Introducing Quantum Mechanics through light polarization: Experiences in Hungary

Kristóf TÓTH
Eötvös Loránd University, Physics Education PhD Programme, Budapest, Hungary
Czuczor Gergely Benedictine Secondary School and College, Győr, Hungary

Abstract. In the 2019/20 school year I directed a teaching unit on quantum mechanics based on light polarization which enriched me with several experiences. Sometimes I faced problems because the obligatory Hungarian curriculum based on the wave nature of particles does not fit perfectly with the polarization approach of quantum physics. Nevertheless, I presented the polarization approach to my physics teacher colleagues too. Then I recognized some of the difficulties of Hungarian physics teachers in relation to this approach because they used to apply the wave approach. Thus, teacher training programs should include the foundations of different approaches on equal footing, and in my opinion, teacher education should also respond to secondary school opportunities. In this article, I summarize the problems that may arise in applying the polarization approach in countries where wave formalism has a great tradition, like in Hungary. I also show why I personally prefer a 2-state approach in secondary school instead of the traditional wave formalism, and present what I have learned as a teacher. I highlight some of the requirements that arise when we intend to use polarization approach in physics teacher training programs, and I make suggestions for teacher education too.

1. Introduction
Introducing quantum mechanics (QM) in school is possible using several approaches as there are many formalisms of QM [1]. The most common ones are wave formalism [2-4], historical framework or a reconstruction of crucial experiments proposing a descriptive path toward the old theory of quanta [5], qualitative discussion of the main concepts of QM [6-8] and a basic vectorial formalism according to polarization approach [9-12]. Dirac was the first to apply polarization to introduce QM [13], which, with high level methodological renewals, is becoming more and more widespread in secondary schools. Today all European high school students become acquainted with elements of QM [14-15] not only because its cultural value [16]. However, existence of several approaches means that the structure of teacher education curricula can vary from country to country. If the wave mechanics has cultural tradition in QM, but we would like to apply the polarization approach, we should highlight the points of connection, build bridges between the two points of view, specify the preferences and disadvantages, because sometimes prior knowledge of people build an obstacle. This paper intends to describe these aspects on the example of Hungary, points out some problematic nodes, by also offering some proposals in teaching / learning QM at different levels.

2. The situation in Hungary regarding QM
While the traditional Hungarian way of teaching QM is the wave formalism [4,17-18], the applied school books [8] contain only qualitative interpretations of the phenomena because previous Hungarian experiences demonstrated that a more detailed wave formalism is too abstract for secondary school students and also for teachers. Furthermore, in the applied schoolbooks some phenomena are misinterpreted from a quantum perspective due to the loose treatment (e.g. of the uncertainty principle) in secondary school books. In addition, only a few experiments (mostly animations) are mentioned, but
many concepts are nonintuitive to communicate in just a single sentence (e.g. the probabilistic interpretation). Analogies are used to understand the wave function (or rather just the matter wave). Hence trainee physics teachers may have misconceptions about QM.

Traditional wave formalism is taught in teacher education at Hungarian universities [17]. We follow the historical development, the students get acquainted with the problem of quantization of light, and then through the wave-particle duality of light and electron we build out the formalism with wave function. One of the central themes is the hydrogen atom, and there is a strong connection with chemistry. The QM course is typically a 1.5 hours lecture per week, augmented with an equally long problem solving session. The key points of the syllabus are the following (not in chronological order) [18]:

2. Basic early concepts: Planck hypothesis, the Bohr model, de Broglie hypothesis.
3. Physical quantities as operators, commutators.
4. The stationary Schrödinger equation.
5. Rectangular potential wells, the harmonic oscillator, its spectrum and eigenfunctions.
6. Angular momentum, spin, Hydrogen atom, quantum numbers, the periodic table.
7. General quantum states, the time-dependent Schrödinger equation.
8. The free particle, wave properties, group velocity, uncertainty relation (ΔxΔp_x ≥ ℏ/2).
9. Probabilistic interpretation, averages, the generalized uncertainty relation.
11. Pauli’s principle, Helium atom, chemical bonds.
12. Perturbation theory, the variational approach.

3. Main features of different approaches
According to international experiences [19-20], if we intend to introduce the formalism, superposition principle and the concept of mixed states in secondary school, it is worth simplifying the scope of problems by narrowing it down to two-dimensional real quantum states. In this case we use mathematical relations with vectors already learned by students. However, we should not forget that we have to choose phenomena that allow self-experimentation. We can conclude that the linear polarization of light meets these requirements. [21] These arguments led me to decide to teach with the worksheets of the Physics Education Research Unit, Udine [22-23] in a secondary school.

The polarization of light allows us to discuss QM first qualitatively, then quantitatively. The qualitative part demands optical experiments (polaroids, birefringent calcite crystals) [24-25], which is useful because the Hungarian curriculum takes optics before modern physics. Hence, I made with my fellow researchers a teaching experiment as a pilot project because we were curious about how Hungarian students accept the teaching material and whether there is a chance for a later implementation of the curriculum in Hungary. We also investigated the difficulties of students (for more detail see [26]). In addition, I created a webpage for online teaching [27] where secondary school teachers and students can join to discover the quantum world using the materials of the University of Udine [21-22, 28]. I made conversations with colleagues and collected data from my website too, then investigated the problematic points appearing in the Hungarian context (see later).

Another option for introducing QM is based on the wave formalism which can be very illustrative and can be simplified to a qualitative level that narrates the wave-particle duality while this approach also connected with historical events. The aim of the wave formalism approach is to understand the atomic structure, so there is a strong connection with chemistry (atomic structure, chemical bond) which can be beneficial in an interdisciplinary perspective. By applying this structure of teaching / learning QM, tunnelling becomes an interpretable principle of quantum phenomena, so students are able to understand nuclear structure, and gain some solid-state physics knowledge. In teaching / learning we focus on eigenstates instead of dealing with mixed states.

However, the polarization approach based on a two-dimensional vector space is more comprehensible than the infinite dimensional wave function in a mathematical perspective. In the polarization approach, the superposition principle is mapped to a well-known problem in math, while its analogue in wave approach, the Fourier transform, although rigorous, along with many other calculations, becomes unmanageable in secondary school. Therefore, the polarization approach is better
suited to a basic understanding of the formalism and the approach also supports the superposition principle. All in all, understanding the formalism gives a better chance to understand the interpretations of quantum phenomena, and assists the concepts of QM [29]. There is interdisciplinarity in polarization approach too because quantum computation is an innovative field in nowadays science and the photon spin is a natural qubit candidate. So, there are points of connection with IT that can be significant for quantum engineers and computer scientists. [30] However, if we do not develop a bridge toward the other approaches, we will have to give up discussing certain points of QM (nuclear structure, chemical bonds, periodic table etc.) because we narrow the state space to two-dimensional and real.

Figure 1. The QM website I created can be seen [27]. On the top left we can see a picture from the website with title: “Modern physics for secondary school student. Introduction to quantum computation”. Then on the top right we can see a screenshot from a video about optical experiments (birefringent calcites crystal) and we can also see the semantic illustration of the calcites on the bottom left: “calcite crystals can slit in two the incident beam. The first beam is called ordinary beam and the other one is called extraordinary beam. We saw from previous videos that the two passing beams have mutually exclusive properties (for example vertically polarized (property $\Delta$) light and horizontally polarized (property *) light.” Finally, we can see a task about trajectory on the bottom right. The task ask that “if we cover the detector $D_o$, the detector $D_e$ goes off (finding a photon): for each incident photon / on average only in 50% of cases, by chance / alternatively i.e. yes for one photon and no for the next / for no incident photons.”

4. Quantum mechanical problems which can emerge in physics teacher training program
While presenting the polarization approach of QM to my teacher colleagues I become acquainted with their opinion from the conversations. I came to the conclusion that if we want to talk about polarization approach in teacher training program, we have to connect the different approaches. Most Hungarian physics teachers do not face QM after graduating from university only in the secondary school curriculum and popular science. This means that they have forgotten the general formalism of QM, but they have strong ideas about quantum phenomena. They mostly use interpretations from popular sciences and from the arguments of schoolbooks (which are sometimes wrong), and my experience is that they mention wave approach at semi-qualitative level in their argumentations. Therefore, they may
have concepts that do not fit into polarization approach. I would like to show some problems that emerged in the conversations.

Problem #1: Physics teacher colleagues had difficulty with translating “physical property” from the photon polarization to wave approach.

Problem #2: Wave-particle duality implies that the nature of the experiment determines which of the two properties dominates. So, if we describe diffraction (or polarization), we have to imagine light as a wave, but if we describe photoelectric effect, we have to think that light is made up of particles. We cannot use the particle view when we describe diffraction (or polarization), nor can we use the interpretation of waves when describing the photoelectric effect. This is also confirmed by a final exam question [31], which is the following:

"Which of the following phenomena can be explained by the particle nature of light?"
A) Diffraction.
B) Polarization.
C) Photoelectric effect."

The official solution is the answer “C”, so the task implies that we cannot analyse polarization in terms of photons like Dirac’s polarization approach.

Problem #3: The uncertainty relation is strongly connected with the image of wave packet. If we know the location of an electron more accurately, the momentum will be more uncertain. These properties are complementary ones. This interpretation is not in agreement with the case of photon polarization because there are no complementary properties in this approach, but are incompatible ones.

Problem #4: One of the schoolbooks describes the uncertainty principle with a wrong interpretation, which I also heard from a colleague: “If we want to know the position of an electron, we have to use microscope. But the electron is small, so we have to use light with small wavelength, that is, photons also have a high frequency and energy. So, the photon collides with the electron, which changes the momentum of the electron. In conclusion the measurement of position negatively effects the knowledge of the momentum”. [8] This description of the uncertainty principle does not allow to understand diffraction or interference where there is no microscope in use. Furthermore, the interpretation uses the logic of classical mechanics, where electrons and photons are objects with well-defined position and velocity, so their state is a point of state space.

Problem #5: A colleague asked me “what is the connection between the wave and the vector formalism? Can I describe wave phenomena with vector formalism too?” This remark can encourage us to connect the different formalisms that take different paths.

5. What are my personal experiences?
As a Hungarian physics teacher, I also went through the way: from the wave formalism to the polarization approach and gained a lot of experiences. My teaching experience also shows that both me and the students enjoyed the polarization approach syllabus [26]. From a pedagogical point of view, I learned how important the meaning of physical property [16, 32] is, which is an unused term in Hungary as mentioned above. Understanding can be a bridge between phenomenology and formalism. Furthermore, before participating in this teaching experiment, I was unaware of the educational potential of light polarization. In addition, my personal preference is polarization to explain quantum effects instead of waves because I like to think about the underlying formalism, and two-dimensional vectors are the simplest. Furthermore, I become more open to quantum informatics, which can be part of my secondary school lessons at a popular science level. I have meet three categories of thinking about QM often appearing in students reasoning as well [29]. Discussing these categories will also help teachers recognising misconceptions about quantum world, perhaps even in their own interpretation:

- The first one is the classical way of thinking. This reflects that “microscopic systems have an analogous nature to classic macroscopic systems. All their observables always own well defined values. In order to describe their evolution, the concept of trajectory can be used, even if it is necessary to use a statistical approach because of a lack of information about the initial state of the system under observation”. [29] In section 4 we provided an example of this way of thinking in problem #4 (uncertainty relation).

- The second one is the hidden variables way of thinking. This is based on that “microscopic systems preserve some properties of the classic macroscopic systems, in particular the
trajectory even if it is not detectable. Their non-classical behaviour is due to uncontrollable disturbances, or rather to some properties that are not directly accessible”. [29]

- The last one is the quantum mechanical way of thinking. Our goal is make students think that way. “Classic and quantum systems are of different nature. It is possible to associate dynamical properties to quantum systems only by means of measurements. These properties are in general incompatible with those that characterize the state before the measurement itself. Position, velocity and trajectory lose their meaning. The process of measurement can be described only as a transition between an initial and a final state“. [29]

6. Conclusions and suggestions
I presented some of the difficulties that can arise when teachers learn different approaches of QM than they are used to. I supplemented these with some experiences of professional conversations and my personal experiences. This assessment suggests that the polarization approach should be extended by discussing possible connection points with wave mechanics in teacher training programs, otherwise teachers may gain incoherent knowledge about QM. If we would like to introduce the polarization approach in teacher training programs, the following points should certainly be discussed in countries like Hungary:

- Problems #2-5 mentioned in section 4 show that we should connect the qualitative wave-particle duality with polarization approach, and we should connect the image of electromagnetic waves and photons (to better understand the polarization process). Typical wave phenomena (diffraction, interference) should also be interpreted by vector formalism and connect wave function with state vector.
- Problems #1-2-3 show that the term “physical property” should be translated in the language of the wave formalism too.
- Problems #2-3-4 show that we should find connection points between polarization and wave packet interpretation of the uncertainty principle or call otherwise. Presenting the three typical ways of thinking about QM would also help the learning / teaching process.

Therefore, it may be worthwhile to bring up different approaches in some places.

In teacher education the experience is that teacher students have a good understanding of quantum mechanics, but they still feel that pedagogical knowledge is poor [33]. Therefore, it is worth to install some two state system tasks in teacher education too. These can be incorporated into the scheme mentioned in section 2 by discarding point 12, replacing point 10 with a specific one concentrating on the 2-state view, and replacing some of the basic experiments and basic concepts by polarization-related ones. In the lectures, we can also pay more attention to the typical preconceptions about QM and highlight aspects related to secondary school physics.

Finally, the requirements of Hungarian high school physics syllabus contain interpretations that are not explained by the polarization approach. If a physics teacher wants to teach this approach the requirements of final exam cannot be ignored. Some of these are interpretable with wave formalism but I think we have a hope to explain them with the vector formalism too at least on a qualitative level. These topics are diffraction, interference (double slit experiment), electron cloud, de Broglie wavelength, uncertainty relation (\(\Delta x \Delta p_x \geq \hbar / 2\)), quantum numbers, electron spin, Pauli exclusion principle, Hund’s rule. However, this paper does not intend to solve these problems, it only intends to formulate a research goal, so a study group based on photon polarization should be organized as conveniently and smoothly as possible in secondary schools such as the Hungarian ones.

7. Acknowledgements
I am truly grateful for M. Michelini, A. Stefanel and the other members of the Research Unit of Udine for presenting their materials on QM. I would also like to thank G. Cynolter and T. Tél for their useful suggestions. This study was funded by the Content Pedagogy Research Program of the Hungarian Academy of Sciences.

8. References


[28] Michelini, M and Stefanel A 2004 Fisica Quantistica, una proposta per la didattica. Università di Udine, Litho Stampa (In Italian)


