Experiential Quantum Mechanic (ExQuMe): Immersive VR for Quantum Mechanics Education

Athanasios Christopoulos
Faculty of Science
University of Turku
Turku, Finland

Stylianos Mystakidis
Museum of Science & Technology
University of Patras
Rio, Greece

Andreas Komninos
Computer Engineering & Informatics
University of Patras
Rio, Greece

Tomislav Stipančić
Robotics & Automation of Prod. Systems
University of Zagreb
Zagreb, Croatia

Alexandros Tampakis
Research & Innovation Office
University of Central Lancashire Cyprus
Larnaca, Cyprus
ATampakis@uclan.ac.uk

Mikko-Jussi Laakso
Research Institute for Learning Analytics
University of Turku
Turku, Finland

***Abstract*—Quantum Mechanics (QM) is among the most demanding subjects of the physics curriculum as the phenomena it describes occur at scales and timescales beyond human perception and contradict the intuitions that learners develop through everyday experience. Immersive Virtual Reality (VR) has repeatedly been proposed as the medium that could close the gap, but most applications are shaped by what the technology makes possible more than by what learners need. In the present work we present 'ExQuMe' (Experiential Quantum Mechanic), an Erasmus+ cooperation partnership (2025–2028) of six organisations from five European countries which develops story-driven immersive VR modules in which women pioneers of physics guide learners through core quantum phenomena. The manuscript is streamlined toward the design decisions that have been made so far as well as the developmental activities that are ahead. All outputs will be released as open educational resources.**

***Index Terms*—virtual reality, quantum mechanics education, digital storytelling, gamification, women in STEM, Erasmus+**

I. Introduction

Quantum Mechanics (QM) underpins technologies that students encounter every day—from semiconductor devices to medical imaging and cryptography—but remains one of the most difficult subjects of the physics curriculum to teach [1]. Interestingly, the difficulty does not stem primarily from the mathematics. Students fail to develop accurate conceptual understanding even when the formalism is deliberately simplified [1]. The relevant phenomena take place at magnitudes that no sense can register, evolve faster than thought can follow, and behave in ways that clash with everything learners have come to expect from the macroscopic world [2]. The resulting alternative conceptions are well documented and tend to survive formal instruction [1], [3]. Immersive Virtual Reality (VR) has, for this reason, attracted considerable attention as a candidate medium for QM instruction. One of the greatest affordances of the medium is its capacity to make visible what is inherently invisible [4]. Nevertheless, the most comprehensive review of Extended Reality applications in quantum education to date concluded that the field is dominated by design-and-development work with little pedagogical grounding and scarce empirical evaluation [5]. The risk is not hypothetical. Adding immersion to a science simulation has been shown to increase presence while decreasing learning [6], an effect that content which already taxes working memory can only amplify. A second, equally persistent, problem concerns who studies quantum physics at all. Women account for roughly one third of researchers worldwide [7]. The share is lower still in Physics, Engineering and Computer Science, where masculine cultures, a weaker sense of belonging and the scarcity of visible role models continue to discourage participation [8]. The two problems are rarely addressed together. Instructional innovations in quantum education take little account of who is represented in them, whereas initiatives for women in STEM, stop short of the content of a quantum course. ExQuMe (Experiential Quantum Mechanic) responds to both. The project develops five story-driven immersive VR modules in which women pioneers of physics guide higher education students through core quantum phenomena and embeds them in a pedagogically grounded, gender-sensitive, educational framework. This paper provides an overview of the project and progress at the end of its first year.

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II. State of the Art

A. Learning Quantum Mechanics

Bouchée et al. [2] identified four sources of the abstractness that sets QM apart from other physics domains: (i) a formalism disconnected from physical experience, (ii) phenomena that contradict classical intuition, (iii) reasoning that is probabilistic where classical physics is deterministic, and (iv) everyday language that proves inadequate for quantum

concepts. The aforementioned sources manifest as coherent alternative frameworks, such as superposition understood as a particle being in two places at once or uncertainty attributed to the limitations of instruments, which students construct while trying to reconcile the formalism with classical intuition [1]. Telling students the right answer is therefore of little use on its own; instruction has to engage the conceptions they already hold. The review of Krijtenburg-Lewerissa et al. [3] documents how visualisation tools and interactive simulations have been used to this end in introductory (lower undergraduate) courses. Desktop simulations, however, cannot exploit spatial visualisation, embodied interaction or the transformation of scale and time, capabilities that only VR affords.

B. Immersive Virtual Reality in STEM and Physics Education

The Cognitive Affective Model of Immersive Learning (CAMIL) [9] explains how presence and agency—the principal psychological affordances of VR—influence learning through six affective and cognitive factors. In addition, it argues that the instructional method, as opposed to the medium itself, determines the outcome. A systematic review of comparative studies in higher education identified interactivity, as opposed to immersiveness, as the feature most closely associated with learning efficacy [10]. Our own experimental work points the same way: lower-fidelity environments with high task interactivity proved equally effective for learning in a VR escape room for biology [11]. Likewise, stereoscopic 360° VR improved motivation and confidence in secondary biology without a corresponding advantage in knowledge gains [12]. The available quantum prototypes visualise atomic orbitals, qubit representations or quantum optics set-ups but they are, however, almost exclusively design-led, focused on cognitive outcomes and built for a single user [5].

C. Narrative, Gamification and Representation

Two motivational ingredients complete the picture. Narrative gives abstract content a human context and a sequence of events that learners can follow and remember. Gamification adds the progression mechanics that sustain engagement across a learning sequence, although its benefits depend on design quality and remain unproven in many implementations [13]. On that note, representation matters too. Stout et al. [14] demonstrated that contact with female experts in STEM protects women's self-concept, attitudes and career intentions, which makes historical women scientists, whose contributions are routinely absent from textbooks, a natural choice of narrator for a quantum story.

III. The EXQUME Project

A. Objectives and Consortium

ExQuMe is a 30-month cooperation partnership (September 2025 to February 2028) coordinated by the University of Turku (FI), and partnered with the University of Central Lancashire Cyprus (CY), the University of Patras (GR), the University of Zagreb (HR), ESTIA (FR) and The Press Project (GR), an independent media organisation. The project pursues four objectives: (i) to enhance the conceptual understanding of QM through immersive VR storytelling; (ii) to raise engagement by turning intimidating content into captivating experiences; (iii) to provide memorable, personalised learning that supports retention; and (iv) to broaden access to quantum studies and encourage young women towards STEM careers. Collectively, the aforementioned objectives serve three Erasmus+ priorities: digital transformation, STEAM approaches that foster women's participation in STEM, and innovative learning and teaching practices.

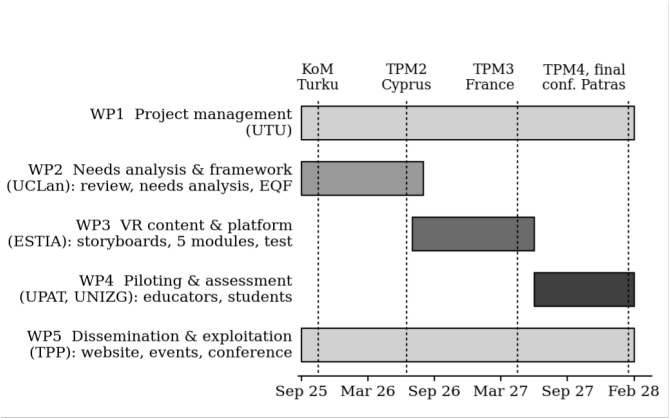


Fig. 1. Work plan of the ExQuMe project

B. Work Plan

The work is organised in five work packages (Fig. 1). WP1 (Uni Turku) provides governance, quality and risk management through monthly online meetings of the consortium and four transnational project meetings. WP2 (UCLan Cyprus) delivers the evidence base: a literature review, a student needs analysis across the partner institutions, the educational framework and a gender-inclusive educational strategy guide. WP3 (ESTIA) translates the framework into storyboards and scripts, develops the five VR modules and the hosting platform, and tests them with pilot users. WP4 (Patras and Zagreb) trains educators in workshops and pilots the modules with students across all partner countries with pre- and post-assessments of conceptual understanding, engagement and satisfaction measures. WP5 (The Press Project) runs dissemination and exploitation (website, newsletters, press releases). All educational outputs are released as Open Educational Resources.

C. Educational Framework

The Educational Framework delivered by WP2 rests on the principle of conceptual change through immersive experience. VR is treated as the pedagogical environment in which learners meet quantum phenomena and storytelling as the mechanism that gives those encounters meaning; the aim is conceptual accessibility, curiosity and cognitive openness, with no pretension to technical mastery. Each scenario follows the four-stage ExQuMe Learning Model. An introductory narrative scene, guided by a woman scientist who acts as narrator, mentor

and cognitive mediator, establishes the context and lowers intimidation. An experiment setup phase has learners construct the apparatus, manipulate variables, observe outcomes and test hypotheses, with guidance embedded in the interaction. The "AHA!" moment confronts classical intuition with the quantum interpretation through a classical–quantum switch that shows the same situation under both descriptions, so that the conflict between expectation and observation is experienced before it is explained. Daily-life analogy challenges and reflection close the cycle by transferring the insight to familiar situations. Gamification is conceived as a structured motivational scaffold within the sequence and a gender-inclusive strategy guide ensures that women scientists appear as protagonists of the story instead of footnotes to it. At the level of the individual scenario, the design draws on the Experiential Quantum Framework (EQF) [4], a domain-specific extension of CAMIL, developed within the project, which maps four VR affordances (presence, agency, embodiment and scale–time transformation) onto six documented learning challenges (inaccessibility, passivity, abstraction, imperceptibility, misconceptions and complexity) and derives six design principles: first-person immersion in the phenomenon (DP1), direct manipulation of quantum parameters with observable consequences (DP2), concepts mapped onto congruent bodily actions (DP3), smooth transitions of scale and time (DP4), visualisations designed against documented misconceptions (DP5) and generative reflection (DP6). Two of its paths carry a warning: (i) visualisation can remediate or reinforce misconceptions depending on design choices and (ii) immersion adds extraneous cognitive load to content that is already complex. The consortium translated the principles into a binding specification. Every scenario is built around one experiment, phenomenon or law of QM; opens in an everyday-life context and returns to it; addresses at least one documented misconception; serves learning objectives formulated with Bloom's taxonomy; contains at least three puzzles or challenges embedded in the narrative; runs for no more than 20 minutes (tutorial included); uses feedforward prompts in place of right-or-wrong scoring; and avoids unguided exploration.

D. Modules and Platform

Five single-player VR modules, each a self-contained scenario, one per academic partner and sequenced from fundamental concepts towards more advanced phenomena, cover the core content of an introductory QM course (Table I). The guide of each scenario is a woman scientist whose own work bears on its phenomenon covering the hydrogen spectra through which Payne-Gaposchkin showed what stars are made of, Goeppert Mayer's theory of two-photon absorption, the random decay that Curie measured, the radiation escaping nuclei that occupied Meitner, and the photon-pair correlations that Wu observed decades before entanglement became a resource. Each follows a common structure—a short tutorial that leads into the central hub from which the learner enters the narrated scenario and returns for feedforward and a summary screen. The scenarios are developed in Unity for the Meta Quest 3 headset in a low-polygon, semi-realistic visual style, in English in the first instance, with multilingual versions to be explored once the designs have stabilised. The experiences are hosted on a platform developed by ESTIA and complemented by a Moodle-based environment that carries the pre-VR preparation, the quizzes and the post-VR reflection tasks and lets educators follow student progress through Learning Analytics. The Universal Design principles apply throughout including subtitles and audio descriptions and adjustable settings. Training guides for educators accompany the modules so that institutions beyond the consortium can adopt them both during and after the completion of the project.

IV. Implementation to Date

A. The First Year

The consortium met for the kick-off in Turku in October 2025, launched the project website [15] and social media channels shortly afterwards, and has met online every month since. The substantive work of the first year belongs to WP2. A literature review of immersive VR in STEM, physics and quantum education found that instructional designs cluster around a few patterns, that evaluation rarely looks beyond cognitive outcomes, and that collaborative experiences are almost entirely missing; its recommendations—among them the multi-dimensional evaluation of cognitive, affective and behavioural outcomes—shaped the framework. A cross-national needs analysis then gave students from the partner countries a voice that the developer-driven literature had ignored. The qualitative findings [16] show that students want quantum content anchored in applications they recognise, explained through concrete examples, and rendered visible and manipulable in immersive settings. Interpretable differences emerged across countries and between female and male students. Three design priorities were derived: interactivity before visual immersion, application before abstraction, and adaptation to curricular tradition before context-blind design. The EQF was formalised and published [4] after the second transnational meeting in June 2026. The same meeting opened WP3 with ESTIA elaborating on the technical architecture and the expected structure of the modules.

B. Design Considerations and Usage Recommendations

Several considerations now govern the development. The first concerns session length and comfort. Students benefit from longer VR sessions but certain outcomes decline after about 45 minutes with individual variance being large [17]. In view of this note, the consortium capped each scenario at a maximum of 20 minutes of active interaction. The second is the immersion paradox. Interface navigation is automated through a short pre-training phase so that working memory stays available for the quantum content. To further facilitate the process, every module closes with reflection prompts and peer explanation tasks in the Moodle environment. The third concerns scientific accuracy against narrative license. A guide may personalise the story but every visualisation is reviewed by the physicists of the consortium against the documented

TABLE I
QUANTUM PHYSICS EDUCATIONAL SCENARIOS AND PROJECT PARTNERS

Scenario	Concepts	Guiding Question	Guide	Partner
Inside the Atom	atomic structure, energy levels, orbitals	What does an atom look like?	Cecilia Payne - Gaposchkin	UCLan
The Nature of Light	photons, wave–particle duality	What is light?	Maria Goeppert Mayer	ESTIA, UCLan
The Quantum State	probability, measurement, quantum states	What does probability mean?	Marie Curie	Uni Turku
When Walls Are Not Walls	tunnelling, energy barriers, probability	How can particles cross barriers?	Lise Meitner	Uni Zagreb
Thinking Like a Quantum Computer	qubits, superposition	How can information behave quantum mechanically?	Chien-Shiung Wu	Uni Patras

misconceptions since a loose visualisation, once perceived as fact, resists correction more stubbornly than one acquired from print [4]. The fourth concerns fidelity against learning wherein development effort goes into manipulable parameters and challenge-based progression instead of photorealistic laboratories, in line with the first design priority of the needs analysis [16]. The last concerns localisation. Developing the scenarios in English first allows a single validated version to be piloted in all five countries with translations to follow where the pilots show a need. Beyond language, the needs analysis argues for switchable curricular presets, formalism-heavy, application-heavy and discovery-oriented, so that one environment can serve cohorts with different traditions [16].

V. NEXT STEPS AND CONCLUSIONS

Storyboards and scripts are due by November 2026, the educational content by January 2027 and the technical development by February 2027, with usability testing and the finalised platform ahead of the third transnational meeting (April 2027). WP4 then trains the educators in the summer of 2027 and pilots the scenarios with students in all five countries during the autumn. The multiplier events and the final conference close the project in February 2028, making the scenarios, the framework and the guides freely available. In conclusion, ExQuMe brings together a pedagogically grounded design framework, evidence on what students themselves expect from immersive quantum learning, and a narrative device that places women scientists at the centre of the quantum story. The first year has delivered the evidence base on which the scenarios are now being built. Whether the propositions of the framework hold when students put on the headset is the question that the remaining months are designed to answer.

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