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Exploring Minority Undergraduate Students' Hands-on and Research Experiences in a Summer QISE Laboratory Course

YiXiang Shawn Sun, Virginia Polytechnic Institute and State University

Shawn Sun is an Engineering Education PhD student at Virginia Tech. He is co-advised by Dr. Qin Zhu and Dr. Jenni Case. He is also the Assistant policy analyst fellow at Research Institute for Democracy, Society, and Emerging Technology (DSET, Taiwan). His research interests include Emerging technologies-informed engineering education; Engineering ethics; Engineering culture; Global engineering education; STEM policy analysis; Global talent. Overall, he aims to address the challenge of cultivating and empowering future engineers in emerging tech fields through effective, inclusive, and globally relevant engineering education and policy initiatives.

Guannan Shi, Virginia Polytechnic Institute and State University
Prof. Wayne A Scales, Virginia Polytechnic Institute and State University

Wayne A. Scales is a Professor of Electrical and Computer Engineering and Affiliate Professor of Aerospace and Ocean Engineering at Virginia Tech. He is also the Director of the Center for Space Science and Engineering Research. He currently teaches gradu

Dr. Pamela Leigh-Mack, Virginia State University

Dr. Pamela Leigh-Mack is Professor and Chair of the Department of Engineering at Virginia State University. She received the B.S. degree in Mathematics from Virginia Union University, B.S. and M.S. degrees in Electrical Engineering (EE) from Howard U

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Backgrounds

Quantum Information Science and Engineering (QISE) is a rapidly growing field of study and is expected to revolutionize society in the coming decades. In the U.S., this talent need has been further emphasized by the launch of *the National Quantum Initiative Act of 2018*, which also calls for expanded education and workforce development in quantum science and engineering. Similarly, on a global scale, China has its *Made in China 2025* and the *Fourteenth Five-Year Plan*, and the European Union has its *Quantum Technologies Flagship* project. Talent and education play a pivotal role in shaping the future of quantum technology and ensuring a country's competitiveness in this rapidly advancing field. As quantum technology continues to gain prominence, we have seen a growing demand for skilled professionals who can drive innovation, conduct groundbreaking research, and develop cutting-edge applications. However, the quantum industry is currently insufficient to meet upcoming needs. For example, McKinsey's analysis predicts that after 2025, unless there is a substantial expansion of the global quantum talent pool or a slowdown in quantum technology development, there will be a talent gap exceeding 50% [1].

In response, a growing number of institutions have already launched or are developing master's degree programs, bachelor's degrees with specialized education and professional training to help them transition into the quantum workforce, and Ph.D. programs. Still, QISE education still faces key challenges, including accommodating diverse technical backgrounds, supporting a broader student population, and addressing the shortage of qualified interdisciplinary instructors [2]. Moreover, research has shown that hands-on laboratory experience is essential for such QISE talent cultivation [3] and a "quantum smart workforce" [4]. However, as educational disparities continue to exist in access to quantum education in the U.S. [5-6], many universities, such as Historically Black Colleges and Universities (HBCUs), lack the infrastructure to provide such experiences, limiting access to resources for minority students to engage with the ongoing development of QISE, as well as to build a support network when learning [7]. To tackle this, for example, the IBM-HBCU Quantum Center represents an industry-academia strategic initiative for a more diverse workforce in the quantum field [8].

Here, we argue that establishing teaching partnerships between research universities and HBCUs at the state level could be highly beneficial. In line with this belief, we developed an intensive summer QISE laboratory course at SCHOOL #A that: (1) invited minority students from both SCHOOL #A, a Research 1 university and a Predominantly White Institute (PWI), and SCHOOL #B, an HBCU, and (2) implemented an experiential learning theory-based approach (Kolb et al., 2014) that combined lectures with hands-on laboratory. Students that are enrolled in this course are all with minority backgrounds. The course provided students with weekly lectures and lab sessions covering a range of foundational and advanced topics in quantum mechanics and engineering, such as wave-particle duality, quantum entanglement, quantum communications, quantum cryptography, and quantum sensing [11].

In this exploratory paper, minority student learning experiences were evaluated both qualitatively and quantitatively. Given the nature of a small number of students in this class, quantitative data was mostly interpreted descriptively, while qualitative data was gained through two-round individual interviews. In the following, we begin by introducing theorical framework and an overview of the course design, along with sections on methodology. The findings are then presented, and this paper concludes with the discussion and conclusion section.

Theoretical Framework

Kolb's Experiential Learning Theory (ELT) provides a foundational framework for understanding how students learn through experience, and serves as a key theoretical guide in the design of our summer course. Learning, according to [9], is defined as "the process whereby knowledge is created through the transformation of experience," which shows that experience and reflection form the core of meaningful learning. As for the ELT model, a four-stage learning cycle is outlined: Concrete Experience (CE), Reflective Observation (RO), Abstract Conceptualization (AC), and Active Experimentation (AE). Here, such a cyclical model is rooted in constructivist principles, viewing learners as active constructors of knowledge And in this model, effective learning involves first engaging in a concrete experience, then reflecting on that experience, deriving abstract concepts or generalizations, and finally testing those concepts through active experimentation. Overall, Kolb's theory posits that an optimal learning process entails a balanced progression through all four stages of this cycle. A key implication of Kolb's ELT is that *experiential learning* activities should be designed to engage all stages of the learning cycle. Learners benefit not only from hands-on experience but also from opportunities to reflect, conceptualize, and apply ideas. More specifically, Kolb's framework suggests that simply having students perform an experiment (Concrete Experience) is not sufficient for deep learning; they must also discuss and reflect on what happened (RO), connect it to theory (AC), and perhaps design new experiments or applications (AE) to fully "close" the learning cycle. In this regard, ELT aligns with other active learning and constructivist approaches which assert that engagement and reflection lead to better understanding.

In STEM fields like engineering and physics, hands-on learning has long been recognized as essential for developing practical skills and deepening conceptual understanding. Laboratory education is especially a domain where ELT is applied by allowing students to directly interact with materials, instruments, and phenomena [16-18]. Numerous studies in science and engineering education affirm the importance of laboratory experiences in the curriculum. Feisel and Rosa, for instance, argued that engineering is fundamentally an applied discipline requiring skills in experimentation, design, and problem-solving, all of which are best cultivated through well-designed lab work [12]. Laboratory sessions provide concrete experiences that can enhance students' analytical thinking and bridge the gap between theoretical knowledge and real-world application. Indeed, a strong lab component in undergraduate programs has been correlated with improvements in students' hands-on competencies and their ability to apply concepts to solve practical problems. In the context of an emerging field like QISE, experiential learning is arguably even more critical. Quantum engineering education involves complex and abstract concepts (e.g. qubit behavior, quantum circuits) that students often find challenging to grasp through lectures alone. Engaging students in interactive labs, demonstrations, or projects can concretize these abstractions.

However, implementing hands-on experiential learning in quantum engineering comes with unique challenges. Modern quantum research typically requires specialized, high-cost equipment (such as cryogenic systems, lasers, or quantum processors) and advanced technical expertise, which are not readily available to most undergraduate programs. As a result, opportunities for students to gain experiential training in QISE remain scarce, especially at early educational stages. Many institutions struggle to provide access to state-of-the-art quantum labs, and students consequently lack sufficient practical exposure to complement their theoretical coursework. Consequently, the absence of experiential learning opportunities can hinder the preparation of a "quantum-ready" workforce. In summary, while the benefits of experiential learning in quantum engineering are clear, there is an urgent need to address logistical and resource barriers so that these benefits can be realized broadly.

Another important consideration in any theoretical framework is how it addresses diverse learners. Experiential learning has significant implications for educational equity, benefiting not only the general student population but also students from underrepresented minority groups in STEM. Active, hands-on pedagogies can make learning more accessible and engaging for a wider range of learners by accommodating different learning styles and providing multiple entry points to complex material. For example, some students (who might struggle with purely abstract instruction) excel when they can manipulate equipment or visualize concepts through experiments – aligning with Kolb's idea that concrete experience can provide a powerful route to grasping knowledge. There is evidence that these approaches improve outcomes across the board: as noted earlier, active learning strategies improve overall performance for all students in STEM courses. More strikingly, they have been shown to disproportionately benefit minority students, thereby helping to close achievement gaps. A recent meta-analysis by Theobald et al. found that in courses employing active learning, achievement gaps between underrepresented and majority students were significantly reduced – with exam score gaps decreasing by an average of 33%, and gaps in passing rates narrowing by 45% compared to traditional lecture [13]. This suggests that experiential and active learning techniques can play a role in leveling the playing field, giving students who might otherwise be at a disadvantage a better chance to succeed. The reasons for this likely include increased student engagement, more frequent feedback and interaction, and a greater sense of belonging in an active classroom environment.

Finally, in the context of quantum engineering, a field where women and certain minority groups are often underrepresented, experiential learning opportunities may be particularly impactful. Hands-on projects and labs can boost students' confidence and identity as emerging scientists or engineers. Research on undergraduate research programs (which are a form of experiential learning) supports this: studies have found that when students from underrepresented backgrounds participate in authentic research or lab experiences, their self-efficacy in STEM increases and their aspirations for STEM careers grow. For instance, a program documented by Carpi et al. showed significant gains in underrepresented students' belief in their capabilities and commitment to pursuing science after they engaged in mentored research experiences. These outcomes are critical, as self-efficacy and sense of belonging have been identified as key predictors of minority student persistence in STEM fields [14]. Experiential learning environments can foster a sense of community and belonging by allowing students to work closely with peers and mentors on tangible problems. In a quantum engineering lab, a student who sees themselves successfully controlling a quantum system or analyzing quantum data may start to view themselves as a "quantum engineer" in the making, countering stereotypes or imposter syndrome that they may face in more abstract settings. It is therefore, after all, essential that experiential learning opportunities in QISE be designed to be equitable and inclusive.

Research Questions

This study aims to explore the learning experiences of minority students participating in a summer QISE laboratory course. Grounded in Kolb's Experiential Learning Theory (ELT) and informed by prior work on equity in STEM education, the study seeks to understand both the cognitive and affective dimensions of student learning, as well as how the program supports diverse learners through hands-on experiences. The following two tiers of research questions guide this investigation:

Learning Experiences

1. *What are the key challenges and successes that students encounter when learning quantum science concepts during the summer laboratory program?*
2. *In what ways do hands-on laboratory activities influence students' understanding, application, and confidence in quantum science and engineering principles?*
3. *How do students navigate the abstract and complex nature of QISE topics, and what support structures within the course help or hinder this process?*

Inclusion

2.1. *How does the summer QISE laboratory course address the unique needs of students from underrepresented minority backgrounds in STEM?*
2.2. *To what extent does participation in this course influence students' sense of belonging, STEM identity, and confidence in pursuing future careers or education in QISE?*
2.3. *What aspects of the course design (e.g., mentorship, institutional collaboration, inclusive pedagogy) are perceived by students as particularly supportive or limiting for underrepresented learners?*

The Course

As mentioned earlier, QISE is a rapidly growing field of study and is expected to revolutionize society in the coming decades. Currently there is a lack of courses nationally that provide experiential learning through a hardware laboratory experience in this field. The SCHOOL #A QISE laboratory is unique in the US since it is one of a very few that can provide hands-on laboratory hardware training for students in a wide spectrum of disciplines within QISE. The laboratory suite includes equipment for quantum photonics based investigations and also characterization of quantum properties of materials (electric, magnetic, and thermal). The first laboratory course to train advanced undergraduates and beginning graduate students was developed during summer 2021.

This course addresses this talent need by providing introductory hands-on laboratory experience of key aspects of quantum science and engineering including wave-particle duality, quantum entanglement, quantum communications, quantum cryptography, and quantum sensing. As per the justification, the laboratory course provides training in basic quantum science concepts such as wave-particle duality and quantum entanglement. The latter is one of the hardest to grasp concepts in QISE but also one of the most fundamental and powerful concepts to exploit for practical applications of QISE such as communication systems and cybersecurity. Training students on the hardware implementation of entanglement and practical research applications is expected to be particularly helpful for students starting out in the field. Also, students are exposed to a test for quantum entanglement, Bell's Inequality, which is one of the more profound concepts in physics and caused debate amongst the greatest scientists from the time of Einstein. A modern consequence is that communication link eavesdropping by an adversary can be detected since the eavesdropping detection destroys the quantum nature of quantum information which can be checked with Bell's inequality. This is one of the most fundamental concepts of quantum communication systems and quantum cybersecurity. The laboratory provides investigation of all of these concepts as well as implementation of various quantum-based security protocols.

In this summer QISE laboratory course in 2024 where the paper is centered on, students from both SCHOOL #A and SCHOOL #B, all from minority backgrounds, were recruited. The course spanned two months, with weekly lecture and laboratory sessions. Two authors in the papers are instructors and teaching assistant to the course. Each week, two to three topics were covered, followed by a half-month preparation period for the final project and poster session. An overview of the module taught in this summer QISE laboratory course could be found in table 1. All students attended the course in person at the Blacksburg campus.

12 Modules
Lab 1: Quantum Nature of Light and Photon Detection
Lab 2: Quantum Interference Part One: The Wave Nature of Photons
Lab 3: Quantum Interference Part Two: A Quantum Eraser
Lab 4: Weak Coherent Pulses for Quantum Communication
Lab 5: Quantum Random Number Generation (QRNG)
Lab 6: Quantum Key Distribution (QKD) for Cryptography
Lab 7: Generation and Detection of Quantum Entanglement
Lab 8: Quantum Key Distribution Using Entanglement (aka Ekert91)
Lab 9: Introduction to Quantum Sensing of Magnetic Fields
Lab 10: The Hong-Ou-Mandel (HOM) Effect
Lab 11: Franson Interferometry
Lab 12: Quantum State Tomography

Table 1. Summer QISE laboratory course – module overview

Methodology

The research methods of the study are designed to explore the potential of the use of laboratory-based education in QISE education. This section outlines the research design, data collection methods, and analysis strategies. All participant recruitment, data collection and analysis described in this paper will all be carried out in accordance with the approved procedures for human subjects' research, under SCHOOL #A University's IRB Protocol #24-509. Participants of this study had to be enrolled in the summer QISE laboratory course at SCHOOL #A. Recruitment started after the information session held during first week of the course, and then was followed with outreach efforts to students enrolled, with informational emails as the main approach, all of whom will be conducted by the first author, who was the graduate research assistant in this study. A total number of 6 students were involved, with 3 of them from SCHOOL #A, and 3 from SCHOOL #B.

Two-time semi-structured interviews were conducted, with one mid-semester and one post-semester. Prior to the interview, the enrolled participants will be provided with a set of interview questions. Each interview, lasting approximately 45-60 minutes, would begin with obtaining informed consent from participants and were conducted via Zoom or in person. The interview questions will center on their learning experiences in the summer QISE laboratory course, focusing on feedback on students' experiences, learning, and engagement in a quantum course. Specifically, it covers four main areas: course progress and engagement, feedback on course design, reflection on learning and motivation, and suggestions for improvement. A post-course survey was also administered, providing a more quantitative evaluation for the course.

Each interview was first transcribed verbatim and then coded for specific topics that emerged using thematic analysis, guided by Braun and Clarke's (2006) six-step framework. Data were categorized under specific topic codes using the qualitative data analysis software MAXQDA to aid in data organization. Initial themes within each student's experience were identified and compared across participants, with significant patterns in the data noted by the author, along with commentary on possible explanations drawn from the transcripts and textual content. Particular care was taken to account for potential biases and differences by employing several strategies to ensure validity: triangulation, peer debriefing, and member-checking, as suggested by Creswell [15]. First, data were triangulated by drawing from multiple sources, including students' reflective journals and other materials or artifacts from the course. Second, peer debriefing was carried out through consultation with colleagues who were experts in QISE or experiential learning but had no involvement in the course or data collection. These peers reviewed and provided feedback on the findings, which were considered by the authors; however, the final interpretation of results remained the responsibility of the authors. Lastly, member-checking involved presenting semi-polished findings to students in a follow-up focus group to ensure that their perspectives were accurately represented. For reliability, although not determined at the time, if this study had been conducted jointly with other researchers, a cross-check of independently developed codes prior to full coding would have been conducted.

Two primary ethical concerns were addressed in this study: students' rights and confidentiality/data security. First, to protect participants and ensure transparency, students were thoroughly informed about their rights and the details of the study. An information session was held to explain the purpose and procedures of the research and to address any questions students had. The first author was solely responsible for participant recruitment, data collection, and analysis, and was not involved in any grading activities. Instructors did not participate in the recruitment or data collection processes and were not given access to students' interview content. Only after course grades were finalized and the data had been anonymized by the first author did instructors gain access to the dataset and contribute to the data analysis process. Second, all data were handled with strict confidentiality. Digital files, including transcripts and coded data, were securely stored in a password-protected iCloud account owned and managed by the first author. Access was restricted to ensure data security and participant privacy throughout the research process.

Findings

In the findings section, we divide it into two parts. The first part focuses on students' learning experiences in quantum science, while the second part examines students' perspectives and evaluations of this summer laboratory program, which primarily serves students from minority backgrounds in two universities.

Learning Experiences

To understand the impact of the course on student learning, we examined how participants engaged with the course's technical content, laboratory activities, and overall instructional design. The following findings are organized around three guiding questions that structure our analysis of students' learning experiences: *1. What are the key challenges and successes students face in learning quantum science concepts during the summer laboratory program? 2. In what ways do hands-on laboratory activities influence students' understanding, application, and confidence in quantum science and engineering principles? 3. How do students navigate the abstract and complex nature of QISE topics, and what support structures within the course help or hinder this process?*

Foundational Successes: Building Quantum Intuition Through Labs

Students in the QISE Summer Laboratory Program encountered a range of challenges and successes as they engaged with quantum science content—most of which was entirely new to them. Many core topics, such as wave-particle duality and quantum interference, were perceived as manageable and even exciting, particularly when students were able to engage directly with equipment like the quTools quantum engineering lab kits. Through these setups, students explored key quantum phenomena such as the dual nature of photons, the role of superposition in interference, and how polarization is used to encode and transmit quantum information. They also began to understand how these principles apply to quantum communication systems and cybersecurity—especially in protocols like quantum key distribution (QKD) and random number generation. These hands-on experiences served as a valuable entry point for students to connect theoretical ideas to tangible applications.

Conceptual Difficulties: Quantum Entanglement

While these topics were generally well understood by students, certain concepts, such as quantum entanglement, did pose greater challenges, requiring more time and instructional support to fully grasp. In our module, we introduced students to foundational concepts of quantum entanglement, including the generation of polarization-entangled photon pairs via Spontaneous Parametric Down-Conversion (SPDC) and the verification of entanglement through the Clauser-Horne-Shimony-Holt (CHSH) inequality test. Overall, students found these topics particularly challenging due to their abstract and counterintuitive nature compared to classical physics concepts.

SPDC is a nonlinear optical process where a photon from a laser beam (the “pump”) interacts with a nonlinear crystal, resulting in the emission of two lower-energy photons (signal and idler) that are entangled in polarization. This phenomenon is fundamental in quantum optics and serves as a practical method for generating entangled photon pairs used in quantum information experiments. On the other hand, the CHSH inequality test is an experimental procedure used to demonstrate the non-classical correlations predicted by quantum mechanics. By measuring the polarization correlations of entangled photon pairs at various settings, one can calculate the CHSH parameter. A violation of the CHSH inequality indicates the presence of quantum entanglement, challenging classical notions of locality and realism.

Students often harbor misconceptions about entangled states and struggle with the probabilistic and nonlocal nature of quantum measurements. Figure 1 illustrates survey responses for this module, showing varying levels of conceptual understanding. Given the small sample size, these results should be interpreted descriptively rather than statistically. On top of that, the qualitative feedback offers valuable insights into students’ cognitive engagement and conceptual struggles. One student reflected, *“I learned how to calculate entanglement and how to ‘break’ and ‘create’ it. I could have dived into the theory of Bell’s equation more but I understood the overall concepts of entanglement.”* Other comments reflect the cognitive dissonance and imaginative stretch required to internalize such abstract phenomena. For instance, a student said, *“This is just a bit beyond my imagination, you know? I watched all the Marvel universe but I still do not think I stretched even the surface of the idea of entanglement.”* One student also suggested the need for greater scaffolding: *“I could get more of an explanation and may need a more broken-down meaning of it all.”*

Disciplinary Gaps: Challenges in Quantum Sensing

Another particularly challenging topic for students was quantum sensing. In this module, we introduced the fundamental principles of quantum magnetic field sensing and the operation of nitrogen vacancy (NV) centers in diamond, including the basics of fluorescence and the implementation of Optically Detected Magnetic Resonance (ODMR) techniques. Students were guided through the process of calculating vector magnetic fields using the ODMR method, and were given demonstrations of the underlying experimental setups. However, several students encountered difficulty grasping these topics, particularly those without prior coursework or background in electromagnetics. Students from non-ECE majors noted that they lacked the foundational knowledge (e.g., vector field concepts, spin resonance, and photoluminescence mechanisms) necessary to fully follow the material. These challenges were especially evident when students attempted to connect theoretical content to physical interpretations, such as understanding how magnetic field strength affects the energy levels of NV centers or how optical readouts are generated and measured.

As one student shared during the follow-up discussion: *“It was hard to connect the physics to what’s actually going on in the material... I didn’t really understand how the diamond was sensing anything.”* Another mentioned, *“The formulas made sense once we walked through* *them, but I couldn't quite follow where the signals were coming from or how they relate to the vector fields."* Even among students who reported moderate understanding, some expressed lingering uncertainty, as one wrote, *"I got the idea of using light to detect magnetic fields, but not why NV centers behave the way they do."* Figure 2 shows survey results for this module, where most students reported understanding the concepts. However, this should be interpreted with caution due to the small sample size and the limitations of self-reported data. The qualitative feedback suggests that while many students could follow the procedures and surface-level explanations, deeper conceptual understanding remained limited.

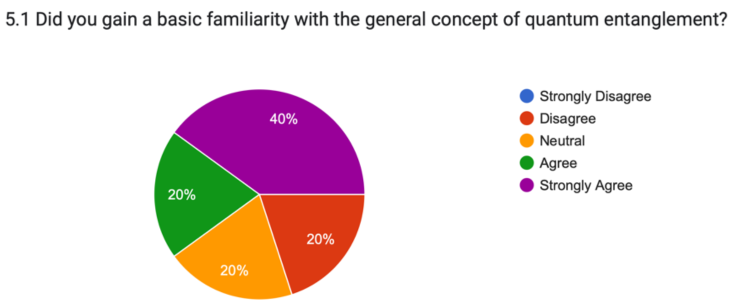

Figure 1. Survey result for quantum entanglement module.

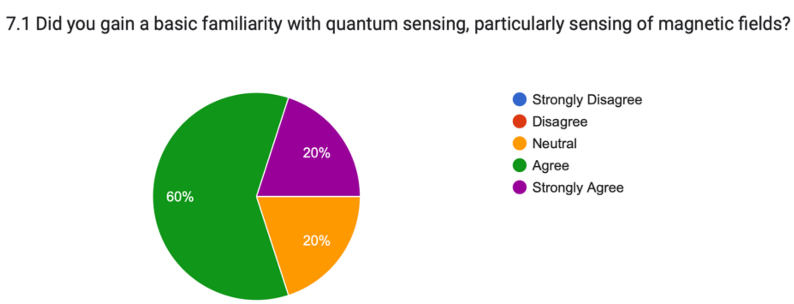

Figure 2. Survey result for quantum sensing module.

The Role of Hands-On Learning: Bridging Theory and Practice

On the other hand, the hands-on laboratory activities were consistently appreciated for their role in connecting abstract theoretical knowledge to concrete, practical applications. Many students shared with us that the synergy between lecture content and lab sessions as a key factor that reinforced their understanding of core quantum principles. Because labs were often conducted immediately after lectures, students noted that the material was still fresh in their minds, making it easier to connect concepts and apply them meaningfully. This pedagogical approach is especially effective in the context of quantum science, where concepts can often feel disconnected from everyday experience.

Hands-on activities helped demystify these ideas by giving students physical or visual anchors to otherwise abstract content. For instance, in the quantum cybersecurity module, students used the BB84 quantum key distribution (QKD) protocol using the quCR (quantum communication rack). This lab allowed them to explore how an eavesdropper might attempt to intercept a quantum key and how such interference introduces detectable errors. In doing so, students not only engaged with quantum information theory but also began to understand its real-world implications for cybersecurity (Fig 3). As one student put it: *"The BB84 lab was one of my favorite parts of this module. I heard a lot about how quantum might be a game changer and how our world might be totally affected by it. But I never realized how that worked and all the cybersecurity stuff. It was pretty fun to see how attackers could break into the system."* Comments like this point to the power of experiential learning in helping students move from passive consumers of speculative discourse (e.g., "quantum will change the world") to active participants in understanding how such change might be technically realized.

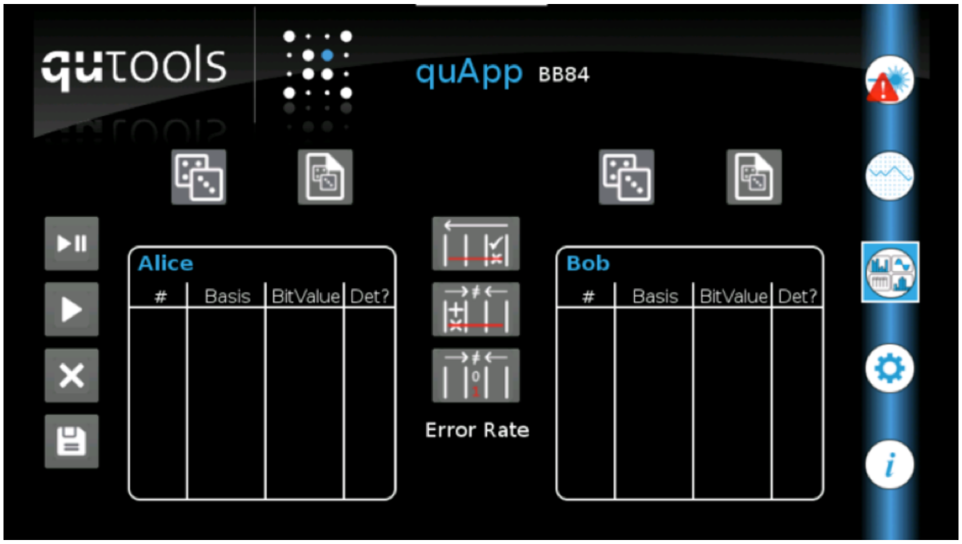

Figure 3. BB84 screen used to perform QKD with the quCR.

Independent Projects: Empowering Ownership and Confidence

Beyond structured modules, the final project stood out as a particularly impactful learning experience. Unlike the guided labs, this component asked students to initiate their own small-scale research efforts, apply quantum principles in novel contexts, and communicate their findings through a professional-style poster session. Students described this opportunity as both challenging and empowering. It required them to synthesize knowledge across the course and make design decisions with limited scaffolding. For many students, especially those from HBCUs, this was their first experience in designing and executing a research project. In interviews, several expressed that they had never been asked to take intellectual ownership of a project in this way. As one student reflected: *"I was nervous at first, because I didn't think I knew enough to come up with something. But once I got into it, I realized I could figure it out. And presenting at the poster session made me feel like I belonged here."* In addition to reinforcing technical learning, the project helped build students' confidence and professional identity, particularly important for those from groups historically underrepresented in STEM.

Areas for Improvement: Meeting Students Where They Are

Despite the program's successes, students identified several areas where the course experience could be further enhanced to better support their learning.

Pacing and Depth of Content

One recurring challenge was the fast-paced nature of the course. Given the compressed summer schedule, the program was designed to introduce a broad range of quantum engineering topics while balancing lectures and hands-on laboratory modules. However, several students noted that the rapid pace limited opportunities to explore complex topics in sufficient depth. In their feedback, they expressed a desire for more time to absorb foundational concepts, ask questions, and revisit difficult material. Slowing down the pace was a common recommendation. As one student put it: *"There were so many cool topics, but we moved so fast that I felt like I could only grasp part of them before jumping to the next."*

Variety in Instructional Materials

Students also suggested improvements in the format and delivery of instructional materials, particularly for the laboratory components. While the current modules are supported by written guides with graphs and figures, many students indicated that additional formats could greatly enhance understanding and engagement. For example, step-by-step video demonstrations of experimental procedures or data analysis techniques could help visual learners and reduce confusion during lab sessions.

Addressing Disparities in Prior Knowledge

Lastly, students shared the challenge of varying academic backgrounds within the cohort. Since participants came from multiple majors, including physics, computer science, and non-ECE fields, their levels of familiarity with key concepts varied widely. While some students could build directly on prior coursework, others required more time and support to catch up on the fundamentals. This disparity occasionally created uneven learning experiences, especially in more advanced modules. Several students expressed appreciation for instructors' patience and responsiveness but suggested more structured scaffolding or optional refresher materials to help bridge these disciplinary gaps. One student from a non-ECE background shared: *"I wanted to keep up, but some concepts were just totally new to me. A crash course or intro would have helped."*

Inclusion

The QISE summer laboratory course was intentionally designed with inclusion at its core. Through deliberate course design, mentorship structures, and resource allocation, the program sought to address structural inequities and meet the unique needs of students from underrepresented minority backgrounds in STEM. This section explores three central research questions: 2.1. *How does the summer QISE laboratory course address the unique needs of students from underrepresented minority backgrounds in STEM?*
2.2. *To what extent does participation in this course influence students' sense of belonging, STEM identity, and confidence in pursuing future careers or education in QISE?*
2.3. *What aspects of the course design (e.g., mentorship, institutional collaboration, inclusive pedagogy) are perceived by students as particularly supportive or limiting for underrepresented learners?*

Expanding Access to Infrastructure and Resources

One of the program's central strengths lies in its ability to provide access to advanced quantum laboratory infrastructure- rsources that are typically inaccessible to students at under-resourced institutions such as many HBCUs and MSIs. By situating the course within a well-equipped PWI and opening enrollment to in-state URM students, the program helps bridge longstanding resource disparities in STEM training. Though remote implementation of complex experiments remains a challenge, in-person access allowed students to work with optical benches, quantum key distribution racks, and single-photon detectors. As one student reflected: *"I had only vaguely heard about quantum back in university, and we didn't have the resources to really learn it—just lectures. Being here and learning intensively feels like a privilege. It's like seeing history itself."* This hands-on access not only enhanced conceptual understanding but also symbolically affirmed students' place in the quantum science community, which is a space they had often seen as inaccessible.

Fostering Belonging, Identity, and Confidence

Equally critical was the program's intentional cultivation of a supportive and collaborative learning environment. The instructor, a Black faculty, created a space in which students of color felt seen and supported. The cohort itself was composed entirely of students from historically marginalized backgrounds, which contributed to a uniquely affirming atmosphere. Students emphasized the emotional and academic impact of this environment. Learning groups became spaces not just for solving technical problems, but for sharing strategies, building trust, and affirming one another's potential. One student described the psychological safety this provided: *"This is the first time I've felt safe not knowing all the concepts. Quantum is definitely hard, but being surrounded by this group of people has restored my confidence when I face difficulties."*

> Another student commented:
> *"We organized a weekly study group where some students helped others who were struggling. We bonded really well—it was inspiring to see other Black students interested in quantum. It made me feel less alone in pursuing something I'm passionate about."*

These social dynamics were not incidental. They functioned as a mechanism for academic persistence, reinforcing students' sense of belonging and STEM identity. In many traditional STEM contexts, underrepresented students experience isolation or imposter syndrome. Here, however, students reported a renewed motivation to pursue quantum science precisely because they felt they belonged. This cohort-based structure maps onto the Reflective Observation (RO) and Abstract Conceptualization (AC) stages of Kolb's Experiential Learning Theory: students were able to collectively reflect on what they were learning, connect ideas, and develop meaning in a socially engaged and culturally informed context.

Mentorship, Representation, and Collaborative Learning

The presence of a racially diverse instructional team, particularly a Black professor leading the course, was deeply meaningful for students. Representation in leadership roles helped students envision themselves as future researchers and educators in the field. Informal mentorship throughout the course (through office hours, lab walkthroughs, and feedback sessions) was cited as particularly impactful. Beyond that, the final project also functioned as an inclusion-enhancing design element. For many participants, especially those from HBCUs, this was the first time they had independently designed a research project and presented their findings in a professional forum. The culminating poster session was not only a venue for public communication, but also a moment of self-recognition. As one student put it:

> *"Presenting our project made me feel like I actually belong in quantum. I wasn't just learning—I was contributing something."*

This sense of ownership and legitimacy is critical in fields like quantum engineering, where students from URM backgrounds are dramatically underrepresented and often excluded from high-prestige research environments. By scaffolding this experience with mentorship, peer support, and visible role models, the program worked to shift not only students' skills but also their internal narratives about what is possible.

Discussion

Drawing on Kolb's experiential learning theory, the summer QISE laboratory course offered students a rich, iterative structure for engaging with unfamiliar and complex quantum science content. The program's hands-on lectures served as powerful Concrete Experiences, grounding abstract topics like wave-particle duality and quantum interference in real-time experimentation using quTools lab kits and quantum communication racks. Students reported that these hands-on activities helped demystify otherwise intangible ideas and brought conceptual clarity, aligning well with the CE stage of Kolb's model. The immediacy of lab work following lectures allowed students to reinforce new knowledge while it was still cognitively accessible, helping bridge the gap between theory and application. Following these experiences, students engaged in Reflective Observation, both individually and collaboratively. Structured class discussions, informal peer learning groups, and feedback sessions provided crucial space for students to process confusion, voice questions, and contextualize new ideas in relation to prior knowledge. For example, when grappling with the probabilistic logic of entanglement or the physical mechanisms behind NV-center-based sensing, students used group discussions to compare interpretations and identify conceptual sticking points. This was especially impactful for students from non-ECE backgrounds, whose reflections often centered on navigating interdisciplinary gaps. The Reflective Observation phase, enriched by peer exchange and guided facilitation, played a crucial role in supporting metacognitive development and conceptual restructuring.

Through these reflective dialogues and structured instruction, students moved into Abstract Conceptualization: the phase in which learners begin to formulate models or mental representations based on their experiences. For many students, this occurred during modules like quantum key distribution (QKD) or the final research project, where they were asked to not only understand how systems work but also articulate or apply principles in new contexts. The QKD lab, for instance, prompted students to abstract concepts about photon polarization, measurement, and error detection into a functional mental model of quantum-secured communication. Similarly, the poster project required students to generalize learning across modules into novel applications, promoting higher-order thinking and deeper conceptual mastery. Finally, students engaged in Active Experimentation through the design and implementation of their own research projects, an essential capstone that allowed them to test and apply their ideas independently. For many participants, this was their first opportunity to engage in self-directed research using advanced lab infrastructure. The opportunity to present their findings in a poster session represented more than just practical, engineering skill development; it, in a way, served as an act of identity formation and professional legitimation. In this way, the QISE program embodied the full Kolb cycle, with each phase designed to scaffold learning, reflection, abstraction, and application in a way that was both inclusive and transformative.

Beyond the immediate benefits to the participants, these results have important implications for STEM experiential learning and specifically for the emerging field of quantum engineering education. They add evidence to the growing consensus that experiential, active-learning approaches can reduce performance gaps and promote equity in STEM classrooms. Prior studies have shown that moving away from passive lecture to active inquiry benefits all students and disproportionately helps those from underrepresented groups. Our work extends this principle into the quantum domain. By demonstrating that minority undergraduates can achieve high learning gains in quantum science through experiential projects, we address a critical gap in both research and practice. QISE is an emerging field where inclusion efforts lag behind national averages. Very few programs to date have explicitly focused on providing experiential quantum training for underrepresented students. This study is among the first to document how such an approach can succeed, offering a model for making quantum education more inclusive. It shows that, when guided through a supportive ELT-informed cycle, students who might otherwise be left at the margins of this high-tech field can not only participate but excel.

The findings also contribute new insights to engineering education literature by bridging theory and practice in a novel context. We illustrate how Kolb's ELT, a well-established framework in education, can be leveraged in cutting-edge STEM domains like quantum engineering to design effective learning experiences. In doing so, we join broader engineering education efforts that call for authentic, project-based learning to better prepare students for real-world challenges. Moreover, our emphasis on community and belonging integrates social learning perspectives with experiential learning. This is a meaningful contribution: it shows that for underrepresented minorities, the social context of learning (peer support, mentors, cultural relevance) is intertwined with the experiential learning cycle. In practical terms, our study suggests that simply offering hands-on activities is not enough; the environment in which those activities occur must be intentionally inclusive. Creating a cohort or "community of practice" can amplify the impact of experiential learning, as students feel empowered and validated by peers and role models. This insight aligns with prior work showing that supportive STEM intervention programs yield higher science identity and belonging for minority students, which in turn correlates with greater involvement and persistence in STEM.

In summary, this study provides evidence-based affirmation that experiential learning approaches, grounded in Kolb's ELT, can greatly enhance quantum engineering education for underrepresented students. It demonstrates concrete strategies, from hands-on labs to reflective discussions and cohort-based mentoring, that educators and institutions can adopt to improve learning outcomes and equity in advanced STEM fields. The positive outcomes observed, from learning gains to increased sense of belonging, are not only successes for the individuals involved but also represent a step toward addressing the wider disparities in access to quantum education. As the demand for a diverse, quantum-savvy workforce grows, our findings contribute knowledge on how to cultivate such talent in an inclusive manner.

Future Directions

Looking ahead, there are several promising directions to extend this work. One immediate avenue is to replicate and scale the experiential program across other institutions, particularly minority-serving institutions and colleges that currently lack quantum offerings. This would test the generalizability of our approach and potentially build a larger pipeline of underrepresented students entering QISE fields. Another future direction is to go deeper into optimizing each stage of the ELT cycle for quantum learning. Educators could experiment with enhanced Concrete Experiences (such as virtual or remote quantum lab access for those without on-site labs) or structured Reflective Observation exercises (like guided reflective lab journals or discussion prompts that specifically target linking experience to theory). Similarly, developing specialized curriculum materials that aid Abstract Conceptualization (like visual simulations that connect mathematical formalisms to the experiments students performed) may help overcome the abstraction challenges identified. Finally, there is also room to explore integrating culturally responsive teaching practices, ensuring that examples and applications of quantum technology resonate with diverse students' backgrounds to further strengthen their engagement.

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