world applications may increase career aspirations in these fields [13,14]. However, QIST topics are typically not covered until the advanced undergraduate level, so by the time students learn about these topics, they may have already chosen a different academic and/or career path [15].

1. Inclusion of QIST topics in high school curricula

Quantum topics are not often taught in high school classrooms in the United States. The high school section of the *Next Generation Science Standards* only contains the word "quantum" once, under Performance Expectation HS-PS4-3 in the topic area *Waves and Electromagnetic Radiation*, where it lists quantum theory as a part of the standard that will not be assessed [16]. Some states, such as New York, require some additional coverage of quantum, where the performance expectation has been modified slightly to include some qualitative descriptions of quantum theory topics [17].

This amount of coverage may be considered minimal, but there are additional high school opportunities for gaining more QIST-relevant knowledge if students take Advanced Placement (AP) Chemistry and Physics courses. The AP Chemistry curriculum includes some quantum concepts as students learn that electron configuration is explained by quantum mechanics [18]. Another option is AP Physics, which is split into four different course options: AP Physics 1 and AP Physics 2 (both algebra-based), AP Physics C Mechanics, and AP Physics C Electricity and Magnetism (both calculus-based). Of all these advanced physics courses, only AP Physics 2 includes quantum topics, with an entire unit on *Quantum, Atomic, and Nuclear Physics* [19]. Notably, only 21 835 students in the United States took the AP Physics 2 course in 2020, although there were over 15.3 million high school (grades 9–12) students in public schools alone [20,21].

Despite some coverage of quantum physics in advanced high school physical science courses, many topics that are foundational to QIST are not a part of any science curriculum. Experts in the field suggest that the quantum physics topics needed to introduce QIST include the wave-particle duality of light, probabilities associated with wave functions, and an in-depth knowledge of atoms [22–24]. Of these topics, the study of atoms is included in high school chemistry, and some aspects of wave-particle duality are often addressed in physics and chemistry; however, these courses may not cover de Broglie waves, Heisenberg's uncertainty principle, or wave functions [23]. Once students have a foundation in these quantum concepts, they may advance to QIST principles and skills, which research has suggested should include quantum states and their measurement; the quantum bit or qubit; entanglement; coherence; quantum operations using quantum computers; and quantum communication and quantum sensing [25].

2. Challenges in QIST teaching and learning

To teach high school students about the topics described above, one must consider the conceptual difficulties that may arise, many of which result from the abstract nature of quantum topics and the inability to directly observe quantum phenomena [26–28]. In addition, the language that experts and teachers use to describe concepts in quantum physics may be confusing for students [26]. Quantum physics is described in many ways, including with spoken and written words, mathematical expressions, and visual representations, often with little transition among them [26,29]. Even if students can follow the linguistic inconsistencies, many have difficulty reconciling quantum physics with their prior physics knowledge [26]. This difficulty is often apparent when discussing atomic models, as many students select which version of the atomic model best suits the questions they are trying to answer [26,30]. Another common area for misconceptions is in the discussion of light—although light is typically discussed as either a particle or a wave, many students develop their own hybrid model that includes both aspects simultaneously [31,32].

B. Informal science education to address the quantum gap

Informal science education has shown promise for addressing the goals of the *QIST Workforce Development National Strategic Plan* by educating the general public about QIST through outreach that is both engaging and appropriate for the audience [6]. Informal science consists of out-of-school learning experiences that tend to be voluntary and less structured than those in formal classrooms and generally occur at universities, museums, camps, and other locations [33].

Informal enrichment programs have been shown to increase student motivation, confidence, in-school performance, and career interest in STEM fields [34,35]. These experiences also provide additional time beyond the typical school day, making it possible to cover topics that do not fit into school curricula while also fostering students' engagement through internships, mentoring, and career awareness [36]. This type of setting aligns with what the National Q-12 Education Partnership described as the ideal learning environment for quantum topics, where students are encouraged to ask questions and explore, collaborate with their peers, and learn without the stress of assessments and grades [37].

C. QIST programs for high school students

There have been many informal science education programs with a focus on QIST-related topics for high school students and several have reported the disciplinary content and pedagogical methods [38–47]. However, few researchers have published empirical data about student outcomes, making it challenging to identify effective instructional elements.

Publications about teaching QIST to high school students in both formal and informal settings include pedagogical strategies for providing comprehensive and age-appropriate experiences for high school students. Because of the abstract nature of quantum topics, many QIST programs include two or more ways of introducing abstract and/or challenging concepts [39–41,45,47]. Many have provided a combination of hands-on activities and computer-based activities to aid in student understanding, especially when considering quantum computing topics [39–41,47].

To facilitate understanding of abstract topics, it is common to create physical models that describe quantum phenomena that would otherwise be difficult or impossible for students to observe [39,40]. If a physical model is not available, other programs have included computer simulations in place of physical objects [41–43,46]. Another method to reinforce these concepts is to play quantum-themed games, including *quantum tic-tac-toe* [42], *Entanglion* [39,40], *Money or Tiger* [41], and *Qubit Touchdown* [48]. These can be completed as tabletop board games, using pencil and paper, or on a computer.

Most QIST-themed workshops for high school students include the use of advanced computational tools, with most choosing to use *IBM Quantum Composer* [49] as their tool of choice for developing and running quantum algorithms, as well as identifying the most likely output of a series of quantum gates [39–44,46,47]. This open-sourced platform has many visuals and tools for building quantum circuits and exploring probability. Other tools include *Jupyter Notebooks* and *Qiskit*, which may be used to incorporate computer coding elements in a QIST workshop [39,40,44].

For students to envision themselves using QIST knowledge in future careers, the presence of role models is effective in informal instruction. This could be in the form of teaching assistants [42,46] or talks and tours led by QIST professionals [43]. Teaching assistants are a resource who are often similar in age to the students in the workshop, making them more approachable [42,46]. Interactions with professionals in the field further expand the students' STEM network and provide the students with a view into what a career in QIST may look like [43].

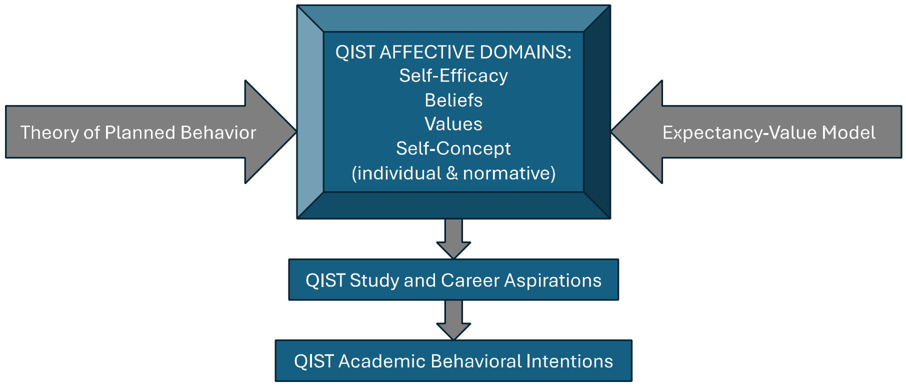

FIG. 1. Theoretical framework of psychosocial factors influencing QIST attitudes [50–59].

Students' science and mathematics preparation varies depending on grade level and precursor coursework, consequently, many high school QIST programs aim to provide an experience that is approachable regardless of STEM background [39–41,43,44]. Research has suggested that students entering a QIST program would benefit from having a basic understanding of high school level physics, however, no previous mathematics or coding skills would be required for participation [42].

III. THEORETICAL FRAMEWORK

The theoretical framework for the present study was derived from psychosocial theories that characterize students' academic and career choices and actions, and how informal physics educators might interact with students to influence STEM understanding, interest, and career aspirations. The *theory of planned behavior* suggests that students make academic decisions based on their cognitive understanding, confidence, self-concept, and sense of controllability [50]. That is, career goals are influenced by a student's self-assessed capability of meeting desired academic benchmarks. The theory states that human behavior is guided by likely consequences, the normative expectations of others, and beliefs about inhibiting factors [50]. STEM careers may be viewed as achievable choices if students have disciplinary knowledge, confidence they may overcome academic obstacles, understanding of vocational roles, and goals and behaviors consistent with their aspirations [50].

Fishbein and Ajzen [51] expanded upon the theory of planned behavior with their *expectancy-value model*, in which the perceived value of an outcome influences a student's beliefs and the desirability of that outcome. These psychosocial theories also incorporate perceived self-efficacy in performing given tasks that successively accumulate to achieve a particular outcome [50]. In the case of the present study, a student's self-efficacy in QIST tasks may relate to the perceived behavioral control necessary to succeed in a QIST-related major or career. Students may strive for a given career only if it aligns with their personal values and expectations of societal value and relevance [51]. Furthermore, self-concept, or the belief that one belongs in a disciplinary domain, is often formulated by success within that domain when evaluated both individually and with respect to the performance of others [52]. However, it is hypothesized that the inherent complexities of quantum principles and skills must be carefully navigated for students to develop QIST self-efficacy and self-concept.

Physics educators may facilitate knowledge and self-efficacy through attention toward the counterintuitive, abstract nature of quantum ideas [53] and cognitive load reduction [54]. 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 not be able to conceptualize the relevance of quantum computing in solving problems that classical computers cannot [55]. When students are exposed to QIST principles and skills, whether in formal or informal settings, they may gain an appreciation of quantum computing, strengthen their knowledge of foundational quantum concepts, and gain insights into academic coursework that will prepare them for QIST-related careers. Sociocognitive influences on the development of QIST aspirations and persistence may include self-efficacy, self-concept, and resonance with students' values and prior experiences [56–59]. The theoretical framework is represented in Fig. 1.

IV. METHODS

A. Research design

This mixed methods, explanatory sequential quasiexperimental study [60] measured outcomes of a *QIST Camp* intervention for students entering grades 10–12 using a pretest and posttest design with follow-up interviews. This research design was selected to analyze quantitative survey data with descriptive and inferential statistics, followed by qualitative interviews with participants to provide more nuanced interpretations of their experiences in the program.

QIST Camp was run twice in the summer of 2023, once at Stony Brook University (SBU) and once at an urban informal science institution (New York Hall of Science), and a third time in the summer of 2024 at SBU. Permission for research with human subjects was provided by the SBU Institutional Review Board (No. 2022-00244).

B. QIST program structure

This research analyzed the experiences of high school students from the Northeast United States that self-selected into *QIST Camp*, a weeklong program that introduced topics in QIST. These topics were designed by a theoretical quantum physicist, an experimental quantum physicist, and a physics education researcher, all of whom were faculty members at a research university. The 25-h program aimed to provide equitable QIST education for U.S. high school students, while also improving students' attitudes toward QIST, particularly their interest and career intentions.

The *QIST Camp* featured lectures, demonstrations, and hands-on experiences in classical physics, quantum physics, and quantum computing. It also included strategies identified in the literature review for QIST workshops for high school students [38–47]. The conceptual progression is described in more detail below.

1. Wave behavior

To set the stage, the program began with an introduction to the behavior of electromagnetic waves, which was then used as a foundation for introducing quantum ideas. Most students had not taken physics, and the introduction ensured that they were on equal footing in terms of their knowledge of diffraction and polarization. Students performed experiments to estimate the wavelength of a laser pointer, built a two-slit diffraction grating with a human hair, and explored Malus's law by rotating two or three polarization filters and taking measurements with a light sensor app on their cell phones.

2. Conceptual progression to quantum mechanics

As a bridge to quantum mechanics, the students learned about the photoelectric effect and the existence of photons, which illustrated quantum superposition and the wave-particle duality of single particles. Students viewed a live recording of the buildup of a double-slit diffraction pattern from a weakened laser emitting one photon at a time. The production of photons was related to the Bohr model and quantum jumps between stable orbits. This model was used to introduce wave-particle duality for electrons (and by extension, other massive particles) as seen in the diffraction of atoms from a double slit.

A second kind of quantum superposition between polarization states was illustrated with a Gedanken experiment in which a weak laser emitted single photons onto a polarizing beam splitter cube that separated the output into two modes. Which slit did the photon go through in a double slit? Which path did the photon take after the beam splitter? Thus, the concepts of diffraction and polarization provided a unifying, direct entry into the quantum realm.

More elaborate quantum concepts were similarly scaffolded for the students through both lecture and interactive simulations and demonstrations. These included entanglement between polarization and propagation (on the single particle level) with the Mach-Zehnder interferometer, which served as a transition for understanding multipartite entanglement. The latter was introduced in a Gedanken experiment on Schrödinger's cat entangled with the polarization state of a photon incident on a beam splitter and then generalized to include the state of the observer in a rendering of Wigner's friend's paradox, which led to a basic description of entanglement spreading and the measurement problem.

These discussions thus solidified multipartite entanglement, together with the quantum superposition on the single-particle level, as the two key quantum concepts with deep practical and philosophical consequences. Finally, a simple extension to polarization states of distant photons led to a discussion of Bell's inequality and a third key concept, quantum nonlocality.

3. Quantum computing and communications

The units on quantum computing began with a discussion of quantum states and the Bloch sphere. Students created Bloch sphere models with tennis balls and rubber bands, labeling the three axes so they could continuously return to their model when learning about quantum gates. This was followed by a description of unitary evolution, quantum measurement, and two-qubit quantum gates. The tenets of quantum computing were introduced through models, simulations, and games before students constructed simple quantum circuits (including those describing Schrödinger's cat and Wigner's friend) with *IBM Composer* [49]. Activities for classical encryption and one-time pad were introduced before the explanation of quantum key distribution by the BB84 protocol. Moreover, Ekert's entanglement-based protocol was linked back to Bell's inequality violation.

4. Pedagogical approach and standards alignment

Researchers have sometimes differed in their approach to introduce quantum mechanics and quantum computing to secondary students. The *QIST Camp* conceptual progression was consistent with Sutrini *et al.* [61], who introduced the electromagnetic nature of light and linear polarization prior to the notion of polarization-encoded qubits and quantum logic gates. However, the *QIST Camp* approach was differentiated from Bondani *et al.* [62], who introduced quantum mechanics through quantum technologies without addressing classical physics; this strategy was employed to reduce "students' perceived abstractness of quantum mechanics" (p. 1151). The *QIST Camp* curricular design

TABLE I. QIST camp scope and sample quantum science and computing activities.

Scope and select NGSS standards alignment	Sample student activities
Foundational concepts: (1) superposition and entanglement, (2) unitary evolution, (3) measurement. *NGSS Physical Science HS-PS4-3: Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model and that for some situations one model is more useful than the other* [16].	Wave interference; Mach-Zehnder interferometer; double and single slit diffraction; *Mathematica* simulations; *Qubit Touchdown* game [48].
Classical bits vs quantum bits, quantum gates, entanglement, quantum circuits. *NGSS Physical Science HS-PS1-1, 2, 3, 5: Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena* [16].	Polarization and waveplates; comparisons of classical and quantum gates; constructing simple quantum circuits with *IBM Quantum Composer* [49]; Bloch sphere models (tennis balls).
Modern applications in AMO laboratories (e.g., macroscopic coherence, quantum gases, classical to quantum transitions, quantum simulations); quantum science careers and pathways. *NGSS Physical Science HS-PS2-6: Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials* [16].	Quantum simulations vs quantum computations; laboratory visits with physicists (at university) or light exhibits (informal science institution); graduate student panel; discussion of college admissions and STEM precursor coursework.
Quantum information communication, application of photon concept, atom-photon interaction, photon storage, and retrieval, producing entangled photons, quantum repeaters, and Internet. *NGSS Physical Science HS-PS2-6: Investigating or designing new systems or structures requires a detailed examination of the properties of different materials, the structures of different components, and the connections of components to reveal its function and/or solve a problem. HS-PS2-1: Analyze data using tools, technologies, and/or models (e.g., computational, mathematical) in order to make valid and reliable scientific claims or determine an optimal design solution* [16].	Quantum measurements and quantum eraser thought experiments; polarization manipulation and measurement; Bell's inequality test with *IBM Quantum Composer* [49]; cryptography with quantum key distribution; career panel; student team presentations on quantum applications of choice.

was aligned with U.S. secondary STEM standards so programmatic elements could be easily implemented in formal academic settings. For example, many of the curricular connections to quantum information science were drawn from the National Q-12 Education Partnership's publications *QIS Key Concepts for Early Learners: K-12 Framework* [24]. Instructional modules and activities were aligned with the *Next Generation Science Standards* [16]. Conceptual complexity was scaffolded through vertical, grade-level curricular alignment with integrated principles from physics, chemistry, mathematics, and computer science. This was consistent with our strategy to introduce classical concepts prior to quantum mechanics and quantum computing.

5. Academic and career pathway awareness

Students also met with a panel of QIST graduate students (who also assisted with instruction) to discuss their academic pathways to graduate QIST study. Admissions staff from the university held an interactive workshop on optimal precursor coursework for postsecondary STEM study. A career panel from SandboxAQ spoke to students about their career pathways and their current work in quantum applications. Students visited a quantum simulation laboratory at Stony Brook and optics exhibits at the New York Hall of Science, depending on which site they attended. Sample ideas, activities, and select standards alignments are represented in Table I and further detailed in Ref. [63].

C. Study sample

The intervention group included 77 self-selected high school students, with 41 identifying as female and 36 identifying as male. The students were all entering grades 10–12 in the fall after the program was completed (ages 15–18 years old). They came from a variety of socioeconomic profiles, based on the demographics of the schools they attended (62 from suburban schools and 15 from urban schools). In terms of course preparation, 65% of students had taken chemistry prior to the camp, 25% had taken physics, 36% had taken computer science, and 28% had enrolled in a science research course. Student participation was fully funded by the National Science Foundation.

Students completed both the pre- and postsurveys and 12 students participated in postprogram interviews. To measure whether the self-selected students were differentiated from typical high school students, a control group of 65 students from regional schools completed the same attitude survey for comparison with the self-selected treatment students. These students were enrolled in high school physics classes taught by teachers who had participated in a QIST professional development workshop [64]. This may have resulted in more positive attitudes toward QIST than students who did not have physics teachers who were more likely to implement QIST in their instruction.

D. Quantitative data collection and analysis

A QIST attitudes survey was developed by the research team based on existing surveys measuring affective domains in STEM [65–69], and several new items were specifically designed for the present study. There was no existing QIST-specific attitudes survey designed for high school students that aligned with the theoretical underpinnings of the present study. Items were related to QIST attitudinal constructs including self-concept, self-efficacy, interest, relevance, and career aspirations. Additional items were related to students' views of quantitative and conceptual fluency related to QIST ideas, problem solving, and programming. Latent attitudinal constructs were not identified due to the limited sample size for exploratory factor analysis, although this will be done in future studies.

The survey was validated by physics and science education experts. Since both treatment and control students were not expected to be familiar with QIST, the instructions for the survey stated "Please indicate the extent of your agreement or disagreement with the following statements. Use the following definition of *quantum information science and technology (QIST):* A general field that brings together the disciplines of quantum mechanics and information technology." Students electronically selected Likert-scale responses via Qualtrics to each of the 25 statements both before and after the intervention. Students' responses were rated on a five-point Likert scale (5 = strongly agree, 4 = agree, 3 = neutral, 2 = disagree, 1 = strongly disagree); composite scores were compiled by adding the numbers associated with each response. Higher composite scores were viewed as more favorable attitudinal responses. Some questions (No. 7, No. 23) were reverse coded when calculating composites, so a response of strongly agree was rated 1, agree = 2, etc. Survey reliability was established via the combined sample of treatment and control groups (Cronbach's $\alpha = 0.866$), indicating high internal consistency [70]. Survey items are listed in Table II.

The presurvey data were analyzed with independent-sample t-tests to compare the treatment and control groups.

TABLE II. Survey of students' QIST attitudes.

Survey items
1. Learning about QIST topics is interesting and engaging [69].
2. Learning about QIST changes my ideas about how the world works [65].
3. It is possible to explain QIST without mathematical formulas [65].
4. To understand QIST, I sometimes think about my personal experiences and relate them to the topic being analyzed [65].
5. I enjoy learning about current events that involve QIST [68].
6. I view myself as a QIST person.
7. QIST careers are only for the academically brilliant [65].
8. Knowing QIST will give me a career advantage [67].
9. I am confident I can learn QIST skills [67].
10. I am curious about discoveries in QIST [67].
11. I will use QIST problem-solving skills in my career [67].
12. Reasoning skills used to understand QIST can be helpful in my everyday life [65].
13. I know what science, mathematics, and technology courses that will prepare me for QIST careers.
14. I am interested in reading articles and/or watching documentaries about QIST [66].
15. I am familiar with different types of QIST careers.
16. I believe I can master QIST knowledge and skills [67].
17. QIST will be part of my future after high school [68].
18. Nearly everyone is capable of understanding QIST if they work at it [67].
19. In QIST, mathematics expresses meaningful relationships among measurable quantities [65].
20. I want to learn more about QIST [68].
21. I can see myself pursuing a QIST-related career after college.
22. I am not satisfied until I understand why something works the way it does [65].
23. I do not expect equations to help my understanding of QIST; they are just for doing calculations [65].
24. Learning QIST will help me get a good job [67].
25. I am interested in pursuing a QIST-related major in college.

TABLE III. Codes for interview analysis.

Coding category 1: Pedagogical strategies	
Axial code: Visualization (VIS)	
Discussions of methods for aiding in student ability to visualize concepts that are nonintuitive or impossible to observe with their own senses.	
Open code	Description
MULT	Multiple methods of visualizing a particular phenomenon were helpful in learning about QIST.
HAND	Hands-on analogs for quantum phenomena were helpful in learning about QIST.
Axial code: Learning tools (TOOL)	
Discussions of the effectiveness of the tools used within the workshop to enhance the student experience with QIST.	
Open code	Description
GAME	Gamification of quantum concepts made QIST more interesting.
COMP	Advanced computational tools (such as IBM's Quantum Composer) made QIST more interesting.
Axial code: QIST identity (QID)	
Discussions of methods for fostering positive student feelings of QIST identity.	
Open code	Description
EXP	Experiences with QIST expert role models (such as the educators of the workshop).
TA	Experiences with student role models (such as the teaching assistants of the workshop).
LAB	Experiences in quantum lab space and other authentic STEM locations.
STU	Experiences with classmates that had an effect on the interviewee.
Axial code: Workshop topics (TOP)	
Discussions of which topics were most interesting, engaging, and/or compelling for students.	
Open code	Description
QP	Descriptions of quantum physics topics being interesting, engaging, or compelling.
QC	Descriptions of quantum computing topics being interesting, engaging, or compelling.
SOC	Descriptions of the societal importance of QIST being interesting, engaging, or compelling.
APP	Descriptions of the applications of QIST being interesting, engaging, or compelling.
Coding category 2: Science and mathematics preparation	
Axial code: Science preparation (SCI)	
Discussions of how comfortable the students felt during *QIST Camp* based on their science abilities.	
Open code	Description
UNP	Feelings of discomfort with content because of being unprepared for the science content.
PREP	Feelings of comfort with content because of being prepared for the science content.
Axial code: Mathematics preparation (MTH)	
Discussions of how comfortable the students felt during *QIST Camp* based on their mathematics abilities.	
Open code	Description
UNP	Feelings of discomfort with content because of being unprepared for the mathematics content.
PREP	Feelings of comfort with content because of being prepared for the mathematics content.
Coding category 3: Motivation	
Axial code: STEM motivation (STEM)	
Discussions of what/who motivated students to be interested in STEM	
Open code	Description
PRNT	Feelings of STEM motivation caused by parents or parental figures
EDU	Feelings of STEM motivation caused by teachers or guidance counselors
SELF	Feelings of STEM motivation caused by own identity
Axial code: Physics motivation (PHY)	
Discussions of how interested students are in taking physics courses or pursuing a physics career	
Open code	Description
CLSS	Interest in taking more physics classes in the future
CAR	Interest in pursuing a physics career in the future
INC	Increased interest in physics after completion of *QIST Camp*
Coding category 4: Self-efficacy	
Axial code: Explaining QIST (EXPL)	
Discussions of the level of confidence in explaining QIST topics to others	
Open code	Description
POS	Feelings of confidence in explaining QIST topics

(Table continued)

TABLE III. *(Continued)*

NEG	Lack of confidence in explaining QIST topics
Axial code: QIST knowledge (KNOW)	
Confidence in self as a person knowledgeable in QIST	
Open code	Description
POS	Feelings of confidence in self as a person knowledgeable in QIST
NEG	Lack of confidence in self as a person knowledgeable in QIST

Pre- and postsurvey data from the treatment group were analyzed using paired samples 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 [71].

E. Qualitative data collection and analysis

To further assess reasons for changes in student attitudes toward QIST, 12 follow-up interviews were conducted. The semistructured interview protocol was developed based on prior research on factors that influence STEM attitudinal domains, including self-efficacy, self-concept, motivation, and expectancy value (see Appendix). Interviews were conducted by one of the three instructors who developed the content of *QIST Camp*, whose area of expertise was physics education research. Interviews of approximately 30–60 min in duration were recorded and transcribed verbatim.

Interviews were coded using a *provisional coding* strategy, in which codes were identified from anticipated categories derived from the literature review, theoretical framework, and previous research findings [72]. The researchers selected four major coding categories, including (i) pedagogical strategies, (ii) prior science and mathematics preparation, (iii) motivation, and (iv) self-efficacy. Within these major categories, a series of axial codes were identified. For example, in the pedagogical strategies category, axial codes included tools that students might identify as helpful in their understanding of QIST concepts and skills (i.e., visualization, learning tools, QIST identity formation, and disciplinary topics). These were considered "start list" codes [72] (p. 118) since the coding categories were expanded upon analysis using elements of *grounded theory* [73], in which the researchers were open to new categories and interpretations that may not have been identified in previous research.

A priori codes were assigned to responses in each interview to note which methods discussed in the literature review were most effective for the students, and new categories were specified as open codes. These codes were also developed based on the quantitative analysis of the QIST attitude survey since explanations for the results could potentially be elicited from conversations with students. These additional emergent codes were identified and then applied to all interviews. This full process was conducted independently by two researchers and then repeated collaboratively to ensure interrater reliability of 90%. The axial and open codes are summarized within the main four coding categories in Table III.

V. QUANTITATIVE RESULTS

The quantitative analysis of survey results included comparisons of means of the presurvey with a control group of high school students (independent samples t tests) and paired samples t tests of the survey composite scores. These results were subsequently examined with the qualitative findings to provide an explanatory framework for students' experiences in the QIST intervention.

A. Comparison of pretest QIST attitude composites with control and treatment groups

An independent samples t test was run to determine whether the treatment students in *QIST Camp* had equivalent QIST attitudes with a control group before participating in the intervention. The self-selected treatment group ($N = 77$) had higher QIST attitude composite scores than a control group of 65 students enrolled in high school physics ($t = 5.872$, $d.o.f. = 132$, $p < 0.001$, 95% CI[6.641, 13.389]), with treatment students scoring higher on the presurvey ($M = 97.75$, $SD = 9.32$) than control group students ($M = 87.74$, $SD = 10.42$), with a large effect size (Cohen's $d = 1.015$). This indicated that the treatment population entered the summer program with more positive attitudes toward QIST than the general population of high school physics students, even though most of the treatment students had not taken physics. This is a consideration for implementing QIST education on a broader scale with students who may not have a prior interest in quantum topics and STEM in general. Although students who self-selected in QIST outreach demonstrated more positive attitudes than physics students taught by physics teachers with some knowledge of QIST pedagogy, physics students who had some exposure may have had more positive QIST attitudes than general science students.

B. QIST attitude survey comparison of means for treatment group

A paired samples t test was performed on the pre- and postdata to determine changes related to participation in *QIST Camp*. Missing data were deleted listwise (e.g., if students skipped questions). The paired samples t test for the survey composite scores showed significant improvement ($t = 3.919$, $d.o.f. = 59$, $p < 0.001$, 95% confidence interval (CI) [2.422, 7.478]) from presurvey ($M = 97.75$, $SD = 9.79$) to postsurvey ($M = 102.70$, $SD = 11.94$), with a medium effect size (Cohen's $d = 0.506$).

VI. QUALITATIVE FINDINGS

After quantitative analyses were complete, follow-up interviews were conducted to further examine student attitudes toward QIST. These interviews were iteratively coded to determine explanatory themes. The students interviewed after completing *QIST Camp* varied in grade level, science background, and mathematics background. The sample included eight girls and four boys. Five students had just completed grade 9, four completed grade 10, and three completed grade 11. Students varied in terms of prior high school coursetaking in chemistry, physics, science research, computer science, and advanced mathematics. Participant characteristics are summarized in Table IV (students were given pseudonyms to protect confidentiality).

Despite the background variation among the 12 students, there were similar ideas expressed in the interviews. The discussions of students' QIST Camp experiences were categorized by the following constructs: (i) perceptions of the instructors' pedagogical strategies and how they facilitated understanding; (ii) self-efficacy and comfort level with physics and mathematical content; (iii) motivations for pursuing or not pursuing STEM and/or quantum-related careers in the future, as well as QIST self-concept and perceptions of QIST relevance; and (iv) self-efficacy in understanding QIST topics and performing related tasks.

A. Perceptions of pedagogical strategies

An important consideration in understanding the effectiveness of the QIST informal educational experience was examining students' perceptions of the pedagogical strategies employed. Several students mentioned the focus on connecting new ideas to prior learning since many quantum concepts and quantum computing were new ideas. For example, Felicity, a rising 12th-grade student who had studied physics and advanced mathematics, stated:

> I think you can definitely learn without that level of knowing everything beforehand, because that first day when we were in class, it covered all the basics and those are the things that I was already familiar with. So you didn't necessarily have to come in with everything or knowing anything.

Thomas, a rising 11th grader with experience in chemistry and advanced mathematics, agreed with this point and appreciated the frequent contrast between classical and quantum ideas, stating, *"I did like that we constantly went from classical to quantum physics, because I felt like that helped me understand it more."* Pedagogical progressions that intentionally elicit students' prior knowledge (in this case, basic classical concepts) before introducing conceptually incongruent quantum ideas have been cited as effective methods for improving student learning [23,26].

When asked about which activities were the most impactful for them, more than half of the students described hands-on activities, which were often done in small groups of two or three. These were opportunities to make sense of classical and quantum ideas while socially constructing knowledge. Yolanda, a rising 11th grader with prior physical science and Algebra II or Trigonometry coursework, shared that the progression from lecture to demonstration to hands-on work was helpful:

> Definitely, the hands-on demonstrations and the way that the concepts were taught, running through a slideshow and then seeing a demonstration or playing a demonstration, like the card game [Qubit Touchdown] really made things piece together and make sense.

TABLE IV. Summary of student background information.

Student	Gender	Grade completed	Highest level of STEM coursework completed
Arianna	F	9	Biology, Science Research, Geometry
Andrew	M	9	Earth Science, Geometry
Antonia	F	10	Chemistry, Algebra II/Trigonometry
Ana	F	11	Chemistry, Computer Science, Algebra II/Trigonometry
Thomas	M	10	Chemistry, Precalculus, AP Statistics
Ambrose	M	10	Chemistry, Precalculus, AP Statistics
Felicity	F	11	AP Physics 1, Precalculus
Justine	F	11	Chemistry, IB Physics 11, Precalculus
James	M	9	Biology, Geometry
Judy	F	9	Earth Science, Geometry
Jennifer	F	9	Biology, Science Research, Geometry
Yolanda	F	10	Chemistry, AP Physics 1, Algebra II/Trigonometry

Judy, a rising tenth-grade student who had completed Earth science and geometry, concurred with Yolanda's experience with hands-on work while emphasizing the social aspect that also facilitated her understanding:

> In general, like, overall, I really enjoyed all of the hands-on activities we did after the lectures, like making the globe [Bloch sphere], which I think I still have with me. And it was a great way to socialize with other people from different schools. And because a lot of the kids, they were older than I was, it was great for me to experience other kids with more experience that also took physics… Even if I didn't understand a lecture or a presentation, the next activity that was more hands-on, it was a visual representation and presentation of what we learned previously. So whatever you were confused about, it was just kind of like, well here's step one, step two, and step three, and this is how it works.

Judy and other students discussed the benefit of learning about quantum subjects via multiple representations, which has been suggested as an effective strategy in teaching physics by leveraging different cognitive processes in problem solving [39–41,45,47,74]. James, a rising tenth-grade student who had completed biology and geometry, discussed the importance of the Bloch sphere model, which students had constructed with tennis balls and rubber bands to geometrically represent the quantum state of a qubit:

> The Bloch sphere was helpful, especially when we made the tangible one, because then you're able to examine it without using a digital representation and you can just actually see it and perceive it and in real life.

He further elaborated on the use of Qubit Touchdown [48] as another mechanism for understanding the qubit and quantum gates (unitary action), which was introduced after students had built their Bloch spheres:

> I also liked the Qubit Touchdown because it kind of helped when I was a little confused to understand how the transitions, I guess, I'm not sure if that's the right word, but yeah, this changes how gates show the logical path.

Intentional socialized learning experiences were mentioned by many students as a positive aspect of the *QIST Camp*. Andrew, a rising tenth grader who had taken courses in Earth science and geometry, was among the youngest students in the camp, and he stressed the importance of meeting and collaborating with other students while learning challenging ideas:

> I think the most compelling thing to me was the group projects. Like working with another partner that you never met before really, like, helps you I guess socialize more. And really fascinating how, like, other people have different ideas. And group projects really made it more lively… you really have to notice how much people have different ideas of really making everything fit together. It is, like, probably one of the best parts about making a group project.

Recruiting a diverse group of participants was important for students to be exposed to a variety of perspectives and experiences during their informal learning.

Socialization with peers was not the only aspect of collaboration that was important for the students. All but one student also described interactions with the graduate and undergraduate teaching assistants as having a positive impact on their learning and providing them with expectancy for quantum study and careers. Thomas stated that "they [TAs] would pick up on the fact that there was a hole in my knowledge, and they'd identify it and then tell me what it was that I was missing." Exposure to "near peers" in the physical sciences has been shown to facilitate positive social rapport and improved learning [75]. Ambrose agreed with Thomas's experience, elaborating that the teaching assistants provided individualized instruction that was critical for his success in the program:

> I thought [the TAs] were useful when it came time to the individual breakout times, where we all broke out into our tables and started working on things. Where they would come over and they were accessible to ask a question. And I definitely thought they were useful for the less organized, sort of, individual work, because they can answer any question that you had on the fly.

In addition to socializing with peers and teaching assistants, several students discussed their interactions with expert faculty members, facilitating their expectancy of quantum experimental research as a career. Students observed one instructor's demonstrations with the Mach-Zehnder interferometer and visited his laboratory, which provided opportunities for spontaneous questions about his research and career. Felicity stated, "I really liked looking at the lab. I found that really fascinating—the lab tour—because again, I've never seen anything like that." Antonia, a rising 11th grader who had taken chemistry and Algebra II or Trigonomtery, shared similar thoughts, stating:

> And I also think the part where we were able to physically walk to the quantum physics lab, I think that was really interesting… it just makes me more interested to want to explore that kind of area.

James expressed similar thoughts about pursuing a possible QIST career in the future, stating:

> I also loved seeing the lab at Stony Brook, that was really cool. That was one of my favorite parts. It just looks like something I'd want to do when I grow up. And so it's a good way to, I don't know, make myself feel like to have something to look forward to.

Observing a working laboratory where quantum simulations were performed with ultracold atoms provided a tangible model of an experimental QIST career. Students often need to see these careers in action to develop similar vocational aspirations [51]. Overall, the pedagogical strategies employed in *QIST Camp* were viewed by most students as helpful in facilitating their understanding of quantum concepts and computing skills, as well as inspiring the pursuit of QIST-related careers.

B. Physics and mathematics prerequisite knowledge and skills

Many of the newly introduced quantum concepts were counterintuitive in nature, presenting some cognitive conflicts when contrasted with classical ideas and basic algebra and geometry concepts. Students who had taken physics and advanced mathematics tended to exhibit the most confidence with the material. Yolanda had experience with the physical sciences and advanced mathematics, which contributed to her self-efficacy in QIST:

> With some knowledge of physics and Algebra II, because the deriving equations and stuff like that, I believe that gave me a really good basis and foundation for understanding quantum concepts and it really made sense and pieced together.

Although most students described feeling their academic background in science was enough to prepare them for this workshop, some felt they could have gotten more out of the activities with additional preparation in physics. Jennifer, a rising tenth-grade student who had studied biology and geometry, stated,

> I feel like if I learned more of physics and calculus, I feel I definitely would've known more about what we were learning. I heard one of the people at my table, they were like, oh yeah, we learned about this already a little bit in physics. And she was explaining the ideas to me.

This difference in prior physics preparation left some students with a sense of inadequacy when compared to their peers. However, Judy viewed her lack of physics knowledge as both a negative and a positive, sharing that she felt more prepared to succeed in physics when she enrolled in the course the following year:

> It might've been different for everybody, but I think that the older students who have taken AP Physics 1 or C, it was probably easier to understand just the basics of quantum physics since they knew what was going on. However, I think that because it started off with basics, it was much easier to understand. And I think when I go into physics next year, also I'll have a little bit of background knowledge on physics.

Andrew expressed a similar experience but shared his belief that the concepts were introduced in a vertical progression that facilitated his understanding:

> At first I noticed, like, I thought maybe I was behind from the rest of the people. But as I started talking to them more, everyone was usually on the same page except for, like, the upperclassmen that took physics before. But it's really—it's easy to catch onto. You don't need a physics or calculus background to really understand what they're [instructors are] saying.

Jennifer had a similar experience but relied on a peer to explain some concepts, supporting the notion that peer-to-peer socialization is often important in learning QIST:

> I heard one of the people at my table, they were like, oh yeah, we learned about this already a little bit in physics. And she was explaining the ideas to me. The parts where I didn't understand it was the wave and particle duality, I wasn't a hundred percent sure about that and she helped me understand better.

Although most students had not taken physics prior to the camp, the majority were comfortable with learning the content. However, it is unsurprising that some would feel this was a limitation that was difficult to overcome.

Most students also believed that their mathematics background was sufficient. Notably, even the students who expressed concerns about their level of mathematics preparation reported they were able to follow what was taught in the workshop. For example, Judy explained that "*In the beginning, my lack of knowledge, I felt like it was a bigger obstacle, but by the end, eventually I felt like I caught up with people in that respect.*" One specific challenge was learning complex numbers, which was largely absent from high school mathematics curricula. Ambrose stated, "The only thing I really felt like would have been nice to have any prior knowledge would've been when I really worked with complex numbers." Antonia was initially challenged by the concept of matrices, but she was able to master this mathematical procedure by working with peers on a group presentation:

> So there was actually a lot of trigonometry that I actually wasn't expecting, but I did have a better

> background in trig, so I was able to understand certain concepts that revolved around that. And actually, for our presentation on vectors and matrices, I had a very bare-minimum coverage over it, so it was actually kind of new for me as I was doing the presentation, too.

Even though some students experienced discomfort with their level of prior mathematics and science knowledge, especially when dealing with challenging mathematical concepts such as complex numbers and matrices, they were mostly able to gain knowledge of QIST concepts and the supporting mathematics that explained qubit measurement and probabilities.

C. QIST career motivation, self-concept, and relevance

Most students entered *QIST Camp* with an interest in STEM, all of whom were self-motivated in their pursuit, with some also sharing stories of parents, teachers, and guidance counselors contributing to their STEM interest. Many also expressed they had taken or planned to take advanced courses in science and mathematics to support their STEM interest, and of those students, six expressed interest in taking physics classes in the future. For example, Arianna shared how her camp experience increased her interest and self-efficacy in advanced physics:

> I feel like it would make it easier in senior year to take AP Physics since I'm already familiar with some of the topics since I took this camp. And I found it really interesting doing the camp. So now after that I was like, oh, okay, well maybe I would actually really continue taking AP Physics.

Even with some students already interested in physics, eight students stated in their interviews that *QIST Camp* had increased their interest level in pursuing further explorations of QIST, physics, or multidisciplinary careers. When asked whether her participation in *QIST Camp* had influenced her career goals, Yolanda shared that her experience had inspired her to seriously consider this path:

> I was not expecting that it would, but it definitely has because I used to want to do something with engineering or civil engineering, structural types, buildings. But now I'm thinking maybe going into the quantum field and somehow developing it to benefit our world, benefit our Earth better. That would be a really great path and definitely interested me.

Through her group projects, Yolanda was able to study potential ways in which quantum computing could solve complex technological problems, such as "climate change, the fertilizers, and then also the one with traffic lights and developing better traffic system that works more efficient." Ambrose shared similar intentions to pursue a physics-related career that is consistent with his fascination with biology:

> After taking this course and delving in more to physical sciences and stuff like that, I'm definitely looking more towards a physics driven college path. But probably something to do with bioengineering because I don't want to drop biology at all.

Thomas also shared that he "would like to apply quantum in a profession," and James viewed quantum computing as a mechanism to solve persistent global issues that impact human existence:

> But the more large scale [applications] relating to climate change and massive simulations and stuff like that, which just wouldn't be feasible with modern computing, were the ones I've probably found most interesting because just the predictions possible with quantum computing are just limitless, seemingly limitless.

All students expressed their beliefs in the potential of quantum computers to make the world better, which contributed to their perception of QIST relevance. Felicity best captured this notion when she commented:

> I got to see how much advancements there have been in the technological field and what we can actually do ourselves at the moment. And I feel like that was really motivating because I didn't even know some of that stuff was possible… the AI stuff, it was really cool to see how much less time certain types of data analysis would take compared to traditional computers versus computing that uses quantum… I definitely think it solidified how much I believe in science.

D. Self-efficacy with QIST concepts

Self-efficacy with QIST concepts was recurring in student interviews, with many students expressing they felt they had only a cursory knowledge of QIST topics. This suggests that students learned enough about QIST concepts and skills to understand there was a vast knowledge base beyond what had been taught. For example, seven students expressed being comfortable with explaining basic QIST concepts to others, while three students described a lack of confidence in their ability to provide adequate explanations. However, several of these students expressed that this lack of confidence was because they could only explain the main ideas of the concepts but were missing depth in their knowledge. Yolanda stated this hesitation when asked about her QIST self-efficacy:

> I feel like with the camp, everything I learned, just every new thing that I've learned, I got ten other questions about this thing, about how much deeper it could be because I know the concept, we were taught the concepts, but it was really on a really surface level.

James shared his interest in pursuing QIST learning on his own, but he encountered challenges along the way. Still, he felt (even without a physics background) that he could make sense of most topics and explain them to others:

> I thought it was very interesting. I was having a little trouble with it since I was trying to grasp some of the stuff. Still, I do much better when I completely understand something. So it was a little bit on the fence of, I was not quite there yet. But I think some of the experimentation with it helped me to get better. There were certain questions that were very hard to find answers to online when I was just doing some research… But overall, for the general concept of what I would be describing to others, I did feel confident in what I learned.

Despite the students' expression of the positive impact of *QIST Camp* overall, many felt that even after the program they did not consider themselves knowledgeable about the subject of QIST. Although they did not feel confident in their quantum knowledge with a one-week-long workshop, more sustained and advanced informal experiences could fill this gap.

VII. DISCUSSION

Based on mixed methods data provided by students via the attitude survey and follow-up interviews, the QIST precollege intervention provided U.S. high school students of diverse STEM backgrounds with a positive experience that improved QIST attitudes and motivated many of them to pursue QIST and/or physics in the future, either as a career or to complement their planned STEM career paths. The present study is one of the first to employ explanatory sequential analysis of precollege student outcomes in QIST outreach programs [76]; these results and findings are important considerations as precollege QIST education is expanded to foster QIST literacy and meet global workforce demands [1,6,8,10,11].

The main outcome for students was improved QIST attitudes with a medium effect size, and contributing factors were identified in the qualitative data analysis. These results and findings may be examined through a theoretical lens of expectancy value and planned behavior, which suggest a formative mechanism for academic and career goals [50]. When students acquire QIST knowledge and skills, confidence, and career expectations, they are more likely to consider future goals in the discipline, particularly if these goals align with their personal values and contribute to positive societal advancement [51,52]. These connections were made explicit for students through interactions with QIST experts, teaching assistants, and peers. This exposure contributed to QIST career aspirations, consistent with prior STEM-related research [13,14].

Students identified programmatic elements that contributed to their improved attitudes. Research-based pedagogical strategies included multiple representations of quantum concepts (models, games, and simulations) [39–41,45,47,74]; explicit conceptual progression from classical to quantum ideas [22–25]; laboratory visits and peer and expert socialization [42,43,46]; and group exploration of potential QIST applications. These strategies facilitated students' QIST self-efficacy and their understanding of the future relevance of QIST advancements. QIST instruction in formal and informal settings should incorporate skilled techniques to help students overcome learning challenges associated with quantum language and symbols, mathematical representations, and probability vs classical determinism [26,28,29].

Since QIST teaching and learning often has an elitist connotation (similar to other physical science and engineering disciplines [77]), it is important to examine how prior science and mathematics knowledge and skills were perceived by students in the intervention. Although most students felt the intervention compensated for their lack of STEM knowledge, others expressed some misgivings about not having a background in physics and/or advanced mathematics. Their normative self-comparisons with peers sometimes resulted in a sense of inadequacy; this has been identified as a barrier to sense of belonging or self-concept [52]. This is a consideration in secondary QIST program design, particularly when working with students who do not self-select participation.

A. Implications for policy and practice

The results and findings of this study offer three main implications for precollege QIST education policy and practice. First, pedagogical practices that have shown to be effective in traditional formal STEM schooling may be even more important in QIST learning. There is a need for a student-centered, hands-on approach to counter learning challenges related to the abstract nature of quantum concepts. Instructional practices that connect concepts to prior learning, facilitate socialization, and present ideas in different ways are necessary to engage students and promote QIST interest and self-concept.

Second, exposure to QIST ideas and skills is fundamentally important in promoting QIST career aspirations [13,14], yet these topics are largely missing from U.S. secondary STEM curricula, even at the AP level. QIST-related topics should be implemented in physical science curricula, where it is largely missing or treated superficially. The *Next Generation Science Standards* [16], which were published in 2013, are now outdated when it comes to QIST concepts, skills, and recent discoveries. Since many states have not yet fully implemented these standards, educators and policymakers may need to initiate grassroots efforts to implement meaningful QIST teaching and learning in K-12 settings. Based on the relatively positive initial attitudes of the control group, there may be further opportunities to increase students' QIST career aspirations by providing teacher professional development.

Third, best practices from QIST informal learning opportunities may serve as models for replicating effective QIST teaching in formal precollege STEM education, however, there is little empirical work to support the adoption of these practices [76]. There is a need for large-scale research with diverse groups of students to identify elements of QIST instruction that should be replicated and scaled in formal and informal settings. This may be challenging—for example, it is difficult to have large groups of students visit quantum simulation laboratories. However, professional organizations such as the American Physical Society offer opportunities for K-12 students to interact remotely with scientists in QIST fields (*Physicists To-Go* [78]). The National Q-12 Education Partnership provides information on careers in quantum information science and academic pathways to get there [79]. These and other programs may be leveraged to communicate the expectancy and value of quantum careers in precollege classrooms.

B. Study limitations

There are several limitations to the present study. The study included a small sample size of students self-selected into the *QIST Camp*. The intervention is ongoing with approximately 90 students participating annually as two new cohorts complete *QIST Camp* each summer. With the increased sample size, future work will examine survey results with exploratory factor analysis. Although the self-selection of students into *QIST Camp* was acknowledged by collecting quantitative data from a control group of high school physics students, the more positive QIST attitudes among the treatment group are a consideration when interpreting the results and findings.

This study did not address cognitive measures of student learning. A QIST concept inventory is in development and will be piloted with additional students in the coming year. Student learning of QIST concepts and skills is an important outcome that will be addressed in future work. This outcome will also be analyzed in relation to affective measures.

The 12 interviewed students had a preexisting connection to the interviewer, as they were all interviewed by the physics education researcher who taught the workshop alongside the two QIST experts. Although this may have introduced bias in student responses, the students who volunteered for interviews may have been more comfortable answering questions from a known individual.

C. Conclusions

The *QIST Camp* intervention was shown to be effective in developing and researching practices and affective outcomes in precollege quantum science and computing instruction. This model demonstrated that students were positively influenced in their attitudes toward QIST learning, most notably improving their QIST self-efficacy, career aspirations, and recognition of the relevance of QIST in solving technological challenges. Research universities with QIST experts are in the unique position of being able to provide these experiences, as they offer access to laboratories and career role models. The experience was rigorous yet accessible to a broad range of high school students. It is recommended that future QIST-related precollege interventions provide hands-on experiences to teach challenging concepts, multiple representations, visits to QIST-related laboratories, and socialization with peers, higher education students, and expert role models.

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APPENDIX

The semistructured interview protocol was developed by the researchers to explore factors related to students' attitudes towards QIST.

Semistructured interview protocol

1. Why did you decide to participate in the camp?
2. What parts of the camp did you find most interesting?
3. Do you feel confident about explaining QIST ideas to others? If so, what aspects are you most confident about?
4. What are your postsecondary college and career plans? Have they shifted as a result of your participation in the camp?
5. Do you feel understanding the physics and mathematics content is necessary to get the most out of the camp?
6. What are your mathematics and science course taking plans in high school? Who influenced your course plans?
7. Do you participate in STEM extracurriculars? If so, what are they?
8. When did your interest in science develop?
9. What were some anchoring QIST phenomena of interest that you learned about in the camp?

10. What questions do you still have about QIST? Would you participate in another camp for advanced topics?
11. Would you recommend this camp to your friends? Why or why not?
12. What parts of the camp do you think could be improved? Any recommendations?
13. Do you think of yourself as a quantum science person? Why or why not?
14. Would you like your teachers to include more quantum science in their instruction?
15. Describe your interactions with the teaching assistants (TAs).

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[1] Subcommittee on Quantum Information Science, *National Strategic Overview for Quantum Information Science* (National Science and Technology Council, Washington, DC, 2018), https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf.
[2] Pacific Northwest National Laboratory, *Explainer Article: Quantum Information Science* (PNNL, Richland, WA, 2022), https://www.pnnl.gov/explainer-articles/quantum-information-science.
[3] Office of Technology Transitions, *Spotlight: Quantum information science and technology* (U.S. Department of Energy, Washington, DC, 2020), https://www.energy.gov/technologytransitions/articles/spotlight-quantum-information-science-and-technology.
[4] C. A. Boulet, O. Kaya, P. MacKinnon, and M. Rowell, *Quantum-safe cybersecurity talent and job market analysis* (Quantum-Safe Canada, 2021), https://quantum-safe.ca/wp-content/uploads/2022/02/GACG-Quantum-Safe-Cybersecurity-Talent-and-Job-Market-Analysis-Final-Report.pdf.
[5] The White House, *National security memorandum on promoting United States leadership in quantum computing while mitigating risks to vulnerable cryptographic systems* (The White House Briefing Room, Statements and Releases, Washington, DC, 2022), https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/04/national-security-memorandum-on-promoting-united-states-leadership-in-quantum-computing-while-mitigating-risks-to-vulnerable-cryptographic-systems/.
[6] National Science & Technology Council, *Quantum information science and technology workforce development national strategic plan* (Subcommittee on Quantum Information Science, Committee on Science, Washington, DC, 2022), https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf.
[7] A. Asfaw, A. Blais, K. R. Brown, J. Candelaria, C. Cantwell, L. D. Carr, J. Combes, D. M. Debroy, J. M. Donohue, S. E. Economou, E. Edwards, and M. F. Fox, Building a quantum engineering undergraduate program, IEEE Trans. Ed. **65**, 220 (2022).
[8] C. Metz, *The Next Tech Talent Shortage: Quantum Computing Researchers* (The New York Times, 2018), https://www.nytimes.com/2018/10/21/technology/quantum-computing-jobs-immigration-visas.html.
[9] M. Bogobowicz, K. Dutta, M. Gschwendtner, A. Heid, M. Issler, N. Mohr, H. Soller, R. Zemmel, and A. Zhang, *Steady Progress in Approaching the Quantum Advantage* (McKinsey & Company, 2024), https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/steady-progress-in-approaching-the-quantum-advantage.
[10] N. Mohr, R. Zemmel, H. Soller, M. Bogobowicz, S. Gao, M. Gschwendtner, A. Heid, M. Masiowski, and M. Zesko, *Quantum Technology Monitor* (McKinsey & Company, 2023), https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20technology%20sees%20record%20investments%20progress%20on%20talent%20gap/quantum-technology-monitor-april-2023.pdf.
[11] H. K. E. Staderman, E. van den Berg, and M. J. Goedhart, Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic, Phys. Rev. Phys. Educ. Res. **15**, 010130 (2019).
[12] J. C. Meyer, G. Passante, and B. Wilcox, Disparities in access to U.S. quantum information education, Phys. Rev. Phys. Educ. Res. **20**, 010131 (2024).
[13] J. A. Kitchen, G. Sonnert, and P. M. Sadler, The impact of college- and unievrsity-run high school summer programs on students' end of high school STEM career aspirations, Sci. Educ. **102**, 529 (2018).
[14] S. Chachashvili-Bolotin, M. Milner-Nolotin, and S. Lissitsa, Examination of factors predicting secondary students' interest in tertiary STEM education, Int. J. Sci. Educ. **38**, 366 (2016).
[15] National Science & Technology Council, *The role of international talent in quantum information science* (Subcommittee on Economic and Security Implications of Quantum Science, Committee on Homeland and National Security, Washington, DC, 2021), https://www.quantum.gov/wp-content/uploads/2021/10/2021_NSTC_ESIX_INTL_TALENT_QIS.pdf.
[16] NGSS Lead States, *Next generation science standards: For states, by states: HS-PS4-3 waves and their applications in technologies of information transfer* (National Academies Press, Washington, DC, 2023), http://www.nextgenscience.org/pe/hs-ps4-3-waves-and-their-applications-technologies-information-transfer.
[17] New York State Education Department, *New York State P-12 Science Learning Standards* (NYSED, Albany, NY, 2017), https://www.nysed.gov/sites/default/files/programs/curriculum-instruction/p-12-science-learning-standards.pdf.
[18] College Board, *AP Chemistry course and exam description* (College Board, New York, NY, 2022), https://apcentral

.collegeboard.org/media/pdf/ap-chemistry-course-and-exam-description.pdf.

[19] College Board, *AP Physics 2 course and exam description* (College Board, New York, NY, 2020), https://apcentral.collegeboard.org/media/pdf/ap-physics-2-course-and-exam-description.pdf.

[20] College Board, *2020 Program Summary Report* (College Board, New York, NY, 2020), https://reports.collegeboard.org/media/pdf/Program-Summary-Report-2020_1.pdf.

[21] National Center for Education Statistics, *Digest of Education Statistics: Enrollment in Public Elementary and Secondary Schools, by Level, Grade, and State or Jurisdiction* (Institute of Education Sciences, Washington, DC, 2020), https://nces.ed.gov/programs/digest/d22/tables/dt22_203.45.asp.

[22] F. Greinert, R. Müller, P. Bitzenbauer, M. S. Ubben, and K. Weber, Future quantum workforce: Competences, requirements, and forecasts, Phys. Rev. Phys. Educ. Res. **19**, 010137 (2023).

[23] K. Krijtenburg-Lewerissa, H. J. Pol, A. Brinkman, and W. R. van Joolingen, Key topics for quantum mechanics at secondary schools: A Delphi study into expert opinions, Int. J. Sci. Educ. **41**, 349 (2019).

[24] National Q-12 Education Partnership, *QIS Key Concepts for Early Learners: K-12 Framework: High School Physics* (National Q-12 Education Partnership, 2023), https://q12education.org/learning-materials-framework/physics.

[25] Center for Integrated Quantum Materials, *Key Concepts for Future Quantum Information Science Learners* (Illinois Quantum Information Science and Technology Center, Urbana-Champaign, IL, 2020), https://files.webservices.illinois.edu/9156/keyconceptsforfutureqislearners5-20.pdf.

[26] T. Bouchée, L. de Putter-Smits, M. Thurlings, and B. Pepin, Towards a better understanding of conceptual difficulties in introductory quantum physics courses, Stud. Sci. Educ. **58**, 183 (2022).

[27] M. Chhabra and R. Das, Quantum mechanical wavefunction: Visualization at undergraduate level, Eur. J. Phys. **38**, 015404 (2016).

[28] I. M. Greca and O. Frieire, Jr., Teaching introductory quantum physics and chemistry: Caveats from the history of science and science teaching to the training of modern chemists, Chem. Educ. Res. Pract. **15**, 286 (2014).

[29] E. K. Henriksen, B. Bungum, C. Angell, C. W. Tellefsen, T. Frågåt, and M. V. Bøe, Relativity, quantum physics and philosophy in the upper secondary curriculum: Challenges, opportunities and proposed approaches, Phys. Educ. **49**, 678 (2014).

[30] G. Papageorgiou, A. Markos, and N. Zarkadis, Students' representations of the atomic structure: The effect of some individual differences in particular task contexts, Chem. Educ. Res. Pract. **17**, 209 (2016).

[31] B. S. Ambrose, P. S. Shaffer, R. N. Steinberg, and L. C. McDermott, An investigation of student understanding of single-slit diffraction and double-slit interference, Am. J. Phys. **67**, 146 (1999).

[32] P. Hubber, Year 12 students' mental models of the nature of light, Res. Sci. Educ. **36**, 419 (2006).

[33] P.-Y. Lin and C. D. Schunn, The dimensions and impact of informal science learning experiences on middle schoolers' attitudes and abilities in science, Int. J. Sci. Educ. **38**, 2551 (2016).

[34] K. L. Knox, J. A. Moynihan, and D. G. Markowitz, Evaluation of short-term impact of a high school summer science program on students' perceived knowledge and skills, J. Sci. Educ. Technol. **12**, 471 (2003).

[35] D. G. Markowitz, Evaluation of the long-term impact of a university high school summer science program on students' interest and perceived abilities in science, J. Sci. Educ. Technol. **13**, 395 (2004).

[36] C. Singh, A. Asfaw, and J. Levy, Preparing Students to be leaders of the quantum information revolution, *Physics Today* (American Institute of Physics, College Park, MD, 2021), 10.1063/PT.6.5.20210927a.

[37] National Q-12 Education Partnership, *Growing the Quantum Workforce* (National Q-12 Education Partnership, 2024), https://q12education.org/.

[38] Z. Akdemir, M. Menekse, M. Hosseini, A. Nandi, and K. Furuya, Introducing quantum key distribution to high school students, Sci. Teach. **88**, 44 (2019).

[39] P. P. Angara, U. Stege, and A. MacLean, Quantum computing for high-school students an experience report, in *Proceedings of the 2020 IEEE International Conference on Quantum Computing and Engineering, Denver, CO* (IEEE, New York, 2020), pp. 323–329, 10.1109/QCE49297.2020.00047.

[40] P. P. Angara, U. Stege, A. MacLean, H. A. Muller, and T. Markham, Teaching quantum computing to high-school-aged youth: A hands on approach, IEEE Trans. Quantum Eng. **3**, 3100115 (2022).

[41] S. E. Economou, T. Rudolph, and E. Barnes, Teaching quantum information science to high-school and early undergraduate students, arXiV:2005.07874.

[42] C. Hughes, J. Isaacson, J. Turner, A. Perry, and R. Sun, Teaching quantum computing to high school students, Phys. Teach. **60**, 187 (2022).

[43] M. Ivory, A. Bettaale, R. Boren, A. D. Burch, J. Douglass, L. Hackett, B. Keifer, A. Kononov, M. Long, M. Metcalf, T. B. Porpp, and M. Sarovar, Quantum computing, math, and physics (QCaMP): Introducing quantum computing in high schools, arXiV:2309.16788.

[44] O. Salehi, Z. Seskir, and T. Ilkner, A computer science-oriented approach to introduce quantum computing to a new audience, IEEE Trans. Ed. **65**, 1 (2022).

[45] S. Satenassi, P. Fantini, R. Spada, and O. Levrini, Quantum computing for high school: An approach to interdisciplinary in STEM teaching, J. Phys. Conf. Ser. **1929**, 012053 (2021).

[46] C. C. Tappert, R. I. Frank, I. Barabasi, A. M. Leider, D. Evans, and L. Westfall, Experience teaching quantum computing, in *Proceedings of the Annual Meeting of the Association Supporting Computer Users in Education* (2019), https://eric.ed.gov/?id=ED597112.

[47] J. Walsh, M. Fenech, D. Tucker, C. Riegle-Crumb, and B. R. La Cour, Piloting a full-year, optics-based high school course on quantum computing, Phys. Educ. **57**, 025010 (2022).

[48] T. Wong, Qubit touchdown (2022), https://www.thomaswong.net/.
[49] IBM Quantum Composer (2024), https://learning.quantum.ibm.com/tutorial/explore-gates-and-circuits-with-the-quantum-composer.
[50] I. Ajzen, Perceived behavioral control, self-efficacy, locus of control, and the theory of planned behavior, J. Appl. Soc. Psychol. **32**, 665 (2002).
[51] M. Fishbein and I. Ajzen, *Belief, Attitude, Intention and Behavior: An Introduction to Theory and Research* (Addison-Wesley, Reading, MA, 1975).
[52] J. Möller and H. W. Marsh, Dimensional comparison theory, Psychol. Rev. **120**, 544 (2013).
[53] S. B. McKagan, K. K. Perkins, M. Dubson, C. Malley, S. Reid, R. LeMaster, and C. E. Wieman, Developing and researching PhET simulations for teaching quantum mechanics, Am. J. Phys. **76**, 406 (2008).
[54] F. J. Scharfenberg and F. X. Bogner, Instructional efficiency of changing cognitive load in an out-of-school laboratory, Int. J. Sci. Educ. **32**, 829 (2010).
[55] S. Gamble, Quantum computing: What is it, why we want it, and how we're trying to get it, in *Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2018 Symposium* (National Academies Press, Washington, DC, 2019).
[56] C. S. Dweck, C. Y. Chiu, and Y. Y. Hong, Implicit theories and their role in judgments and reactions: A word from two perspectives, Psychol. Inq. **6**, 267 (1995).
[57] M. Jansen, U. Schroeders, and O. Lüdtke, Academic self-concept in science: Multidimensionality, relations to achievement measures, and gender differences, Learn. Individ. Differ. **30**, 11 (2014).
[58] A. M. Kelly, Social cognitive perspective of gender disparities in undergraduate physics, Phys. Rev. Phys. Educ. Res. **12**, 020116 (2016).
[59] R. W. Lent, F. G. Lopez, and K. J. Bieschke, Mathematics self-efficacy: Sources and relation to science-based career choice, J. Counsel. Psychol. **38**, 424 (1991).
[60] J. W. Creswell and J. D. Creswell, *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 6th ed. (Sage, Thousand Oaks, CA, 2023).
[61] C. Sutrini, G. Zuccarini, M. Malgieri, M. Bondani, and C. Macchiavello, An educational model of the Deutsch algorithm for secondary school, Eur. J. Phys. **45**, 025302 (2024).
[62] M. Bondani, M. L. Chiofalo, E. Ercolessi, C. Macchiavello, M. Malgieri, M. Michelini, O. Mishina, P. Onorato, F. Pallotta, S. Satanassi, A. Stefanel, C. Sutrini, I. Testa, and G. Zuccarini, Introducing quantum technologies at secondary school level: Challenges and potential impact of an online extracurricular course, Physics **4**, 1150 (2022).
[63] D. Schneble, T.-C. Wei, and A. M. Kelly, Quantum information science and technology secondary outreach: Conceptual progressions for introducing principles and programming skills (to be published).
[64] A. M. Kelly, M. Darienzo, T.-C. Wei, and D. Schneble, Quantum information science and technology professional learning for secondary science, technology, engineering, and mathematics teachers (to be published).
[65] W. K. Adams, K. K. Perkins, N. S. Podolefsky, M. Dubson, N. D. Finkelstein, and C. E. Wieman, New instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey, Phys. Rev. ST Phys. Educ. Res. **2**, 010101 (2006).
[66] R. Aghekyan, Measuring high school students' science identities, expectations of success in science, values of science and environmental attitudes: Development and validation of the SIEVEA survey, Sci. Educ. Int. **30**, 342 (2019).
[67] S. M. Glynn, P. Brickman, N. Armstrong, and G. Taasoobshirazi, Science motivation questionnaire II: Validation with science majors and nonscience majors, J. Res. Sci. Teach. **48**, 1159 (2011).
[68] M. E. Lockhart, O. M. Kwok, M. Yoon, and R. Wong, An important component to investigating STEM persistence: The development and validation of the Science Identity (SciID) Scale, Int. J. STEM Educ. **9**, 34 (2022).
[69] P. R. Pintrich and E. V. De Groot, Motivational and self-regulated learning components of classroom academic performance, J. Educ. Psychol. **82**, 33 (1990).
[70] L. J. Cronbach, Coefficient alpha and the internal structure of tests, Psychometrika **16**, 297 (1951).
[71] F. Faul, E. Erdfelder, A.-G. Lang, and A. Buchner, G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences, Behav. Res. Meth. Instrum. Comput. **39**, 175 (2007).
[72] J. Saldana, *The Coding Manual for Qualitative Researchers* (Sage, Thousand Oaks, CA, 2009).
[73] A. L. Strauss and J. M. Corbin, *Grounded Theory in Practice* (Sage, Thousand Oaks, CA, 1997).
[74] E. Etkina, Pedagogical content knowledge and preparation of high school physics teachers, Phys. Rev. ST Phys. Educ. Res. **6**, 020110 (2010).
[75] A. M. Zaniewski and D. Reinholz, Increasing STEM success: A near-peer mentoring program in the physical sciences, Int. J. STEM Educ. **3**, 14 (2016).
[76] M. Darienzo and A. M. Kelly, Review of literature on quantum information science and technology programs for high school students, Quantum Science and Engineering Education Conference (QSEEC24) (to be published).
[77] S. J. Leslie, A. Cimpian, M. Meyer, and E. Freeland, Expectations of brilliance underlie gender distributions across academic disciplines, Science **347**, 262 (2015).
[78] American Physical Society, Physicists To-Go (APS) (2024), https://www.aps.org/initiatives/physics-education/k-12/physicists-to-go.
[79] National Q-12 Education Partnership, *Careers in quantum information science and engineering* (National Q-12 Education Partnership, 2024), https://q12education.org/careers.