MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2026, 22(8), em2882
ISSN:1305-8223 (online)
OPEN ACCESS Research Paper https://doi.org/10.29333/ejmste/18987

Development of an online teacher training course for modern quantum physics teaching

Kim Kappl [1*], Stefan Aehle [2], Simon Koppenhöfer [1], Philipp Scheiger [1]

[1] Physik und ihre Didaktik, University of Stuttgart, Stuttgart, GERMANY
[2] AG Fachdidaktik der Physik und Astronomie, Friedrich-Schiller University Jena, Jena, GERMANY

Received 21 December 2025 ▪ Accepted 09 June 2026

Abstract

Modern quantum physics is finding its way into education and schools to train specialists for future technologies. Teachers must, therefore, be familiar with modern quantum physics. However, this content was often not a focus of the university training of prospective teachers. Consequently, there is a great need for further and advanced training courses for teachers. In this contribution, we present the concept and implementation of a practice-oriented teacher training course with online self-study units and a focus on physics content. The focus is on the essential features of quantum physics that may be new to many in-service teachers, such as single-photon physics, Dirac formalism, and the quantum mechanical worldview.

Keywords: quantum physics, in-service teacher education, flipped classroom, blended learning, hybrid teaching, online course

INTRODUCTION

Recent curricular developments in several German federal states have strengthened the role of quantum and atomic physics in upper secondary education. The 2020 educational standards of the German Standing Conference of the Ministers of Education and Cultural Affairs (2025) introduced mandatory concepts that had previously not been part of many state curricula, such as the quantum mechanical worldview with its implications for realism, locality, causality, and determinism, as well as experimental methods such as coincidence method to prove the existence of single photons.

At the same time, many teachers are unfamiliar with modern approaches to introducing quantum physics. While historical entry points, such as black-body radiation or the photoelectric effect, are still widespread in teaching practice, modern conceptual pathways such as the "basic principles of quantum physics" proposed by Müller and Küblbeck (2021) are not yet broadly implemented.

In addition, topics within atomic physics (e.g., hydrogen atom and atomic spectra) have been inconsistently included across curricula in recent years. For many teachers, this has led to substantial content-related and educational uncertainties.

To meet this nationwide demand, the physics education research groups at Friedrich-Schiller University Jena and the University of Stuttgart collaboratively developed a blended-learning teacher training format combining online self-study, interactive learning modules, synchronous online sessions, and practice-oriented face-to-face workshops.

The course design systematically operationalizes key recommendations from the GIREP community (Michelini et al., 2022), combining self-paced online modules, synchronous discussion sessions, and hands-on experimental workshops into a coherent professional development format. The article by Michelini et al. (2022, 2023) as well as Ansorge-Grein (2011) calls for flexible, modular course formats that account for the heterogeneous prior knowledge of participating teachers, the emphasis on conceptual understanding as

A preliminary version of this paper was presented at the GIREP 2025 Conference.

✉ kkappl@pi5.physik.uni-stuttgart.de (*Correspondence) ✉ stefan.aehle@uni-jena.de ✉ koppe@pi5.physik.uni-stuttgart.de
✉ p.scheiger@physik.uni-stuttgart.de

Contribution to the literature

- This paper documents some concrete, fully implemented course design that combines self-paced online modules (via Moodle / H5P), synchronous discussion sessions, and hands-on experimental workshops.
- The presented course systematically puts into practice existing guidance from the physics education research community—including flexible modular formats, emphasis on conceptual understanding, integration of real and analogy experiments, and fostering an ongoing community of practice among teachers.
- The lessons learned, feedback from participants, and the resulting adjustments to the course content and this new course design made during the pilot phase are presented to the reader.

a prerequisite for meaningful classroom implementation, the integration of both real and analogy experiments as experiential learning elements, and the importance of fostering an ongoing community of practice that supports teachers beyond the duration of the training itself.

This article represents an important first step in the development, implementation, and evaluation of new teacher training programs, which must meet the standards mentioned above. Because although a growing number of studies have addressed teacher professional development in quantum physics (Holincheck et al., 2024; Legerská et al., 2025; Onorato et al., 2025; Sutrini et al., 2023), fully implemented blended-learning courses for in-service teachers that combine self-paced online modules with synchronous sessions and hands-on experimental workshops remain rare, particularly in the German-speaking context.

The blended learning concept presented here is also based on research findings that demonstrate the effectiveness of "flipped classroom" or "inverted classroom" approaches both in the context of general teacher professional development and in quantum physics education. By engaging with the content independently at their own pace during self-study phases, participants already share a common conceptual foundation by the time of the synchronous sessions, which enables more productive discussions and deeper collective reflection. For an overview, see Weber (2018), Krasnova and Shurygin (2019), and Bitzenbauer and Hennig (2023). This structure is particularly well-suited to in-service teacher training, where participants bring heterogeneous prior knowledge and benefit from the flexibility to study at their own pace and on their own schedule.

Building on both the general pedagogical principles and the field-specific recommendations outlined above, the present course pursues three interconnected learning goals: first, to build robust content knowledge in areas of modern quantum physics that are new to many in-service teachers, including single-photon physics, the Dirac formalism, quantum entanglement, and the quantum mechanical worldview; second, to develop pedagogical content knowledge by supporting teachers in translating these concepts into age-appropriate and curriculum-aligned classroom practice; and third, to foster familiarity with relevant experimental demonstrations and their didactic potential, even where replication under school conditions is not feasible.

In the following section, this paper describes the underlying concept of the training course. Subsequently, the structure and content are described, and the face-to-face events that serve to present experiments and improve learning are introduced. Consequently, initial experiences from test phases and corresponding revisions to the course are discussed. Finally, we conclude the article with a conclusion and an outlook.

MATERIALS AND METHODS

The design of the teacher training course is based on several principles regarding the effectiveness and structure of professional development programs. Our own interviews among physics teachers indicate substantial heterogeneity in preferences concerning both the duration and the format of training, ranging from short online offerings to more extensive face-to-face or hybrid formats. In addition, there is a wide range of prior knowledge that teachers have on the individual topics. Despite these differences, a common expectation emerges across all groups: teachers value training opportunities that provide clear benefits for their own teaching practice and include concrete, ready-to-use instructional materials.

At the same time, research on teacher professional development has repeatedly shown the limitations of so-called "one-shot" training formats. Such isolated and short-term interventions tend to have limited long-term impact and are particularly ineffective for the communication of complex subject matter (Desimone, 2009; Kennedy, 1998).

Additionally, the current version of the course places a strong emphasis on the transmission of technical content. This emphasis arises from the fact that the new educational standards in Germany (German Standing Conference of the Ministers of Education and Cultural Affairs, 2025) mandate the inclusion of several topics in modern quantum physics that are unfamiliar to many in-service teachers. Consequently, many teachers have either not taught these topics for several decades or, in

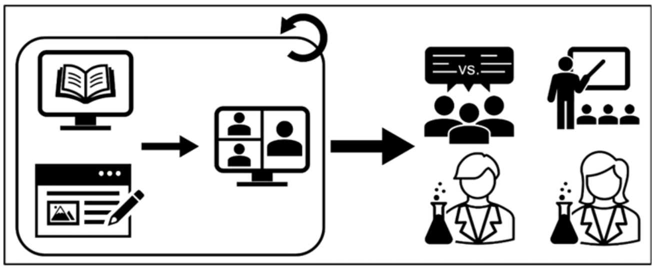


Figure 1. Schematic representation of the teacher training concept (each thematic unit begins with an online self-study phase supported by interactive H5P materials on the Moodle platform, followed by a synchronous online session for clarification and discussion & this cycle is repeated for all modules and concludes with a final on-site session in which relevant experiments are demonstrated) (created by the authors)

some cases, have never encountered them during their own professional training. These topics include the mathematical formalism of quantum mechanics (e.g., Dirac formalism), single-photon physics and its experimental validation, central conceptual features of quantum mechanics as the "basic principles of quantum physics" (Müller & Mishina, 2021), as well as quantum entanglement and the associated quantum-mechanical worldview.

In order to meet this heterogeneous range of requirements and preferences, the training course adopts a predominantly online, self-paced structure supported by interactive materials. A Moodle-based learning environment contains all content-related modules implemented as interactive H5P elements. After gaining access to the platform, participants are assigned a specific topic and given a period of approximately three to four weeks for self-study.

Each self-study phase is followed by a synchronous online session led by the instructors. These sessions provide an opportunity to revisit and clarify the central concepts encountered during the self-study period, allowing participants to ask questions and resolve any conceptual difficulties. In addition, the sessions create a structured space for discussing how the newly acquired content can be meaningfully integrated into classroom teaching. Participants are encouraged to share ideas, reflect on their own teaching contexts, and explore instructional strategies for implementing modern quantum physics at the secondary-school level.

After each synchronous session, a new content module is assigned, and the process iterates until all relevant topics have been covered. The training concludes with an optional on-site workshop at one of the university locations. This final session enables participants to engage with experimental equipment, discuss instructional strategies, and connect with peers. This basic structure of this course is also illustrated in **Figure 1**.

Structure of the Online Course

In this section, we describe the content structure of the course. The online course is divided into the following sections:

- **Q:** Quantum physics content
- **A:** Atomic physics and matter content
- Teaching materials
- Additional resources

Most content is presented through modular H5P units. These include embedded questions, short quizzes, and immediate feedback to engage learners and enable self-monitoring of progress.

Quantum physics modules

The quantum physics section is divided into the following submodules:

Q1: The characteristic principles of quantum physics

Q2: Heisenberg uncertainty relation

Q3: Mathematical description of quantum mechanics

Q4: Entanglement and the quantum worldview (reality, locality, causality, and determinism)

Q5: The photoelectric effect

Q6: The coincidence method to prove the existence of single photons

The structure deliberately aligns with the conceptual areas highlighted in the educational standards. Additional content such as Dirac formalism or extended mathematical treatments is included to support a deeper understanding, while clearly marked as optional background knowledge.

Atomic physics modules

Atomic physics content is structured into eight modules, covering:

A1: Historical developments of the atomic model

A2: Rutherfords atomic model

A3: Bohrs atomic model

A4: The quantum mechanical atomic model

A5: The hydrogen atom

A6: Energy levels, transitions, and spectra

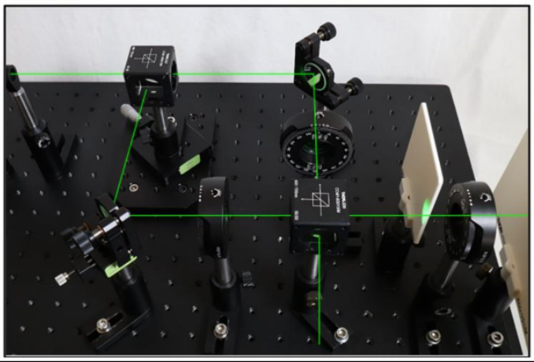
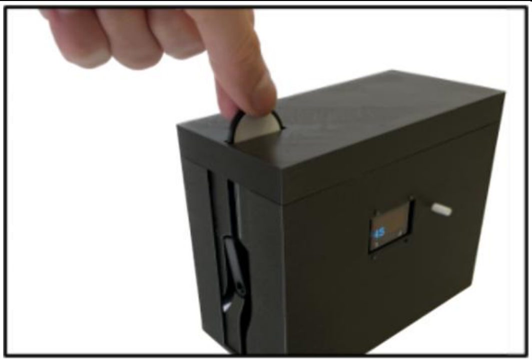
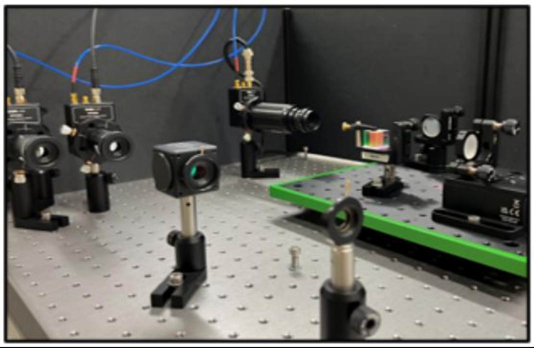
A7: X-ray spectra

This broad selection accounts for heterogeneous teacher backgrounds and diverse curriculum requirements across different federal states.

Teaching materials and additional resources

A dedicated section provides ready-to-use classroom materials including diagrams, experiment instructions, worksheets, and digital simulations. These resources aim to support immediate transfer into teaching practice.

Table 1. Small selection of the experiments presented during the on-site final session for the participants

Experiment	Context	Depicting picture (created by the authors)
Classical interferometers	Since classical interferometers are firmly established in school curricula, they are perfectly suited as an analogy model for discussing the fundamental principles of quantum physics with teachers, as well as high school students. These fundamental principles include, for example, the ability for single quantum objects to interfere, but also the concepts of complementarity, stochastic predictability, and the uniqueness of results.	
3D-printed analogy experiments (Aehle et al., 2022)	Experiments with real single quantum objects cannot realistically be conducted in high school lessons, given the time required for setup and the considerable financial investment such equipment demands. To nonetheless familiarize students with the basic principles of single quantum objects, such as polarized single photons, 3D-printable boxes were developed as a haptic analogy tool. In this setup, individual NFC chips serve as analogues to single photons: just as a photon carries a defined polarization state, each NFC chip is loaded with information encoding the polarization state of the represented "photon." When the chip is inserted into the 3D-printed box, an integrated reader interprets this polarization state and determines whether the "photon" is transmitted or absorbed. Through repeated interaction with the apparatus, students can experimentally reconstruct the behavior of single polarized photons at a polarizing filter and inductively derive central principles of quantum mechanics, including the stochastic nature of individual measurement outcomes and the unambiguousness of measurement results.	
Single photon experiments (Thorlabs, 2025)	To complement the on-site workshop, experiments with real single photon sources form an essential component. In our sessions, we employ a spontaneous-parametric-down-conversion–based source developed by Thorlabs, which enables participants to explore both the generation and detection of single photons in a controlled setting. The setup can be extended with a Michelson interferometer, providing an opportunity to investigate interference phenomena at the single-photon level and to examine further fundamental principles of quantum physics.	

Further references include glossaries, external articles, and supplementary readings to support individual in-depth study.

On-Site Session

Following the online phases, a final in-person session is offered. The workshop serves multiple purposes and complements the digital components of the course. First, participants have the opportunity to engage directly with a wide range of experiments. An excerpt from the presented experiments can be found in **Table 1**. Connecting the theoretical concepts learned during the online phases with the live experiments thereby strengthens the conceptual foundations developed during the self-study phases.

In addition to experiencing the experiments themselves, participants discuss how these setups can support conceptual learning in school contexts. Rather than focusing on acquiring laboratory skills or preparing teachers to replicate complex experiments, the workshop emphasizes the educational value of experimental demonstrations. Together with instructors, participants analyze how experimental evidence supports key ideas in quantum physics, which implementation strategies are feasible under typical school conditions, and how classroom activities can be structured to make abstract concepts accessible to students.

A further central aspect of the on-site session is the opportunity for networking and professional exchange. Teachers share experiences from their own classrooms, provide feedback on the online materials, and collaborate on ideas for integrating quantum physics into the curriculum. This collaborative environment fosters a community of practice that extends beyond the duration of the course and supports long-term professional development.

RESULTS AND DISCUSSION

Initial pilot implementations were carried out with teachers from single secondary schools as well as with participants of a regional teacher training workshops both in Jena and Stuttgart. Building on the positive response in these early trials, the full training series has since been incorporated into the official program of the Thuringian Institute for Teacher Education. Across all pilot phases, feedback has been consistently encouraging. Participants particularly highlighted the clarity and accessibility of the self-study units, noting that the interactive H5P elements provided valuable support for structuring their learning and monitoring their own progress.

The differentiation between introductory and advanced modules was also well received, as it allowed teachers with varying prior knowledge to engage with the materials at an appropriate level. At the same time, several participants indicated that some of the quantum physics content—especially modules with stronger mathematical emphasis—felt too challenging or too far removed from typical school requirements. In response, these sections were explicitly labelled as advanced background material to clarify that they are intended for optional deepening rather than classroom implementation. Overall, the collected feedback underscores both the relevance and effectiveness of the blended-learning format, while also pointing to the need for continued adjustment of the content balance. Future iterations of the training will therefore focus on refining the alignment between conceptual depth and classroom applicability, ensuring that the course remains both scientifically robust and directly useful for teachers' everyday practice.

CONCLUSION AND OUTLOOK

The teacher training course addresses the growing need for comprehensive professional development in quantum and atomic physics. Its blended-learning approach supports flexible, individualized learning while maintaining strong connections to teaching practice.

The course will be fully implemented across Thuringia in 2025, with further pilot studies planned in Baden-Württemberg. Through collaboration with the Stifterverband (2025) and the Quantum Skills Initiative, the entire Moodle course will be publicly available on the MINT-Campus (2025) platform starting in summer 2026.

Author contributions: KK: conceptualization, resources, writing – original draft; **SA:** conceptualization, funding acquisition, resources, writing – review & editing; **SK:** resources, writing – review & editing; **PS:** conceptualization, funding acquisition, supervision, writing – review & editing. All authors agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: An ethical statement is not applicable, as no participants were involved in a study for this article.

AI statement: During the preparation of this manuscript, the authors used Gemini [3.5 Flash] (Google) to refine and improve the phrasing of the manuscript. The authors reviewed and edited the AI-assisted content as needed and took full responsibility for the accuracy, integrity, and originality of the content of the publication.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

Aehle, S., Scheiger, P., & Cartarius, H. (2022). An approach to quantum physics teaching through analog experiments. *Physics, 4*(4), 1241-1252. https://doi.org/10.3390/physics4040080

Ansorge-Grein, K. (2011). *Qualität und Qualitätsmanagement in der universitären naturwisenschaftlichen Lehrerfortbildung* [Quality and quality management in the further training of teachers in natural sciences at university] [PhD thesis, Johann Wolfgang Goethe-Universität].

Bitzenbauer, P., & Hennig, F. (2023). Flipped classroom in physics teacher education: (How) can students' expectations be met? *Frontiers in Education, 8*. https://doi.org/10.3389/feduc.2023.1194963

Desimone, L. M. (2009). Improving impact studies of teachers' professional development: Toward better conceptualizations and measures. *Educational Researcher, 38*(3), 181-199. https://doi.org/10.3102/0013189X08331140

German Standing Conference of the Ministers of Education and Cultural Affairs. (2025). Kultusministerkonferenz, "Bildungsstandards im Fach Physik für die Allgemeine Hochschulreife," [Standing Conference of the Ministers of Education and Cultural Affairs, "Educational Standards in Physics for the General University Entrance Qualification"]. *KMK*. https://www.kmk.org/fileadmin/Dateien/veroeffentlichungen_beschluesse/2020/2020_06_18-BildungsstandardsAHR_Physik.pdf

Holincheck, N., Rosenberg, J. L., Zhang, X., Butler, T. N., Colandene, M., & Dreyfus, B. W. (2024). Quantum science and technologies in K-12: Supporting teachers to integrate quantum in STEM classrooms. *Education Sciences, 14*(3), Article 219. https://doi.org/10.3390/educsci14030219

Kennedy, M. (1998). Form and substance in inservice teacher education. In *Proceedings of the AERA Annual Meeting*.

Krasnova, L., & Shurygin, V. (2019). Blended learning of physics in the context of the professional development of teachers. *International Journal of Emerging Technologies in Learning, 14*(23), 17-32. https://doi.org/10.3991/ijet.v14i23.11084

Legerská, J., Henriksen, E. K., & Boe, M. V. (2025). Learning goals in upper secondary quantum physics: Norwegian teachers' perspectives. *Physics Education, 60*, Article 045030. https://doi.org/10.1088/1361-6552/ade259

Michelini, M., Faletic, S., & Pospiech, G. (2022). Work group 3 position paper: Teacher education and teaching/learning quantum physics. *Journal of Physics: Conference Series, 2297*, Article 012015. https://doi.org/10.1088/1742-6596/2297/1/012015

Michelini, M., Faletic, S., & Pospiech, G. (2023). Approaches and teaching resources for teacher education in quantum physics. In J. Borg Marks, & P. Galea (Eds.), *Physics teacher education. Challenges in physics education* (pp. 77-91). Springer. https://doi.org/10.1007/978-3-031-44312-1_6

MINT-Campus. (2025). MINT-campus. *mintcampus*. https://mintcampus.org/

Müller, R., & Mishina, O. (2021). Milq—Quantum physics in secondary school. In B. Jarosievitz, & C. Sükösd (Eds.), *Teaching-learning contemporary physics. Challenges in physics education* (pp. 33-45). Springer. https://doi.org/10.1007/978-3-030-78720-2_3

Onorato, P., Perli, L. S., Di Mauro, M., Malgieri, M., Cogo, D., Pantano, O., & Carlo, M. (2025). Key topics, motivations, and approaches for quantum physics instruction in Italian secondary schools: A teachers' perspective. *Physics Education, 60*, Article 065025. https://doi.org/10.1088/1361-6552/ae0855

Stifterverband. (2025). Quantum skills. *Stifterverband*. https://www.stifterverband.org/quantum-skills

Sutrini, C., Malgieri, M., Zuccarini, G., & Macchiavello, C. (2023). A teacher professional development course on quantum technologies: Discussion of results. *Journal of Physics: Conference Series, 2490*, Article 012006. https://doi.org/10.1088/1742-6596/2490/1/012006

Thorlabs. (2025). Thorlabs quantum optics kit. *Thorlabs*. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=15827

Weber, K.-A. (2018). *Quantenoptik in der Lehrerfortbildung: Ein bedarfsgeprägtes Fortbildungskonzept zum Quantenobjekt "Photon" mit Realexperimenten (studien zum Physik- und Chemielernen, Band 269)* [Quantum optics in teacher training: A needs-based training concept on the quantum object "photon" with real experiments (studies on physics and chemistry learning, volume 269)]. Logos Berlin.