A new teaching concept on quantum physics in secondary schools

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Abstract

In this article, an approach to integrate contemporary quantum physics into secondary school teaching is presented. The Erlanger concept on quantum optics provides an experimental-based guideway to aspects of modern quantum physics. We avoid the traditional historical approach in order to overcome the lack of modern concepts of quantum physics. In an acceptance survey, initial empirical evidence for the acceptance of the developed explanatory approaches was evaluated.

Keywords: quantum optics, anticorrelation factor, single photons, acceptance survey

1. Introduction

Understanding quantum technologies requires learning about fundamental issues of quantum physics. Such topics from modern research on the quantum physics of light are not only taught in advanced courses, but experiments on complementarity or entanglement are also prepared at the undergraduate level. Thus, laboratories on quantum optics have been established, in order to highlight a modern picture of quantum physics [1–5].

The next logical step is to make experimental approaches accessible to secondary schools. But despite the existence of a huge number of teaching concepts on quantum physics, for example in [6–9], there is a lack of a modern perspective on quantum physics in high school physics. The analysis of quantum physics school curricula in fifteen countries shows that the curricula are mostly oriented to the historical development of quantum theory [10]. Topics such as the Franck–Hertz experiment or wave-particle duality prevail and little is said about contemporary terms and concepts.

We report on a new teaching concept on quantum physics for secondary schools (section 2). Starting with the preparation of single-photon states by coincidence measurement, the anticorrelation of quantum light at the beamsplitter is shown. Interactive screen experiments are the first choice to provide applicable insight into modern research in school [11, 12]. Thus, pupils acquire an improved understanding of modern concepts of quantum physics, which is connectable for
the mediation of quantum technologies. In an acceptance survey with high school pupils, initial empirical evidence for the acceptance of the developed explanatory approaches was evaluated (section 3).

2. Erlanger concept on quantum physics

The Erlanger concept on quantum physics is the result of iteration design and refinement based on several school trials. The focus of the approach presented here is on coincidence and correlation experiments. These experiments shown in our concept are built from the same components as contemporary research experiments [11].

The concept provides an experimental-based approach to quantum physics for the upper secondary school level. Here, quantum physics is formulated as an extension of classical optics by adding temporal references. Therefore, the theory of detecting non-classical light plays a central role [13]. We emphasize the quantum physical measurement process as well as technical aspects of the experiments, in order to avoid mechanistic ways of thinking and speaking that are known to promote learning barriers in quantum physics [14].

We lead pupils to the traits of quantum physics—as formulated by [15]—by discussing in detail ‘theory-driven experiments’. These are typical for quantum physics, since quantum phenomena are not shown in a comparable manner to phenomena known from classical physics, such as rainbows or boiling water. In other words, it is impossible to look at an experiment and conclude some quantum physical law. Therefore, we first deal with certain aspects of the quantum physics experiments with the pupils so that they can understand the experiment. Thus, our concept is divided in two central parts. In the first two lessons, the basics and technical aspects of the quantum optical experiments are dealt with, so that in lessons three and four the experimental results from single-photon experiments can be interpreted. The following four topics will be covered in one lesson each (90 min):

(a) detecting non-classical light
(b) preparation of single-photon states
(c) anti-correlation of quantum light at the beam-splitter cube
(d) single-photon interference.

This approach allows the emphasis on different aspects of the nature of science during the teaching sequence. For example, scientific knowledge is based on empirical evidence or science models serve as tools in the development of scientific theories or in explaining natural phenomena [16].

2.1. Detecting non-classical light

Single-photon detectors emit short electrical pulses upon illumination with the faintest light. According to a wide spread misconception, a pulse or ‘click’ stands for the absorption of a single photon, but this is not in agreement with the theory. A photo multiplier tube (PMT) or avalanche photo diode (APD) sends clicks, because engineers designed them to do so. There is nothing that would cause an APD to do anything other than click. Actually, both PMT and APD send more clicks when heated, and this has nothing to do with a single-quantum object either.

PMT and APD are binary detectors. The count rate of clicks is proportional to the intensity of light and the temporal distribution is random, or to be more precise, Poissonian. A random series of clicks is in agreement with illumination by a classical electromagnetic wave. For example, semiclassical theory correctly describes the thermal light or even dim laser light [17]. This underlines the fact that from individual counts of single-photon detectors, the existence of single photons cannot be deduced.

In the experiments provided by our concept, APDs are used to detect quantum light. Technical details concerning the functioning of the APDs are explained in a learning video.

In this explanatory video, the pupils are guided through the correspondence of an analogy step by step. A comparison to snow avalanches provides a simple picture of the underlying processes in the detection of (non-classical) light. This lays the foundation for an understanding of the preparation of quantum states.
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Table 1. Snow avalanche analogy to explain the functioning of APDs on a secondary school level.

| Avalanche photo diode | Snow avalanche |
|-----------------------|---------------|
| electrons at high electrical potential (metastable state) | snow at high gravitational potential (metastable state) |
| a small amount of energy entering the detector is sufficient to release electrons | a small mechanical disturbance is sufficient to release the snow masses |
| liberated charges release further charges | snow moving down the mountain takes more and more snow with it |
| dead time | time until snow has settled on the mountain again |
| dark count | spontaneous (minor) snow departure |

Figure 1. Extract from the explanatory video on the functioning of APD detectors. Functioning of the single-photon detectors is explained in analogy to a snow avalanche.

A key question of this section remains: which are sources of quantum light and how do you work with them under reproducible conditions?

Nonlinear optical crystals are frequently used to generate non-classical light in research [18]. We use spontaneous parametric downconversion (PDC) in beta barium borate (BBO). An incident photon with a wavelength of 405nm is converted into two photons at double wavelength of 810nm. Conservation of energy and momentum of the coupled light is fulfilled by non-collinear phase matching. The photon pair at 810nm is emitted on a cone with a 3° opening angle.

Another method to generate photon pairs is cascaded fluorescence from atoms, for example, Ca. Ca atoms are illuminated with two laser beams at \( \lambda = 406 \) and \( \lambda = 581 \) nm and emit two photons at \( \lambda_1 = 551 \) and \( \lambda_2 = 423 \) nm, respectively [19]. Due to the short lifetimes of both excited states, the two photons occur simultaneously on the time scale of the detectors. Since the quantum effects are only observed with single atoms, this method is technically challenging. It is easier to understand, however. We found that pupils like the model of cascaded fluorescence and easily accept the choice of the technically simple, but conceptually advanced PDC.

We learned from our pupils that when the non-locality of single photons is discussed later, many pupils note that the explanation of the PDC process has been somewhat questionable. This is a good result, as the picture of light consisting of several individual particles is obviously questioned by these pupils.

2.2. Preparation of single-photon states

The PDC process has an internal temporal symmetry, as discussed in the section above. This allows the expectation of photon pairs at the same time. This motivates the introduction of the coincidence method, which is a fundamental measurement technique, not only in quantum optics [20]. Coincident events define the preparation of single-photon states. The simultaneous detection of an event in both arms of the experiment (see figure 3) can be attributed to the parametric fluorescence in the BBO crystal, apart from random coincidences. The preparation leads to the detection of one of the PDC photons at the gate detector, while the other photon is available for single-photon experiments.
In the experimental set-up, the exits of a beamsplitter cube is in contradiction with any classical wave model of light. Any experiment with classical electromagnetic waves provides coincidences between the detectors at the reflecting and transmitting output of the beam splitter cube [29]. In the words of Grangier et al: ‘A single-photon can only be detected once!’ [29, p. 173]. The way we treat anticorrelation of quantum light in this concept is based on the article ‘Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences’ by Grangier, Roger and Aspect from 1986. It is worth reading this paper together with the pupils. The authors introduce the anticorrelation factor $\alpha$ [29]: $\alpha$ relates the probability of coincident events between the two outputs of a beam splitter to the probability of random coincidences. This means that in the classical case, one expects coincidences between the two outputs of the beamsplitter and thus $\alpha \geq 1$, while non-classical light is observed when $\alpha < 1$. Therefore, $\alpha$ gives a quantitative measurement to estimate the purity of single-photon states [30] and allows a boundary between classical and quantum light. In the case of our experimental set-up with a gate detector $B$ (see figure 4), $\alpha$ is defined by,

$$\alpha := \frac{N_{A_B} \cdot N_B}{N_{A_B} \cdot N_{A_B}}$$

where $N_B$ is the count rate at the gate detector Bob, $N_{A_B}$ is the rate of triple coincidences between Bob and the detectors at the transmitted ($A_T$) and reflected ($A_R$) output of the beamsplitter. Furthermore, $N_{A_B}$ and $N_{A_B}$ are the corresponding rates of the two-fold coincidences. The size $\alpha$ is embedded in the theory of optical correlations in quantum optics and is then designated as $g^2(0)$.

2.3. Anticorrelation of quantum light

After the first two lessons clarify technical and methodical issues, the next two lessons concern quantum effects. The first quantum effect that could be measured in a laboratory was antibunching [24]. In order to show antibunching, many educational experiments use correlation measurements at two channels of a beamsplitter, for example in [3, 25–27]. Antibunching shows up for quantum light, which is anticorrelated at the two exits of a beamsplitter cube. For experiments with heralded photons a three-detector measurement is used.

An anticorrelation between detections at both exits of a beamsplitter cube is in contradiction to the classical case, one expects coincidences between the two outputs of the beamsplitter and thus $\alpha \geq 1$, while non-classical light is observed when $\alpha < 1$. Therefore, $\alpha$ gives a quantitative measurement to estimate the purity of single-photon states [30] and allows a boundary between classical and quantum light. In the case of our experimental set-up with a gate detector $B$ (see figure 4), $\alpha$ is defined by,

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2.3.0.1. Example: In the experimental set-up from figure 4, we measured $\alpha = 0.04 \pm 0.003$. Thus, triple coincidences actually occur less frequently than expected. Only $\frac{1}{15}$ of the number of triple coincidences expected by random coincidences was measured.

The derivation of the anticorrelation factor with pupils is based on elementary probability theory, for example, stochastic independence of events. A kind of contradiction argument is pointed out with the pupils. If a photon was divisible,
triple coincidences would be the rule. In fact, the number of triple coincidences is less frequent than can be expected from random coincidences, which expresses $\alpha \ll 1$, for example, see the measurement reported above for comparison. Before we finally present the measurement of $\alpha$ in an interactive screen experiment showing the experimental set-up from figure 4 [11], pupils are asked to suggest convincing values for $\alpha$. This allows us to explicitly emphasize central aspects of the nature of science [31], for example, that scientific knowledge is based on empirical evidence or that scientists formulate hypotheses to test their theories. Thus, this experiment on anticorrelation of quantum light at a beamsplitter cube may promote the pupils’ development of ‘an understanding of the enterprise of science as a whole—the wondering, investigating, questioning, data collecting and analyzing’ [16]. The final physical interpretation is that the photon cannot be split at the beam splitter and quantum light shows anticorrelation.

2.4. Single-photon interference

Adding a Michelson interferometer to the experimental set-up in figure 4, one can observe single-photon interference. This experiment shows that the wave model remains valid, even in the case of quantum light, but that the idea of the photon as a localizable particle is invalid. This means that quantum objects cannot be permanently assigned the property 'location'.

3. Acceptance survey

Acceptance surveys are often used to evaluate teaching concepts in a stage of development [32]: Didactically developed explanatory approaches to certain topics are used in a combination of intervention and interview phases with individual pupils in order to investigate whether these are accepted by pupils [33]. Their results contribute to the further development of the concept [34].

3.1. Research questions

The main focus of this survey was placed on the elementarizations of quantum optical experiments presented in this paper (section 2). The research questions discussed here are:

- do the pupils accept the explanation of the basic functioning of single-photon detectors and are they able to paraphrase the given explanation in their own words?
- do the pupils accept the concept of coincidence and are they able to paraphrase the given explanation in their own words?
- do the pupils accept the explanation of the anticorrelation factor and are they able to paraphrase the given explanation in their own words?

3.2. Sample and procedure of the survey

An acceptance survey was carried out with $N = 13$ pupils from the 12th grade (7 male, 6 female);
Figure 3. Set-up of a coincidence experiment for the preparation of single-photon states. In the first chapter, the functioning of single-photon detectors is explained to the pupils, before in the next chapter the coincidence measurement is introduced. Conservation of momentum results in the emission of the photon pairs on a cone, which justifies the symmetrical alignment of the detectors. In our experiments, the APDs are placed at $3^\circ$ off the optical axis.

Each lasted about two hours. According to [35], acceptance surveys generally consist of four steps, which can be repeated cyclically within a survey.

Our acceptance survey included seven key ideas of the concept, especially the ones presented in section 2. None of the pupils had any previous knowledge of quantum optics. As an external criterion, the last two testimonial grades of the test pupils were noted and their average was calculated ($m = 2.04$, $SD = 1.03$).

3.3. Evaluation method

Both the survey of acceptance and paraphrasing were coded using an ordinally scaled category system [36]. This provides a topography across all key ideas (see tables in 3.2), which can be used to isolate those aspects of the concept that cause difficulties for pupils. The exact codings were based on a coding guide (see 3.3.1 and 3.3.2). To ensure the highest possible interrater reliability of the coding, all codings were re-encoded by an independent person using the same coding scheme (see sections 3.3.1 and 3.3.2). With a Cohens kappa of $\kappa = 0.87$, a high interrater reliability was shown.

3.3.1. Coding scheme for acceptance. The acceptance survey was evaluated based on three acceptance levels in accordance with [33, 37]. The acceptance levels are defined as follows:

- complete acceptance (coded with a numerical value of 0): the explanation is accepted by the pupils without restriction.
Figure 5. Overview of light models. In our concept, we see the quantum model of light as an extension, which is shown in experiments by adding temporal references. Therefore, coincidence measurements play an important role. Thus, with the example of light models, the role of models in science in general is emphasized [16].

Figure 6. Four steps of acceptance survey following Blumör [35]. In this study, the application phase was omitted due to the large number of new physical concepts.

- limited acceptance (coded with a numerical value of 0.5): the pupils only criticize individual aspects of the explanation.
- no acceptance (coded with numerical value 1.0): the pupils describe the central aspects of the explanation as incomprehensible.

3.3.2. Coding scheme for paraphrasing. During the paraphrasing phase, pupils express the explanations of the above-mentioned facts in their own words (see figure 6). Those aspects of the explanations that are transformed or omitted in the pupil’s paraphrase provide important insight into possible learning barriers of our concept.

As in the case of the acceptance survey, the paraphrasing of the pupils was encoded on a three-point scale, using the following categories:

- successful paraphrasing (coded with a numerical value of 0): complete paraphrase with correct use of technical terms.
- satisfactory paraphrasing (coded with a numerical value of 0.5): predominantly
Table 2. An overview of the results of the survey on acceptance (Akx stands for acceptance on key idea x). Ak3 is on single-photon detectors, Ak5 on coincidences and Ak7 on the $\alpha$ – factor.

| Code  | Ak1 | Ak2 | Ak3 | Ak4 | Ak5 | Ak6 | Ak7 |
|-------|-----|-----|-----|-----|-----|-----|-----|
| ANWO  | 0   | 0.5 | 0   | 0   | 0   | 1   | 0.5 |
| BARA  | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| BIST  | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| CLMA  | 0.5 | 0   | 0   | 0   | 0   | 0   | 0   |
| GESI  | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| MAHE  | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| PEPE  | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| SAKO  | 0   | 0   | 0   | 0   | 0.5 | 1   | 0.5 |
| SICH  | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| SOWO  | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| SUAM  | 0   | 0   | 0   | 0   | 0.5 | 0   | 0   |
| DAJE  | 0   | 0   | 0   | 0   | 0   | 0   | 0   |

Table 3. An overview of the results of the paraphrasing of the pupils (Px stands for acceptance on key idea x). P3 is on single-photon detectors, P5 on coincidences and P7 on the $\alpha$ – factor.

| Code  | P1 | P2 | P3 | P4 | P5 | P6 | P7 |
|-------|----|----|----|----|----|----|----|
| ANWO  | 0  | 0.5| 0  | 0  | 0  | 0  | 0  |
| BARA  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| BIST  | 0  | 0  | 0  | 0.5| 0  | 0  | 0  |
| CLMA  | 0  | 0  | 0  | 0  | 0.5| 0  | 0  |
| GESI  | 0.5| 0  | 0  | 0  | 0  | 0  | 0  |
| MAHE  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| PEPE  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| SAKO  | 0.5| 0  | 0  | 0  | 0  | 0  | 0  |
| SICH  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| SOWO  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| SUAM  | 0  | 0  | 0  | 0.5| 0  | 0  | 0  |
| DAJE  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |

3.4. Results

A correlation between the average degree of acceptance of the pupils and the external criterion ‘average grade in physics’ is shown by a correlation of $r = 0.55$ ($p = 0.026 < 0.05$).

More detailed information was provided by an overview of the pupils’ assessments of the paraphrasing of the various explanations. A correlation between the average quality of the pupils’ paraphrasing and the external criterion ‘physics average grade’ is shown by a correlation of $r = 0.63$ ($p = 0.01 < 0.05$).

The acceptance values for all chapters of the course are positive. The mean values for paraphrasing are slightly higher, but all average values are in the positive range. In the following section, we will only refer on the results concerning key ideas 3, 5 and 7 in order to clarify the research questions.

3.5. Discussion

3.5.0.1 Research question 1: The explanation of the single-photon detectors in analogy to the avalanche was rated very positively (Ak3-mean: 0.00). The aspect of dark count events was accepted by all respondents. The well-received explanations are not only shown by the low acceptance values, but by the high quality of the paraphrasing (P3-mean: 0.23), e.g.

SUAM: [...] And you just have to be careful that you remember that there is also a dark count rate, that something may be measured there even though nothing is detected at all.

In the context of the snow avalanche analogy, only the electrical potential caused difficulties for
the pupils, especially in paraphrasing. This finding matches previous research in physics education [38].

3.5.0.2. Research question 2: The explanations on the concept of coincidence and on the coincidence method were also fully accepted by 12 of the 13 pupils (AK5-mean: 0.04). In particular, the pupils highlighted the prepared worksheet with which they could independently discover the importance of coincidence measurements. The paraphrasing of the pupils was also of high quality (P5-mean: 0.15), e.g.

BARA: So coincidence means that two detectors measure an event at the same time. You basically need it to be able to say that it was really a photon now and not some random event. This means that if you carry out the experiment, you can use this coincidence measurement to filter out which measurement values have to be used.

3.5.0.3. Research Question 3: The derivation of the anticorrelation factor consistently leads to high acceptance among the pupils. The fact that the number of events corresponds to the number of events registered by the gate detector was problematic for two of the test pupils. As an implication for the revision of the teaching concept, the counting rates and their interpretation are first highlighted. For this purpose, a corresponding Section is set up on the intended worksheet. Nevertheless, the degree of acceptance of 0.08 (AK7-mean) indicates that a didactic reconstruction of the anticorrelation factor $\alpha$ can be successful. It is not surprising that the average value for the quality of paraphrasing in this section is slightly higher at 0.46 (P7-mean). The number of technical terms to be known for a complete paraphrasing is high and there have already been a lot of new concepts for the pupils. 77% of the pupils succeeded in paraphrasing at least satisfactorily and the value is still in the positive range, e.g.

PEPE: The assumption was that these detectors detect events independently of each other and that the probabilities are stochastically independent that an event occurs in A or B [...]. These were the basic considerations on which we then based this calculation and then we talked about the probabilities that an event would occur in any detector which always depends on the count rate in A [the trigger detector]. For example, the count rate in B is the count rate in A times a detection probability that an event will occur in B and the same for C [...]. We used probability equations to express the probability for triple coincidences [...] and received a fraction called $\alpha$. If $\alpha$ is not zero, then the counter of $\alpha$ is greater than zero. And if $\alpha$ equals zero, then the counter must also be zero. And that would mean that the $\alpha$ is zero and so there are no triple coincidences.

3.6. Limiting factors
The main factor limiting this study is the sample size. To date, no empirical findings exist on pupils’ ideas about quantum optics. Furthermore, the pupils’ associations that are awakened by the quantum optical experiments have not been researched before this investigation. Consequently, we could not include a transfer task as is common in acceptance surveys [35]. This will be the subject of future research on larger samples.

4. Conclusion
The Erlanger concept on quantum physics directly leads from modern quantum optics experiments to the characteristic traits of quantum physics. The results of an acceptance survey provide initial empirical evidence that the Erlanger concept can be carried out with high school pupils and show that the explanations developed can be fruitful. According to common sense, a teaching concept mainly based on a research paper is likely to be too advanced for high school pupils. The present investigation shows that this is no problem in the present case. The pupils can cope with central
concepts including coincidence counts and anti-correlation. Future work will include the learning effectiveness of the concept. A mixed-method design will be chosen in order to investigate learning growth and the pupils’ ideas about quantum physics, which are initiated by our concept.

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