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UNDERSTANDING THE PHOTON CONCEPT AND THE QUANTUM NATURE OF LIGHT: A CASE STUDY OF LEARNING DURING AN INSTRUCTIONAL UNIT DESIGNED FOR STUDENT TEACHERS

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Abstract. *Many teachers in upper secondary school find that teaching about the quantum nature of light and the photon concept is a demanding and difficult task, and that the university level instruction gives little if any support to overcome these difficulties. An instructional unit, which uses classical analogies in supporting the formation of new concepts and ideas, has been developed in order to help student teachers to acquire better qualitative understanding about the quantum nature of light and the photon concept. It is shown, that by using this approach, good learning results are obtained and student teachers develop physically sound conceptions of the quantum nature of light and the photon concept.*

Key words: *modern physics, teacher education, history of physics.*

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Introduction

Learning about the quantum nature of light and the photon concept in introductory courses of quantum physics is notoriously difficult for most students. It is well known that learning results and resulting conceptual understanding are often very poor. This seems to be the situation equally well in upper secondary level instruction (Fischler and Lichtfeldt, 1992; Muller and Wiesner, 2001) and university level instruction (Johnston et al., 1998; Greca and Freire, 2003; Mannila et al., 2002). One problem is clearly the order of instruction, where quantum nature of light is the opening topic of introductory quantum physics. In an attempt to improve the learning results, the basic question is how *university level teaching* should approach the topic of the quantum nature of radiation and the photon concept, so that it provides a suitable background for teachers to teach the topic at school level.

To the problems of learning about the quantum nature of radiation and the photon concept, several practical solutions have been proposed. For example, Müller and Wiesner (2001) have developed an approach, where quantum phenomena and the quantum nature of light are addressed in terms of statistical interpretation. Another promising approach by Greca and Freire (2003) emphasises the phenomenological basis of quantum physics and pays attention to quantum states instead of quantum objects. Both groups have reported improved learning results. However, there is still need to address the problems of learning about the quantum nature of light and the photon concept by using the more traditional approaches and accepting the traditional contents of instruction. The question is of particular importance in teacher education, because teachers need to make use of already learned classical physics as a starting point for learning. Towards this goal, the history of physics and its conceptual analysis opens up a rewarding viewpoint. In this report, we propose an instructional unit for student teachers, which draws insight from physics history and which is designed to support qualitative understanding of the quantum nature of light and the photon concept. We give evidence that student teachers' conceptualisation process can be helped greatly and the learning results improved by paying proper attention to the continuity of concept formation process and to the physically correct use of classical analogies throughout learning.

The contents of the instructional unit

We have developed an instructional unit for student teachers (third year students), which is based on the well-known historical discoveries (e.g. black body radiation, photoelectric effect and Compton's effect) originating from the old quantum theory of radiation fields during 1900-1926 (Jammer, 1974). In the instructional unit, these discoveries are reinterpreted from the point of view of modern conceptions, in particular without using the idea of light-quanta (Kidd et al., 1989). The unit is designed specifically for physics teachers, and it focuses on the qualitative and phenomenological aspects of quantum physics, needed in introductory high school level teaching. The unit consists of 7 weeks of lectures (2 weeks on present topic); each week two 90 min. lectures and one 90 min exercise session (4 on present topics). In the following, we describe briefly the content of the unit.

Quantization of energy and energy quanta

1. Molecular specific heats (MSH) of diatomic gases provide the first experimental evidence of the limitations of classical principles in interaction processes where energy is exchanged. The discontinuous, step-wise increase of specific heats with increasing temperature, known already in late 19th century, was a clear sign of the breakdown of the classical principle of equipartition of energy (EE) between degrees of freedom of motion (Pais 1982). Consequently, the specific heat problem in the case of molecular hydrogen is used to invoke an idea of non-classical restrictions on the energy exchange process. In the context of this problem, students are introduced to use the concept of degrees of freedom (DoF) in their reasoning

2. Black body radiation (BBR) is the next example, which is used to generalise the idea of non-classical restriction on energy exchange process. The history of BBR is introduced briefly in the instructional unit; the regularities (Kirchhoff's and Wien's laws) contained in it are pointed out as well as Planck's initial role in deriving the spectral energy distribution in agreement with experimental results. The non-classical features of the spectral energy distribution are discussed. This requires that the predictions based on the equipartition of energy between DoF are shown to contradict the observed behaviour (the well-known UV catastrophe). Students are then invited to discuss the problem again by using the constraining condition that $E=hf$ represents finite *energy quanta* exchanged between oscillators DoF. Guided by this *principle of quantized energy exchange* (QEE) it is relatively easy to understand qualitatively the behaviour of black body radiation spectrum (Pais, 1982).

The photoelectric effect is briefly discussed in the instructional unit after blackbody radiation, following the exposition of the topic as found e.g. in refs. (Kidd et al., 1989; Pais, 1982). The regularities contained in the photoelectric effect are explained by *extending the idea of quantized energy exchange to all events of absorption and emission of light in the interaction between radiation and matter*.

Quantization of energy and momentum

3. Compton's scattering (CS) discovered in 1922-1923 show that the shift in frequency (or wavelength) in scattered radiation of X-rays from light elements is an observation contradicting the expected classical conception of scattering. As a possible solution to the problem it can be assumed that in the scattering process a single light-quantum of energy hf and directed momentum hf/c collides (as a single entity) with a single electron (Stuewer, 1975; Jammer 1974). However, here, in order to explain Compton scattering, we invoke the idea of directed exchange of momentum associated with the emission and absorption process. In effect, the *principle of* QEE *is extended to hold for momentum also* (through relation $p=E/c$ holding for the classical electromagnetic field). This approach is adopted in the instructional unit, and the explanation of the Compton scattering is based on it. This view is closely related to the modern semi-classical conception of *the photon as a concept describing the quantum state of the radiation field* (Kidd et al., 1989; Pais, 1982). Moreover, the object of interest becomes then the quantum state (QS) and the extended principle of quantization QEE concerns events, where the quantum state changes. This view stresses the photon as a processual concept used to describe the changes in the state of the field.

Quantum nature of radiation and photons as field quanta

4. Double slit experiment with low intensity light illustrates the quantum nature of radiation as it is manifested in interaction with matter. First, the particle-like aspect or rather, the localisation of quantum events is revealed as isolated hits on the screen. Second, the fundamental role of the principle of linear superposition of quantum states is reflected by the gradual development of interference fringes in the double slit experiment (Paty, 1999; Jones, 1994). It is well known that this experiment yields two different interpretations, which give different status to photon; photons are understood either as particle-like field quanta or as quantized states of radiation field. These views are both contained in the picture of photons as field quanta, either in field-ontology or in particle-ontology. *Photons as quanta in field ontology* is a view, which connects photons with quantized states of the field, and they are thus non-localized or extended entities. On the other hand, the localization is a property of quantum events. This conception thus entails the fully dualistic view on photons. *Photons as quanta in particle-ontology* is a view, which takes photons (as field quanta in general) as particle-like entities, carrying energy and momentum. Moreover, *quanta of the field can be created or destroyed*. Energy and momentum (and polarisation) become then attributes defining the state of such quanta. Essentially, it means that *properties of field* (its quantized energy and momentum) *are identified with discrete substantial entities* (photons) (Jammer, 1974; Omnes, 1999; Home and Whitaker, 1992).

Learning goals of the instructional unit

The general learning goals of the present instructional unit can be seen first, in learning what is the empirical support of the photon concept itself, and second, how the construction of these concepts takes place by using the empirical support. In order to achieve these learning goals students should become familiar in thinking in terms of the *system's internal states*, which for classical systems are degrees of freedom of motion or field (DoF), and for quantum systems, they are quantum states (QS). Students should also learn to reason in terms of generic interaction processes without the support of Newtonian mechanistic or causal models. In particular, students must understand the principle of *probabilistic* or *statistical determination*; probabilities of changes in QS are determined, although single outcomes of the interactions events are not (Home and Whitaker, 1992). These analogies between classical and quantum systems, given in Table 1, are called *systemic,* when they are related to systems' internal states and *processual* when they are related to processes.

Table 1. The systemic and processual analogies as used in the design of the instructional unit.

Analogy	***Classical***	***Quantum***
Systemic	*Degrees of freedom (DoF).*	*Quantum states (QS).*
Processual	*Localization of particles,*	*Localization of events.*
	Non-localization of fields	*Non-localization of QS.*
	Linear superposition of fields	*Linear superposition of QS.*
Determination	*Causal determination*	*Statistical determination*

Methodology of Research

The learning results during the instructional unit are evaluated by focusing on students' understanding of the quantum nature of light, and in particular, how they construct the photon concept. The specific research questions are:

1. What are the conceptions of the photon expressed by student teachers?
2. How do the conceptions change during the instructional unit?

In order to answer these questions data was gathered from students responses on qualitative problems in four tasks 1-4 introduced in the section 2. The problems were designed so that an ascending level of abstraction and sophistication in use of the concepts and associated principles was required. The problem solving tasks contained typically six to ten conceptual questions related to the task (details of the problems are available from authors). The research data was partly in written form, partly in drawings in the form of concept maps. In analysing the students' responses, we use interpretative analysis, categorize students' replies according to their similarities and differences, and finally compare them with the physical content of the tasks. We then formulate the main categories students used in their explanations. Based on the categories, we construct the classes of responses, which can be used to classify students' responses, and on the level of details of interest here. The classification is done first for tasks 1-3 connected with quantization and formation of a precursor of the photon concept. The fourth task is for the completion of learning process of the photon concept.

Results of Research

The analysis of student responses to tasks 1-3 give 4 *systemic categories* (denoted by S) and 4 *processual categories* (denoted by P), described in more detail in Table 2. In addition to these categories, there are also three central *principles:* equipartition of energy **(**EE) and quantized energy (and momentum) exchange (QEE) between DoF, and the principle of linear superposition (LS).

Table 2. The structural (S) and processual (P) categories from students' explanations in tasks 1-3.

Task	**Category**	**Description**
MSH	***S-DoF***	*Degrees of freedom: Motion of molecules, monochromatic components of field*
	S-Mol	*Molecules and mechanical and thermal motion of molecules.*
	P-Mech	*Mechanical microscopic events, usually elastic collisions.*
	P-Int	*Generic interaction between DoF. Energy is exchanged in amounts of hf.*
BBR	***P-Dipole***	*Classical model of oscillating and radiating dipole. Emission and absorption process.*
	S-Wave	*Standing electromagnetic waves treated as storages of energy. Not connected to DoF.*
CS	***P-Scat***	*Microscopic model for classical scattering.*
	P-Int(E)	*P-Int extended by combining energy and momentum exchange in quantized way.*

Tasks 1-2: Learning the quantization of energy. The purpose of tasks 1-2 was to make students familiar with systemic thinking by using DoF as system's internal states and by using the idea of interaction between them as a central generic process. Based on results contained in the classification in Table 3 the learning goal is reached in classes I and II. 14 students out of 19 (about 74 %) belong in these classes. These classes make use of the systemic and processual elements listed in Table 1 and students within them have developed good understanding of DoF, the energy exchange process between them and a physically sound idea of QEE in interaction. The major difference between classes I and II is that in II the structure of system and DoF as well as the generic interaction process are interpreted microscopically. Moreover, only in class II the principle of LS appears explicitly. In class III, explanations are severely deficient and even unphysical. Explanations concentrate on the question, how energy is stored as thermal motion. Mechanistic pictures and models are used extensively, and in case of BBR, light-quanta are used often.

Task 3: Quantization of linear momentum and precursors of photon concept. The task 3 introduces a context, which makes possible to understand that not only energy but also momentum is quantized in an interaction between radiation and matter. In the context of this task, physically sound precursors of the photon concept begin to emerge. Classes I and II (14 students, 74 % of all 19) again contain responses, where systemic and processual aspects dominate, while class II contains more microscopic models of interpretation (see Table 2 for details). In these classes extended version of generic interaction category P-Int(E) are developed. By using it, the idea of quantized energy exchange is augmented by introducing the quantized exchange of momentum and the principle of QEE becomes completed. The major difference is now that in Class I (7 students, 37 %) these notions are taken as justification to introduce the photon concept to describe quantized interaction event between radiation and matter. This kind of photon concept is called in the following the *process-photon* (P-photon). In Class II (8 students, 42 %) photons as quantum particles or *quantum-photons* (Q-photon) are introduced. However, it is understood that such photons are not ordinary particles, and they can for example be created and destroyed. Class III (4 students, 21 %) contains responses, where explanations are simply given in terms of classical-like corpuscular photons, simply treating the interaction as an elastic collision process. In this class, the photon is taken simply as a *light-particle* (L-particle) and radiation field as collection of light-particles.

Table 3. The interpretative categories discerned in case of two-slit experiment (task 4).

Key Notion	Description
1. Probability interpretation	*Probability has meaning for single physical system or for single events.*
2. Statistical interpretation	Probability refers only to the statistical ensemble of outcomes of the experiments.
3. Particle ontology (PO)	*Particles are basic entities and primary in ontology.*
4. Dualism in PO	*Dual aspect is incompatible with single entity (particle)*
5. Indeterminacy in PO	Indeterminacy principle refers to the properties of statistical ensemble.
6. Quantum State (QS)	*Object of interest is the quantum state of system. Process of interest (detection, measurement) is the change in quantum state.*
7. Field ontology FO	Fields form the basic ontology, they are substantial.
8. Quanta of fields	a. Quanta are secondary manifestations of the field, occupation numbers of QSs. b. Quanta are observed (created and destroyed) in events. c. Quanta are indistinguishable.
9. Dualism in FO	Wave-particle duality is an essential property of quanta and quantum events.
10. Indeterminacy in FO	The indeterminacy is the constraining principle governing single events.

The second stage of the analysis is to see whether or not the learning results obtained in tasks 1-3 are stable and context independent. Towards this purpose, we have chosen task 4, the double-slit experiment conducted with low intensity light (for details, see ref. 5), where the properties of the photon are addressed differently. The interpretative categories discerned from students' responses in task 4 are given in Table 4. The categories in Table 3 were then used in classifying students' responses in three different classes of description. The categories referred to are given in parenthesis.

CLASS I: Dualistic description (9 responses, 47%). In this class, photons are taken as non-localized or extended entities obeying the principle of LS (6, 7 and 9). In most responses, QS have a central role (6). The probability to detect events is understood to be determined by (deterministic) quantum mechanical principles (in some responses related to the probability field or wave-function) and statistical outcome of events is connected to the observed intensity distribution. Localisation is attributed to interaction events accompanied by changes in QS (transition in QS, measurement, or detection). Statistical determination and probability is assigned to these events (1, 6 and 8). Indeterminacy is understood as a conditional or constraining property for these events (10). In this class of responses, the probabilistic nature of single events (1) is meaningful and the principle of statistical determination is understood.

CLASS II: Statistical description (5 responses, 26%). In this class, the role of multiplicity of events or number of photons is considered important (2-4). Interference is understood as a consequence of repeated occurrence of hits. In all responses, there is a tendency to define how particle-like observations or measurements are made (2, 3), but particles are no more conceived classically. In this class, students' conceptions are rather similar to the "statistical interpretation of quantum mechanics" (2-5). Statistical determination and the deterministic probability field (unspecified) or wave function acquires a central role and is used to explain the wave- and particle-like properties of phenomenon. Linear superposition is associated with the underlying probability field or wave-function, not with the entities themselves.

CLASS III: Hybrid description (5 responses, 26%). In this class, photons are seen simply as objects having simultaneously properties of classical particles and waves, sometimes following trajectories. In these trajectory-based responses the conceptions of classical particles following certain trajectories form the dominant pattern of explanations. This class contains thus most of the characteristics of unphysical and untenable photon models documented in literature, usually referred as hybrid model of photon (Fischler and Lichtfeld, 1992; Johnston et al., 1998).

Answers to the research questions: learning the photon concept

The student teachers' understanding of the quantum nature of light and the photon concept can be now inferred from precursors of the photon concept (P-photon, Q-photon and L-particle) discerned in tasks 1-3, and on the other hand, descriptive classes (Dualistic, Statistical and Hybrid) in task 4. These results are summarised in Table 4, which shows the cross-tabulation of the results. We can now address research question 1 and conclude that students construct a physically sound conception of the photon either as a process based concept (P-photon, 7 students, 37% of all) or as a particle-like entity Q-photon (8 students, 42 %).

Table 4. **Relative fractions of photon conceptions discerned in tasks 1-3 (P-photon, Q-photon, L-particle) and descriptive classes in task 4 (Dualistic, Statistical and Classical). Number of students is given in parenthesis, total number of students is N=19.**

	Dualistic	Statistical	Hybrid	*Total*
P-Photon	32 % (6)	5 % (1)	-	37 % (7)
Q-Photon	16 % (3)	21 % (4)	5 % (1)	42 % (8)
L-particle	-	-	21 % (4)	21 % (4)
Total	47 % (9)	26 % (5)	26 % (5)	100% (19)

The research question 2 is answered by noting how the different classes are related to each other. The classes of P-photon and Q-photon are related to the following descriptive classes: Dualistic (9 students, 47 %) and Statistical (5 students, 26 %). With one exception, students in classes of P- and Q-photon are the same ones found also in classes Dualistic and Statistical. However, the P-photon is most often related to the class Dualistic (32 %), while Q-photon seems to be preferentially linked with Statistical (21 %). Students (4 students, 21 %) who did not manage to develop neither the P-photon nor the Q-photon picture but use instead a simple corpuscular picture were without exception unsuccessful in forming physically correct views of quantum entities and events in general. They are ultimately found in class of hybrid-descriptions.

Discussion and conclusions

Student teachers following the instructional unit described here developed quite successfully two physically correct views about the quantum nature of light and the photon concept. The first one is a dualistic picture (9 students, 47 % of all), based on conception of the photon as a non-localized entity. This is essentially the conception of the photon, which stresses its role as the quantum of field, and is consistent with semi-classical and field-ontology views. The second one stresses particle aspects of quanta (5 students, 26 % of all), seeing them as constituents of fields rather than their manifestations. These views are in concordance with the statistical interpretation of quantum physics and the particle-ontology based views on quantum fields. The physically acceptable views are combinations of the P- and Q-photon with classes Dualistic and Statistical. The good correlation in the distribution of students in the physically acceptable classes suggests that these students use the photon concept coherently, and that for their part learning result are stable. We thus conclude that 14 students out of 19 (about 73 %) reached acceptable learning results. In this group, the quantum nature of light also becomes understood on a qualitative level as required for successful introductory teaching. However, 5 students of 19 (about 26 %) remained stuck on the unphysical classical-like views and stayed with hybrid model of photon. For their part, instruction was clearly unsuccessful.

Table 5. The comparison of present learning results with results reported by Mannila et al. (2002) and by Greca and Freire [4]. The classification to classes I, II and III is as explained in the text. Note the re-grouping of results in case of Mannila et al. (2002).

		Class I (Dualistic)	Class II (Statistical)	Class III (Hybrid)	Unclass.
Present study		47 %	26 %	26 %	-
Mannila et al.	**A**	37 %	-	63 %	-
	B	17 %	29 %	58 %	-
Greca and Freire		65 %	18 %	17 %	

The present results can be compared with results of two similarly focused studies of quantum entities' properties. In a study by Mannila et al. (2002), two groups of students following traditional instruction on quantum physics were investigated; one group (A) aimed at a physics teacher's degree and the other one (B) a degree in physics. In that study, four categories of description for quantum entities were found. Two of the categories by Mannila et al. are essentially the classes I and II here, while two other ones are contained in our class III of hybrid conceptions. After re-grouping, each response in Mannila et al. belongs now only in one class, and there are no unclassified responses. The results after this re-grouping are compared in Table 5 with the present ones. It is seen that in the present case the relative fraction of students who achieved physically acceptable results (classes I and II) is significantly higher (73 %) than in groups A (37 %) and B (46

%) reported in ref. (Mannila et al., 2002). In a study by Greca and Freire (2003), students followed instruction, which emphasised phenomenological aspects of quantum physics and quantum states as central objects instead of quantum entities. Greca and Freire resolved categories, which they call quantum object nucleus (category I), incipient quantum object nucleus (II) and classical nucleus (III). The characteristics of categories I and II introduced by Greca and Freire overlap with our classes I and II so that combined results I+II can be compared. Similarly, their category III is essentially similar to class III here. In the case of Greca and Freire, 65 % of students belong to categories I+II, and 18 % to class III (17 % were unclassified). The results are comparable to ours (see Table 5), and also significantly better than in the case of traditional teaching.

In summary, we have described here an instructional unit for learning the quantum nature of light and the photon concept, designed for student teachers. The instructional unit stresses the continuous development of concepts, and learning proceeds by finding support from classical analogies based on the systems' internal states and on the role of generic interaction processes. We have shown here that the instructional unit helps to improve student teachers' qualitative understanding of the quantum nature of light and the photon concept. In practical teaching, an advantage of the suggested approach is that good results are achieved by using the traditional content of the instruction and there is no need for radical reformulations of the content itself.

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Резюме

ПОНИМАНИЕ КВАНТОВОЙ ПРИРОДЫ СВЕТА И ПОНЯТИЯ ФОТОНА: ОПЫТ ПИМЕНЕНИЯ УЧЕБНОГО МОДУЛЯ ДЛЯ СТУДЕНТОВ – БУДУЩИХ УЧИТЕЛЕЙ

Исмо Копонен, Матти Гейккинен

Многие учителя средней школы находят, что изучение квантовой природы света и понятия фотона представляется требовательной и сложной задачей, а университетское образование даёт мало или даже ничего для преодоления этих трудностей. Чтобы улучшить качественное понимание квантовой природы света и понятия фотона студентами – будущими учителями, нами разработан учебный модуль, в котором используются классические аналогии, помогающие формированию новых понятий и идей. Нами показывается, что применение такого подхода приводит к хорошим результатам обучения и студенты развивают физически содержательные представления о квантовой природе света и понятии фотона.

Ключевые слова: современная физика, образование учителей, история физики.

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