Quantum mechanics curriculum in the U.S.: Quantifying the instructional time, content taught, and paradigms used

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Quantum mechanics is an integral course for physics students. An understanding of quantum concepts is imperative for enrollment in physics graduate programs, participating in research within physics fields, and employment with companies developing quantum technologies. This study analyzes 188 U.S. research-intensive institutions' course catalogs to determine the role and extent of quantum mechanics in their undergraduate physics programs. All of the institutions required one course on quantum concepts, 92% required two courses, and half required three. Among institutions with complete class data ($n = 56$), the quantum curriculum was analyzed using course syllabi. The mean number of classroom hours spent on quantum concepts was 63.5 h with a standard deviation of 28.1 h. The most commonly taught themes in the quantum curriculum were the equation and three-dimensional quantum mechanics. However, the Stern-Gerlach experiment was only included in 28% of the course outlines. Despite current efforts to promote a spin-first approach, this study found the traditional position-first approaches were still more common as they were used by 73.7% of instructors.

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I. INTRODUCTION

Popularized by Gladwell's *Outliers: The Story of Success*, there is a common notion that it takes 10 000 h of practice to become an expert at a skill [1]. While this idea is an oversimplification, as Gladwell himself and others have pointed out, factors such as family, culture, and friendship also play roles in success [1,2]. While time is not a perfect indicator of expertise, it is one of the many factors that are important. As the quantum workforce grows, the field of physics must determine how much time institutions should devote in their physics curriculum to quantum concepts.

Institutions have popularized the notion that for every 1 h spent in lecture or class, students should expect to spend 2 to 3 h studying on their own [3–7]. This number may vary depending on the individuals' abilities and outside commitments, but it does provide a relative gauge on the number of hours students are expected to spend on a topic during their 4-year degree, based on the scheduled lecture times of their courses. As physics educators, we may want to know how much time is necessary for a student to be considered an expert and prepared to work in the quantum workforce. As outlined by the U.S. National Quantum Initiative in the Quantum Information Science and Technology Workforce Development National Strategic Plan, current goals for the quantum workforce are to assess gaps in education and training opportunities, as well as make the quantum sector more accessible and equitable [8]. This study will support this effort by determining the current state of U.S. physics programs' quantum educational training, as well as assessing whether there is equal access to educational opportunities across institutions.

Building on previous work analyzing modern physics syllabi [9], this paper will be the first to quantify the current quantum mechanics curriculum at research-intensive institutions in the U.S. This study will answer the following research questions:

1. *How many courses on quantum concepts are physics students required to complete in order to earn a 4-year degree?*
2. *How many classroom hours on quantum phenomena are physics majors required to take in order to graduate with a 4-year degree in physics?*
3. *What quantum mechanics topics are students required to learn in order to be awarded a 4-year degree in physics?*
4. *Are institutions using a spin-first (using linear algebra) or a position-first (using differential equations) pedagogical approach?*

II. LITERATURE REVIEW

Previous work found that the modern physics course is most often students' first introduction to quantum concepts within the U.S. physics curriculum [9]. However, since the most common prerequisite for modern physics is calculus II, it was concluded that physics students would need to enroll in another course on quantum mechanics in order to be able to solve the Schrödinger equation at the level of Griffiths' textbook [10], a commonly used undergraduate textbook. Additionally, work by Singh has suggested that quantum mechanics education in physics programs may not be satisfactory for career preparedness in quantum-related fields (e.g., quantum computing) [11]. The conclusions of the modern physics course analysis [9], along with Singh's findings [11], motivated this study to characterize the quantum curriculum across all 4 years of undergraduate physics programs in the U.S. Quantifying the current quantum curriculum should initiate an ongoing conversation in the physics community to determine whether physics programs are preparing students for careers in quantum-related fields and ensuring that students at all U.S. institutions have access to a comprehensive quantum education.

While no study has previously characterized whether U.S. institutions are meeting a common set of goals in their quantum mechanics courses, a survey of 13 quantum mechanics instructors found they all shared common objectives for their courses [12]. These 13 instructors expressed a desire for their students to learn the postulates and the formalisms of quantum mechanics and to be able to apply these formalisms to solve a variety of different problems.

Within the physics education research community, there have been many efforts to achieve these commonly shared goals and improve student learning in the abstract realm of quantum mechanics. One such effort is the ongoing debate between spin-first and position-first approaches to teach quantum mechanics. Within a position-first paradigm, students are introduced to the Schrödinger equation early in the course [13,14], specifically in the context of wave functions in position space [13]. Differential equations serve as the primary mathematical tool for understanding these equations, and the time-independent Schrödinger equation is the first eigenvalue equation introduced. As Sadaghiani and Munteanu note, "The focus is more on carrying out mathematical calculations rather than sense making from experimental results" [14]. A typical textbook used in these courses is Griffiths' *Introduction to Quantum Mechanics* [10,13].

In a spin-first paradigm, the Stern-Gerlach experiment (SGE) is often used to introduce quantum concepts to students [13]. The postulates of quantum mechanics are usually explored through the SGE and explicitly discussed [13,14]. In this paradigm, students encounter the Schrödinger equation in the context of spin-$1/2$ particles, having regularly used eigenvalue equations in the context of quantum mechanics before the Schrödinger equation is introduced [13]. Matrix equations and linear algebra serve as the primary mathematical tools for understanding the phenomena. McIntyre's *Quantum Mechanics: A Paradigms Approach* is a commonly used textbook in this paradigm [13,15].

Some of the supporters of the spin-first paradigm argue that this approach can help students overcome the common difficulty of distinguishing between physical space and Hilbert space that arises in position-first approaches [13,14]. Singh illuminated this difficulty in a previous study, which found that only 41% of students were able to sketch the physical results on the detector of the SGE, revealing their difficulty with physical space versus Hilbert space [16]. However, after the development of the SGE Quantum Interactive Learning Tutorial (QuILT), 22 students in a course improved their pretest scores from an average of 53% to 92% on the post-test [17]. This finding confirmed the potential that a spin-first paradigm could offer students in combating this common misconception. Singh has also hypothesized that, without the knowledge of wave function collapse, linear algebra students may answer similar questions correctly more often than students in a quantum mechanics course using a position-first paradigm [11].

To compare the two paradigms, Sadaghiani and Munteanu [14] conducted a study with two sections of a sophomore-level modern physics taught by the same instructor at Cal Poly Pomona: one using the spin-first paradigm and the other using the position-first paradigm. The results concluded that the spin-first students outperformed their position-first counterparts, with average scores of 63% compared to 57% and 55%. The survey results revealed that students in the spin-first approach shifted their focus from computation to sense making by providing concrete experimental evidence and simplifying the mathematical calculations involved.

Other scholars have also studied a spin-first paradigm [13]. Using a resources lens, Passante examined the tools and methods employed by students instructed through each paradigm to solve questions related to energy measurement. Specifically, Passante is interested in how energy and the Hamiltonian are introduced within each paradigm and how these introductions affect students' conceptualizations of energy measurement. Both paradigms introduce energy as the eigenvalue of the Hamiltonian operator in the Schrödinger equation, but the form of the Hamiltonian differs in the two paradigms. Passante found that the most common resources students used in the spin-first paradigm were (i) energy is an eigenvalue (43%), (ii) probability is calculated from $|\langle\psi|\psi\rangle|^2$ (38%), and (iii) the operator associated with energy is the Hamiltonian (38%). In contrast, the resources used by students in the position-first paradigm were most commonly: (i) multiple values are possible for a probability measurement of a superposition state (33%), (ii) use of the expectation value (17%), and (iii) coefficients in the state are meaningful (13%). Passante's preliminary findings suggest that students in the position-first paradigm activated resources related to the role of imaginary numbers and expectation values that were not activated by the spin-first students, and that students in the spin-first paradigm may form a more pronounced connection between the Hamiltonian and energy. Other work has focused on faculty perspectives, rather than student progress.

Siddiqui and Singh [12] uncovered the student difficulties most commonly observed by instructors in quantum mechanics courses. The instructors commented on the inaccurate descriptions the students learn in modern physics courses, which often exacerbate these difficulties. One instructor noted that misconceptions in quantum mechanics could be avoided if we stopped teaching students inaccurate descriptions of quantum systems, commonly presented in modern physics courses. One instructor stated, "I find the Bohr model hideous. I really wish modern physics classes could go beyond the Bohr model someday, so that we don't have to unteach it later" [12]. Two-thirds of the instructors shared this belief. This argument, along with the support for a spin-first paradigm, suggests that the traditional position-first approach in modern physics courses is one component contributing to students' lack of understanding of quantum phenomena. This finding motivated the current study to characterize which paradigms institutions are using in their courses.

III. METHODS

The *U.S. News* rankings of "The Best Physics Programs" was used as a reference list for institutions in this study [18]. This list primarily ranks research-focused physics programs that offer graduate-level physics education. We chose to focus on this group of schools because they are producing the next generation of physics faculty and have been shown to educate the majority of students pursuing a physics degree [19]. This list ranks 190 institutions, of which 188 offer a 4-year physics degree. In the 2021–2022 academic year, these institutions collectively granted 4772 bachelor's degrees, representing 56.7% of the total bachelor's degrees in physics granted that year. This same list was also utilized in our previous study on modern physics course syllabi [9].

Using this reference list of 188 institutions, the number of courses on quantum concepts required for a 4-year degree in physics was determined by referencing publicly available course catalogs online. Of these 188 institutions, 74.5% are classified as having very high research activity, and 22.3% as having high research activity, according to the Carnegie Classification of Higher Education Institutions [20], with six institutions whose research activity is not defined by these metrics. Additionally, 69.7% of the institutions are public while 30.3% are private [20]. Furthermore, 16.5% are minority serving institutions (MSIs, $n = 31$), including Hispanic serving institutions (HSIs, $n = 17$), Asian American and Native American Pacific Islander-Serving institutions (AANAPISIs, $n = 13$), historically Black colleges and Universities (HBCUs, $n = 3$), predominantly Black institutions (PBIs, $n = 1$), and Alaska Native-Serving institutions or Native Hawaiian-Serving institutions (ANNHs, $n = 2$) [21]. Recognizing the uniqueness of MSIs, we sought to characterize their quantum curriculum separately. To do so, the required course data from MSIs was included in the larger dataset but was also analyzed independently.

The requirements for a 4-year degree in physics were gathered by referencing each institution's course catalog. All required course descriptions were analyzed and coded as either including quantum concepts or not. Elective options were also reviewed to ensure they were included if the elective could only be fulfilled by taking a quantum-related course. Any required course that included quantum topics, "modern physics," or "modern topics" was recorded as a quantum-related course, as a previous finding indicated that quantum is the most commonly taught topic within modern physics courses [9].

If an institution offered different concentrations that altered degree requirements, the most generalized degree option was selected for coding. For example, if a school offered both a bachelor of arts and a bachelor of science, the bachelor of science was selected for coding. Similarly, if an institution offered an applied physics degree alongside other concentrations, the applied physics degree was selected for coding.

To determine the number of classroom hours scheduled for required courses, syllabi were collected, particularly for courses like modern physics or those with "modern topics" in their course descriptions. In cases where courses covered topics beyond quantum physics (such as relativity or thermodynamics), a detailed course schedule was necessary to discern how many lectures were spent on quantum topics compared to other subjects.

Utilizing the modern physics syllabi collected in a previous study made this process easier for the introductory courses [9]. If a needed syllabi had not already been collected from the previous study, an online search was first conducted to determine if the syllabus was publicly available. If it was not, an online course schedule was used to identify a recent instructor of the course, and an email was sent to request a copy of their syllabus and course schedule.

This syllabi collection process resulted in a total of 300 syllabi across the 188 institutions. However, only 56 institutions provided syllabi that specified which lectures covered quantum topics versus relativity, thermodynamics, or other topics in their introductory courses, so only these

TABLE I. Codes for a lecture to be considered a quantum related lecture.

Codes to be considered a quantum lecture	
Schrödinger	Fermi's golden rule
Schrödinger equation	Photons
Photoelectric effect	Pauli's exclusion principle
Wave-particle duality	Square well
Operators	Identical particles
Eigenvalues	Matter waves
Tunneling/reflection	Frank Hertz experiment
Stern-Gerlach experiment	Wave mechanics
Dirac Notation	Wave functions
States	Wave properties of particles
Quantum measurement	Particle properties of waves
Expectation value	de Broglie Hypothesis
Uncertainty	Quantum theory of light
Superposition	Blackbody radiation
Mixed states	Planck's postulate
Quantization	Spin

institutions were included in this portion of the analysis. From these 56 institutions, a total of 129 syllabi were collected—51.2% from public sources and 48.8% through private correspondence. These 56 institutions awarded 1746 physics bachelor's degrees in the year 2021–22 [19], accounting for 20.8% of physics bachelor's awarded that year. Of these institutions, 69.6% are public universities, 82.1% are classified as having very high research activity, and 16.1% having high research activity [20]. Additionally, 16.1% of these institutions are MSIs [21].

In order for a lecture to be coded as a quantum-related lecture, the same codebook used in the previous modern physics study was applied [9]. A lecture had to include one of the terms listed in Table I in order to be classified as a "quantum-related lecture."

Using this coding scheme, the number of quantum lectures in each course was tallied. If the course was not an introductory course but rather a traditional quantum mechanics course—i.e., one that covers only quantum concepts throughout the entire semester—the institution's publicly available academic calendar was consulted to determine the number of lectures held during the semester. The scheduled lecture time was then used to calculate the number of minutes per lecture. From this, the total number of quantum-related lecture minutes was calculated by multiplying the number of quantum lectures by the number of minutes per lecture.

To ensure both methods of counting were equivalently weighted (syllabus schedule vs academic calendar), midterm exams held after quantum concepts were introduced were included in the calculation for courses with a syllabus schedule. Recitations or discussion sections were not included in the count, as not all courses had these sections, and they may be considered part of the time students spend studying outside of lecture hours since these sections are usually reserved for practice problems and group work.

In order to characterize the topics taught within the quantum curriculum, analysis was restricted to the 56 institutions for which all quantum-related course syllabi were available. This restriction ensured that the entire quantum curriculum for each institution was characterized rather than only one or two courses. From these 56 institutions, only 50 could be analyzed for their topics, as one or more syllabi from six institutions did not list the topics covered in the course.

To determine the topics taught, an emergent coding method was used [22]. All topics mentioned in the syllabi were recorded. Using the table of contents from the Griffiths [10] and McIntyre [15] textbooks, closely related topics were combined together. Table II below presents the overarching themes within the syllabi, along with the topics coded under each theme. Some topics appeared so infrequently that they could not be grouped with others and will appear in the results despite not being included in Table II. Examples of these topics include an introduction to quantum field theory and the Dirac equation.

Finally, the paradigms used by institutions (spin-first or position-first) were analyzed twice: once for institutions' introductory quantum courses (i.e., modern physics courses) and another time for their traditional quantum mechanics courses. The rationale for this approach stemmed from a previous study that found the most common prerequisite for modern physics was calculus II [9]. Given that students may lack a foundation in linear algebra, the question arose as to whether they were prepared for a spin-first approach. Therefore, this study aimed to determine if any institutions were utilizing a spin-first approach in their modern physics or equivalent courses.

For the modern physics or equivalent courses, 112 syllabi from different institutions were collected and analyzed. These institutions awarded a total of 2785 physics bachelor's degrees (33.1%) in 2021–22 [19]. Of these institutions, 74.1% are public, 75.0% have very high research activity, and 21.4% have high research activity [20]. Additionally, 16.1% are MSIs, including HSI ($n = 10$), AANAPISI ($n = 7$), and ANNH ($n = 1$) [21].

For the quantum mechanics courses, 99 syllabi were collected and analyzed. From these institutions, a total of 2920 physics bachelor's degrees (34.7%) were awarded in 2021–22 [19]. Of these institutions, 70.7% are public, 79.8% have very high research activity, and 17.1% have high research activity [20]. Additionally, 17.2% are MSIs, including HSI ($n = 10$), AANAPISI ($n = 7$), HBCU ($n = 1$), and ANNH ($n = 1$) [21].

The syllabi were coded using the coding scheme in Table III below, which was developed from the literature [13,14]. For a course to be considered a spin-first course, the introduction to the SGE needed to precede the introduction of the Schrödinger equation. If the syllabus did not

TABLE II. Topics combined into overall themes for coding syllabi.

Themes and related topics present in the syllabi		
Quantum theory of light	*Schrödinger equation*	*Particles*
Photons	Time-independent Schrödinger equation	Pauli exclusion principle
Compton effect	1D quantum mechanics	Elementary particles
Wave-particle duality	Solutions to different potentials	Fermions
Particle nature of matter	Infinite potential well	Bosons
Wave nature of particles	Harmonic oscillator	Identical particles
	Bound states	
Wave functions	*Scattering theory*	*EPR paradox*
Wave mechanics	Born approximation	Bell's theorem
Applications	*Tunneling*	*Adiabatic approximation*
Quantum computing	Finite square well	Adiabatic theorem
Quantum teleportation	Reflection/scattering	Berry's phase
Cryptography	Unbound states	
3D quantum mechanics	*Formalism*	*Early quantum experiments*
Spherical coordinates	Operators	de Broglie wavelengths
Hydrogen atom (in context of Schrödinger equation, no Bohr model)	Observables	Blackbody radiation
Angular momentum	Measurables	Planck's hypothesis
	Expectation value	Photoelectric effect
	Hilbert space	Double slit experiment
	Eigenvalues/functions	Frank Hertz experiment
	Normalization	
	Probability	
Perturbation theory	*Time evolution*	
Time-independent perturbation theory	Time development	
Time dependent perturbation theory	Quantum dynamics	
Nondegenerate perturbation theory	Spin procession	
Degenerate perturbation theory	Lamor procession	
Fine structure	Neutrino oscillations	
Zeeman effect	Time-dependent Hamiltonians	
Hyperfine splitting		
Spontaneous emission		

TABLE III. Codes to determine paradigm used by each course.

Coding for paradigm used by course	
Spin-first	Position-first
Stern-Gerlach experiment [13]	Schrödinger equation introduced early on Refs. [13,14]
Postulates of quantum mechanics [13,14]	Schrödinger equation in context of position space wave functions [13]
Schrödinger equation in context of spin 1/2 particles [13]	Differential equations [13]
Matrix equations [13]	Time-independent Schrödinger equation is the first eigenvalue equation introduced [13]
Eigenvalue equations regularly used before Schrödinger equation introduced [13]	Griffiths' textbook used [10,13]
McIntyre's textbook used [13,15]	

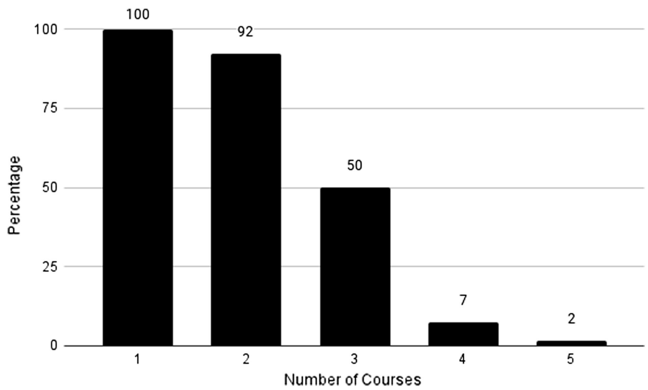

FIG. 1. The number of required quantum related courses at 188 institutions.

provide a course outline for lecture topics (32.3% of syllabi), the table of contents from the listed textbook was used to determine the sequence of topics.

IV. RESULTS

From the 188 institutions offering a 4-year degree in physics, the results of the required number of quantum-related courses are shown in Fig. 1. All institutions require at least one course, with the vast majority (92.0%) require two courses. Exactly half of the institutions require a third course. The outliers in this dataset are the institutions that require four (7.0%) or five (2.0%) courses. Among the 8% of institutions that require only one course, 87% require modern physics while only 13% specifically require a quantum mechanics course.

As stated in the methods, the MSIs were also analyzed separately for comparison with the larger dataset. The number of required quantum-related courses at the MSIs is presented in Fig. 2. Comparing Figs. 1 and 2, we can concluded that the same trend in number of courses is present in both MSIs and non-MSIs.

From the 56 institutions for which syllabi were collected for their entire quantum curriculum, the total lecture hours

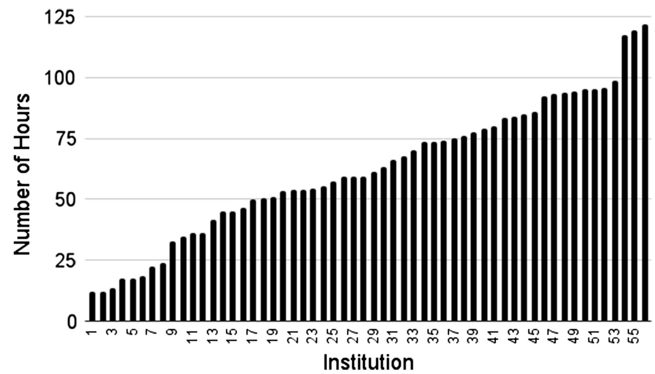

FIG. 3. Number of lecture hours on quantum concepts required for each individual institution.

spent on quantum concepts are presented in Fig. 3. The mean for these institutions was 63.5 h, with a standard deviation of 28.1 h. The median was 60.3 h, and the mode was 53.8 h. The minimum was 12 h, while the maximum was 121.7 h.

The MSIs were again analyzed independently, and their results are presented in Fig. 4. From these 9 institutions, the mean was 79.4 h, with a standard deviation of 31.2 h. The median was 73.7 h, while the minimum was 24.0 h and the maximum was 121.7 h. Comparing Figs. 3 and 4, the MSIs show a higher mean than the larger data by 15.9 h, suggesting that no disparity is present in this dataset.

From the 50 institutions whose syllabi were analyzed for themes, it was found that the Schrödinger equation (98%) and three-dimensional quantum mechanics (94%) were the most commonly identified themes (Fig. 5). Interestingly, the SGE appeared in only 28% of the curricula, despite research highlighting its benefit for helping students discern between physical space and Hilbert space [17].

Of the 112 modern physics or equivalent courses, *all* used a position-first approach. In contrast, for the quantum mechanics courses, some instructors (26.3%) adopted a spin-first approach, but position-first approaches remain the

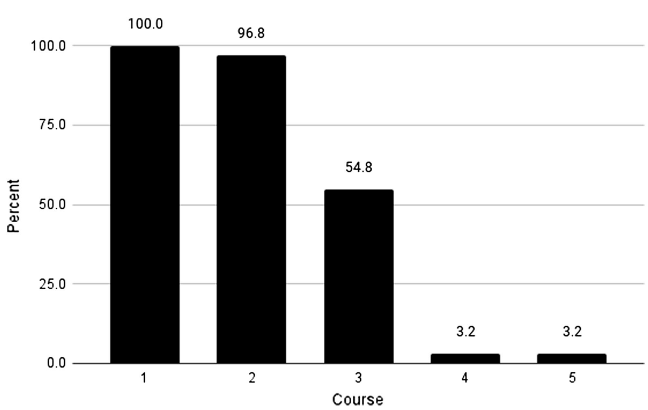

FIG. 2. The number of required quantum-related courses at 31 MSIs.

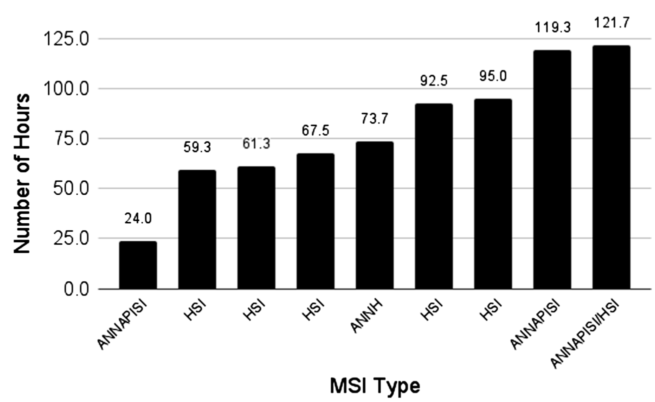

FIG. 4. Number of lecture hours on quantum concepts required for each individual MSI.

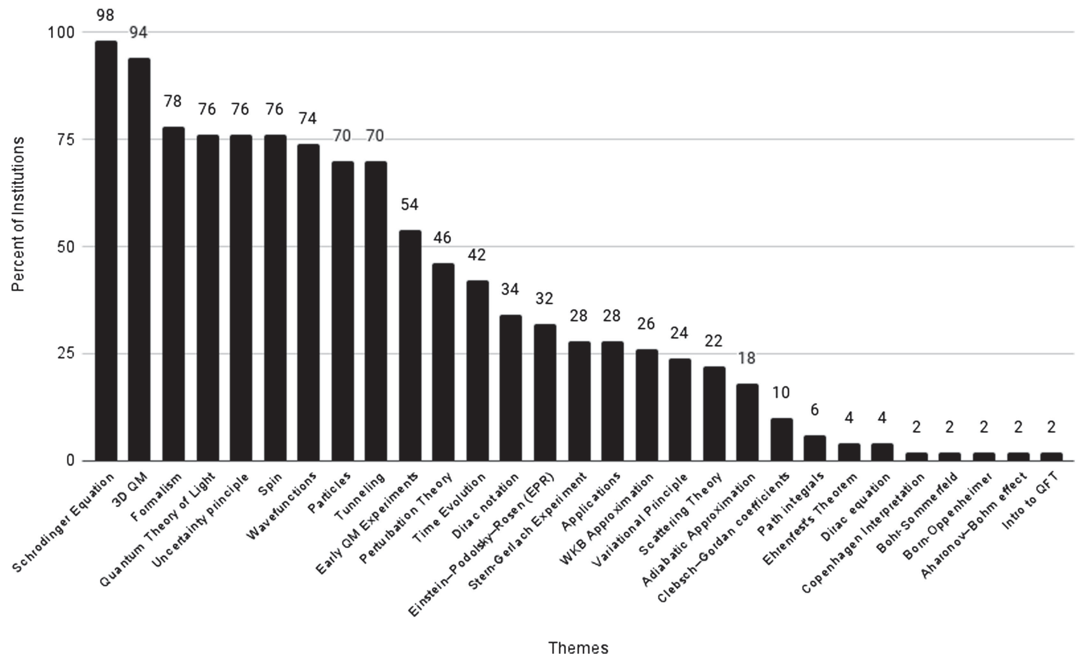

FIG. 5. Percentage of themes taught within 50 institutions' quantum curriculum.

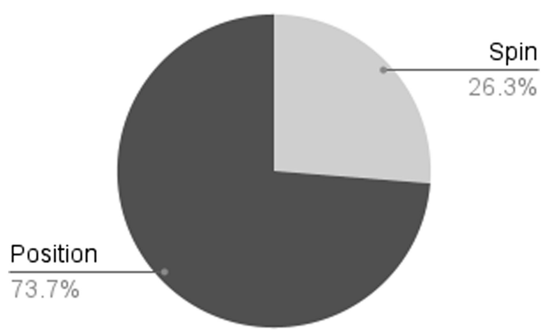

FIG. 6. Spin-first versus position-first paradigm used in the quantum mechanics courses of 99 institutions.

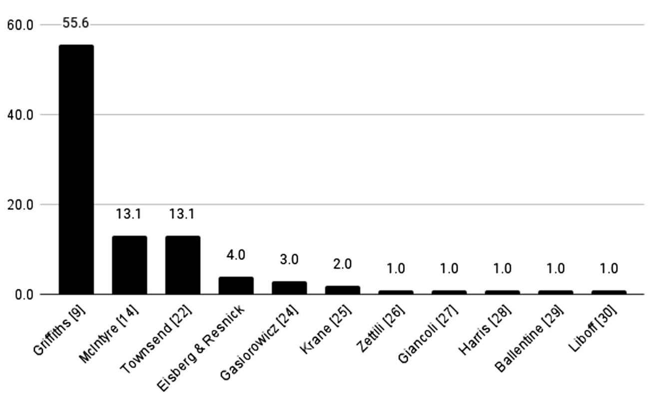

FIG. 7. Textbooks used by quantum mechanics courses at 99 institutions.

more prevalent method, accounting for 73.7% of quantum mechanics courses (see Fig. 6).

The textbooks used in the 99 quantum mechanics courses were also coded, with the results presented in Fig. 7. Griffiths' textbook [10] was the most commonly used, accounting for 55.6% of institutions. Both McIntyre [15] and Townsend [23] were used by 13.1% of institutions. Eisberg and Resnick [24] was used 4% of the time, followed by Gasiorowicz [25] at 3%, and Krane [26] at 2%. Textbooks by Zettili [27], Giancoli [28], Harris [29], Ballentine [30], and Liboff [31] were each used by 1% of institutions.

Additionally, the correlation between the textbooks used and each paradigm was analyzed. It was found that all courses using Griffiths, Eisberg and Resnick, Gasiorowicz, Krane, Giancoli, Harris, and Ballentine adopted a position-first approach. Conversely, all courses using McIntyre, Zettili, and Liboff employed a spin-first approach. Notably, Townsend was the only textbook where instructors employed both paradigms, with 69.2% of instructors using a position-first approach and 30.8% using a spin-first approach.

V. DISCUSSION

Across the dataset, significant disparities in access and opportunities for learning quantum mechanics were observed. The results reveal a broad range of expectations regarding required quantum-related courses and the associated course time. Some students are only expected to enroll in a single quantum-related course, resulting in as little as 12 h of instructional time. In contrast, other students are required to take as many as five courses, accumulating up to 121.7 h of course time.

One notable finding of this study, though not unexpected, is that no modern physics courses are using a spin-first approach. This aligns with the anticipated mathematical preparation of students enrolled in modern physics courses. However, this observation illuminates two key points: (i) institutions may face challenges in implementing a spin-first approach in their quantum mechanics courses if students have previously been exposed to a position-first approach in their modern physics classes, and (ii) the implications of these approaches may extend beyond individual courses, affecting the entire curriculum. Future studies should investigate whether the position-first approaches in modern physics influence student learning in subsequent spin-first quantum mechanics courses.

Despite ongoing research and discussions with the physics education community regarding the spin-first versus position-first approach [13,14], the majority of quantum mechanics instructors continue to favor a position-first approach. This study also demonstrated that a significant emphasis in these courses is placed on the Schrödinger equation and its solutions for various potentials, which is typical of position-first paradigms [13]. Interestingly, even though instructors predominantly choose the traditional position-first approach, only a notably low percentage (28%) include the SGE in their course outline. This presents an opportunity for instructors: even if they are hesitant to adopt a spin-first approach, they could still incorporate the SGE into their position-first courses to help address the common difficulties students face in distinguishing between position space and Hilbert space [17].

An interesting finding is that both spin-first (69.2%) and position-first (30.8%) paradigms are used with Townsend [23], whereas all other textbooks adhere to a single paradigm. Notably, Chapter 1 of Townsend focuses on The Stern-Gerlach Experiment [23], which makes this textbook particularly conducive to a spin-first approach [14]. This suggests that instructors who choose to use Townsend while electing for a position-first approach may be deviating from the intended chapter sequence in their courses. Furthermore, this may also signify that not all instructors are aware of the benefits of implementing a spin-first approach [13,14,16]. Future studies exploring instructors' perspectives on the two paradigms could provide valuable insights into their hesitancies to modify their courses.

VI. CONCLUSION

The current quantum curriculum at research-intensive institutions in the U.S. exhibits significant variability. It is essential to address this disparity and enhance student access to quantum education. Despite the physics education research community's advocacy for a spin-first approach that emphasizes the SGE, most instructors continue to adopt a position-first approach, focusing heavily on solving the time-independent Schrödinger equation.

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