# **Finnish pre-service physics teachers' opinions about core concepts of quantum optics:** Comparison to European multi-stakeholder perspective

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**Abstract:** Quantum optics, information and quantum technologies are today becoming increasingly important within European educational initiatives. Many recent roadmaps emphasize the urgency to include these topics as part of teacher education as well as part of secondary education. In Finland we also face the pressure to modernize the secondary level teaching of quantum related topics and familiarize the future teachers with topics of quantum optics, information and technology. Here, we report Finnish pre-service physics teachers' opinions about the importance of core concepts as they appeared in a recent course focusing on quantum optics and information. It is found that results align well with recent surveys based on European stakeholder's views. This we take as a sign of promising prospects for including many modern quantum optics and technology topics as part of Finnish teacher education, in level available for pre-service teachers, and through that, hopefully, to prepare ground to include similar topics also as part of future secondary level curriculum in Finland.

**Keywords:** quantum optics, 21st century skills, quantum information, STEM

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## 1 Introduction

Rapid advancement of quantum technologies and quantum computing and their expected societal and economic impacts (Riedel et al., 2019) have prompted urgent need to renew quantum physics education in secondary level of teaching and, consequently, in physics teacher education (Krijtenburg-Lewerissa et al., 2017, 2019; Nita et al., 2023; Seskir et al., 2024; Stadermann et al., 2019). The foreseen demand of ”quantum workforce” for new quantum technologies (Aiello et al., 2021; Greinert et al., 2023) is today a pressing issue in European countries and to meet the foreseen needs is an educational challenge the teacher education should respond.

Several surveys have charted opinions of teachers, experts, and stakeholders from technology industry to find out views about core topics and key concepts that should be included in secondary level teaching of physics. Many of them mention key topics, key concepts and themes that focus on modern quantum optics, information and computation which are in the core of the ”second quantum revolution” and modern quantum technologies (Gerke et al., 2022; Krijtenburg-Lewerissa et al., 2019; Merzel et al., 2024; Seskir et al., 2024). Although there is no complete consensus, it is nevertheless by now possible to identify a rather extensive set of about 30-40 most important core concepts and topics (Mayer et al., 2024; Merzel et al. 2024)

In European countries, in particular in Germany, curricula of upper secondary level physics education have responded on the ”quantum workforce” demands and included some of the key concepts and topics that have been identified to be of most importance (Stadermann et al., 2019). In comparison to European initiatives on secondary level education the progress has been very slow in Finland. The role of modern quantum physics, with focus on topics that are noted to be relevant is still very low in Finnish secondary level teaching and curriculum. The approach to fundamental issues and core topics as recognized in existing surveys – in breadth and depth they are included in curriculum at all – is still driven by historical views and order of introduction of topics. This situation has also reflected on physics teacher education, where the role of modern quantum physics, quantum optics and technology has been low or even non-existent.

To improve the situation, we have in University of Helsinki, Faculty of Science, designed a new (obligatory) course for pre-service physics teachers, targeting at better familiarity with modern quantum optics, quantum information and technology. The motivation is to keep up with European developments and hope that with increased awareness, pre-service teachers in Finnish secondary education are more equipped for similar development as in leading European countries.

In this study, we briefly describe the content and goals of the course and report feedback collected from pre-service teachers, providing information about their attitudes towards presented themes and topics. The results of the survey are compared with recent reports about the opinions of teachers, experts, and other stakeholders (i.e. the survey about multi-stakeholder views). To facilitate the comparison, we have used the classification of key concepts and topics paralleling a categorization in recent extensive study by Merzel et al. (2024) as augmented with concepts included in study focusing on quantum information science (Mayer et al., 2024). These recent studies cover well the collection of most important key concepts and topics included in several previous surveys.

## 2 Methods and materials

A course focusing on modern quantum optics and quantum technology (computing and cryptography) was arranged for 25 pre-service physics teachers in spring 2024, in the Department of Physics, University of Helsinki. The course was obligatory and meant to meet the shortcoming that pre-service teachers have had no courses that introduce even the rudiments of modern quantum optics and technology based on it. The course was of seven weeks duration (4 ECTS) and consisted of eight 2-hour lectures, two laboratory sessions and of a visit to quantum computer in VTT Technical Research Centre of Finland (for more details, see Table 1).

During the course, after each lecture, feedback was collected to identify, which topics pre-service teachers thought of importance for their learning or of which they wanted to know more (taken to indicate positive attitude) and which topics they felt too difficult to be useful for their learning or alternatively, uninteresting (taken as negative attitude). The research question posed is: How do the pre-service teachers' positive and negative attitudes of the topics in the course compare with the key concepts and items as they are recognized in recent surveys of multi-stakeholders' views?

### 2.1 Description of the course and its key-topics

The course consisted of eight lectures, which focused on key topics, most of them as they are identified also in recent surveys (Merzel et al., 2024; Mayer et al., 2024). The selection of topics was informed by surveys available at the time the course was planned 2023–2024 but, however, was not strictly limited to them. The pre-service teachers (N=25) participated the course were 2nd or 3rd year students in BSc level studies, with background of the usual introductory physics courses (including introductory quantum physics). No special mathematical background going beyond requirements in calculus based introductory physics courses was assumed. Six of the course attendees had physics as a major subject, and 15 mathematics majors and four chemistry majors.

The topics of lectures 1–8 of the course is provided in Table 1 with key concepts and terms summarized. Lectures were divided on four weeks, two lectures in a week. Other three weeks were for laboratory exercises and a visit to see quantum computer in VTT Technical Research Centre of Finland. In most cases, the introduction of the topics was connected to real experiments, as reported in research publications.

**Table 1.** Summary of key-topics in the course in lectures L (1-8) and the key concepts introduced or discussed from new viewpoint after the first introduction. Laboratory exercises X1 and X2 are also located on the list. Only those key concepts of interest for comparison to multi-stakeholders' views in Table 2 are included in the list. Items "didactics" and "historical views" in Table 2 are not included here because they appear as themes throughout. Theme "classical vs. quantum" in Table 2 was not explicitly discussed and thus excluded.

| L | Key items and topics | Key concepts |
|---|---|---|
| 1 | Quantum physics. Didactic role in secondary level education. The most common quantum optics didactic experiment: Double-slit experiment (DSE) of single photons. Bohr-Einstein debate (of thought experiment). | Interference, superposition. Heisenberg uncertainty, quantum measurement, quantization. Operators. |
| 2 | Quantum theory of light and photon concept. Photon as quantized degree of freedom of electromagnetic field. Photon as quantum state (Fock-state). Dirac notation. Single photon interference in Mach-Zehnder interferometer (MZI) (Grangier's 1986 experiment). Interpretated by using photon states. | Photon as description of quantum state. Entanglement, qubit. Probability, statistical nature. Two-level system. |
| 3 | Which-Way experiments. Delayed-choice experiment. MZI and DSE versions. Quantum eraser experiments | Entanglement, qubit. Quantum measurement. Probability, statistical nature. Two-level system. |
| 4 | Quantum correlations and quantitative wave-particle duality (WPD) as inequality relation. Distinguishability, predictability, and visibility of quantum state. Connection to complementarity of conjugate variables. | Inequality (duality) relation. Operators. Quantitative WPD. Heisenberg-Robertson uncertainty, complementarity. |
| X1 | Laboratory: Single photon interference in DSE (count statistics & interference) | Photon, quantum state. Interference, DSE |
| 5 | Interferometric experiments with electrons, atoms, and molecules. Electrons as excitation of fermion-field. Description in terms of Schrödinger and Dirac's equation (briefly, basic idea only) | Matter waves. Schrödinger equation. Dirac equation. WPD of electrons |
| 6 | Bell's inequality (Clauser-Horne-Shimony-Holt form). Bell-states. EPR-experiment, Aspect et al. 1982 experiment. Quantum state teleportation. | Bell inequality. EPR-paradox. Qubit, Entanglement. Q. state teleportation |
| 7 | Qubits as registers. Quantum computing (simplest principles). Quantum cryptography (BB84 protocol). Bloch-sphere. | Qubit. Quantum computing & cryptography. Bloch-sphere |
| 8 | Quantum computers and Quantum gates (basic). Quantum technologies (for Quantum computers). | Quantum computers. Quantum gates. |
| X2 | Laboratory: Quantum eraser (semi-quantum) with diode laser Mach-Zehnder interferometer (MZI) setup. | MZI experiment. Quantum measurement. (Entanglement) |

The experiments were discussed only at the level accessible to the pre-service teachers, to provide an overall understanding of the design and operation of the measuring apparatus. Usual didactical simplified thought experiments were avoided. In each case, description of how quantum light behaved in the experiments was discussed, using Dirac's bra-ket notation for quantum states. That notation as well as description of quantum states as numerable states (Fock-states) was introduced for bookkeeping and no advanced mathematics was required. Mathematical descriptions were in level used in textbook by Scarani, Chua and Liu (2010), requiring no previous familiarity with quantum optics and information, nor in advanced mathematics. During the course, two laboratory exercises were completed (in groups of two or three). First experiment (X1 in Table 1) was a single photon interference in a double-slit. It was conducted with dim monochromatic light, with set-up securing good phase-coherence. The counting statistics was recorded to provide mostly only single counts, to make plausible the assumption that single photons could be used at least in operational sense to describe the experimental situation. Another experiment (X2) was Mach-Zehnder interferometer experiment emulating the quantum eraser experiment. It was conducted with diode laser (coherent, monochromatic light) but with no single photon statistics (thus only emulating the quantum eraser situation). However, it was discussed how the outcome of experiments could be understood if single photons were assumed.

Course evaluation was based on reports written about the two laboratory exercises, final written description (based on structured and guided sequence questions) of explanations what happens in single photon double-slit experiment. In addition, additional credit points (amounting up to max 15% of total credit points in the course) were provided from feedback of each lecture.

## 2.2 Materials

Data analyzed here is from the pre-service teachers' feedback, asked after each lecture and provided on Moodle-platform for course management. Providing feedback was voluntarily but credit was provided for giving the feedback. Informed consent, and anonymity of the participants were ensured during the research process. In collecting the data, the pre-service teachers were asked for permission to use their written reports as research data. Consent forms, which explained the purpose of the research, were used to obtain their permission. The pre-service teachers were also given the option not to participate in the research. All researchers had agreed to follow the regulations conforming to the national laws for handling data.

The feedback had three parts. First part asked to provide three items or concepts that pre-service teachers felt to be most important for their learning or most interesting. The second part asked three items and concepts pre-service teachers would have liked to learn more. The third part asked to mention three items or concepts pre-service teachers found too difficult or uninteresting. Sometimes, pre-service teachers mentioned less than three, sometimes more than three items or concepts. The items and concepts mentioned in first and second parts were taken as sign of “positive” attitude, while items and concepts mentioned in third and last were taken as indication of “negative” attitude. The number of feedback ranged from 18 to 25.

## 2.3 Analysis

The items and concepts of interest in the feedback were decided to be the key items and concept that were identified in the planning of course and its goals. The list is nearly identical to the items mentioned in two recent surveys of experts and multi-stakeholders’ views about core concepts in teaching about quantum physics, quantum optics and quantum information science. These key items and concepts are listed in Table 2.

**Table 2.** List of key items (core concepts and experiments with abbreviations: Q. for Quantum; H. for Heisenberg; M-Z for Mach-Zehnder; DC for delayed choice and QE for quantum eraser). In addition to items 1–40 as listed, an item 41 Didactics was included for didactical notions. The items 4, 6 and 7 not explicitly included in course as key topic are with grey, slanted font. The alphabets used in abbreviations in Fig. 1 are bolded.

| **Key-item** | | **Key-item** | | **Key-item** | | **Key-item** |
|---|---|---|---|---|---|---|
| 1. **Sup**er**pos**ition | | 11. **Bra-ket** notation | | 21. **Stat**istical **n**a**t**ure | | 31. **Hist**o**r**ical **v**iew |
| 2. **Interf**erence | | 12. **Bloch s**phere | | 22. **Probab**ility | | 32. **Sch**rödinger **eq**. |
| 3. **Q. meas**u**r**ement | | 13. **Oper**at**or**s | | 23. **WPD-p**hotons | | 33. **Dir**ac **eq**. |
| 4. ***Quant**ization* | | 14. **Qubit** | | 24. **WPD-e**lectrons | | 34. **Compl**ementarity |
| 5. **Q**uantum **state** | | 15. **Bell**’s **th**eorem | | 25. **WPD-q**uantitat. | | 35. **D**ouble-**s**lit **ex**p. |
| 6. ***Ener**gy **q**uantiz.* | | 16. Q. **telep**o**rt**ation | | 26. **Non-loc**ality | | 36. **M-Z I**nterf. e**x**p. |
| 7. ***Q**. **numb**ers* | | 17. **Q**. **comp**uting | | 27. **Non-det**erminate | | 37. **Mat**ter **w**ave e**x**p. |
| 8. **Ent**an**gl**ement | | 18. **Q**. **crypt**ography | | 28. **Two-lev**el system | | 38. **EPR** paradox e**x**p |
| 9. **H. Unc**e**rt**ainty | | 19. **Q**. **gates** | | 29. **Spin**/polarization | | 39. **DlC** & QEr e**x**ps. |
| 10. **Math**. **found**ats. | | 20. **Q**. **alg**orithms | | 30. **Cl**a**s**sic. vs. **QM** | | 40. **Other** e**x**ps. |

Table 2 includes key items listed in Merzel et al. (2024) augmented with some items mentioned in Mayer et al. (2024). These were included in Merzel et al. only as part of more covering category (e.g. “quantum computation” as part of “qubit”-

category), but which were in the course discussed as topics of own standing, not subordinated to qubits. On the other hand, topics “quantization” (4), “energy quantization” (6) and “quantum numbers” (7) were not explicitly discussed but assumed as pre-requisites e.g. in discussing quantization of degrees of freedom of electromagnetic field and how concept photon describes it.

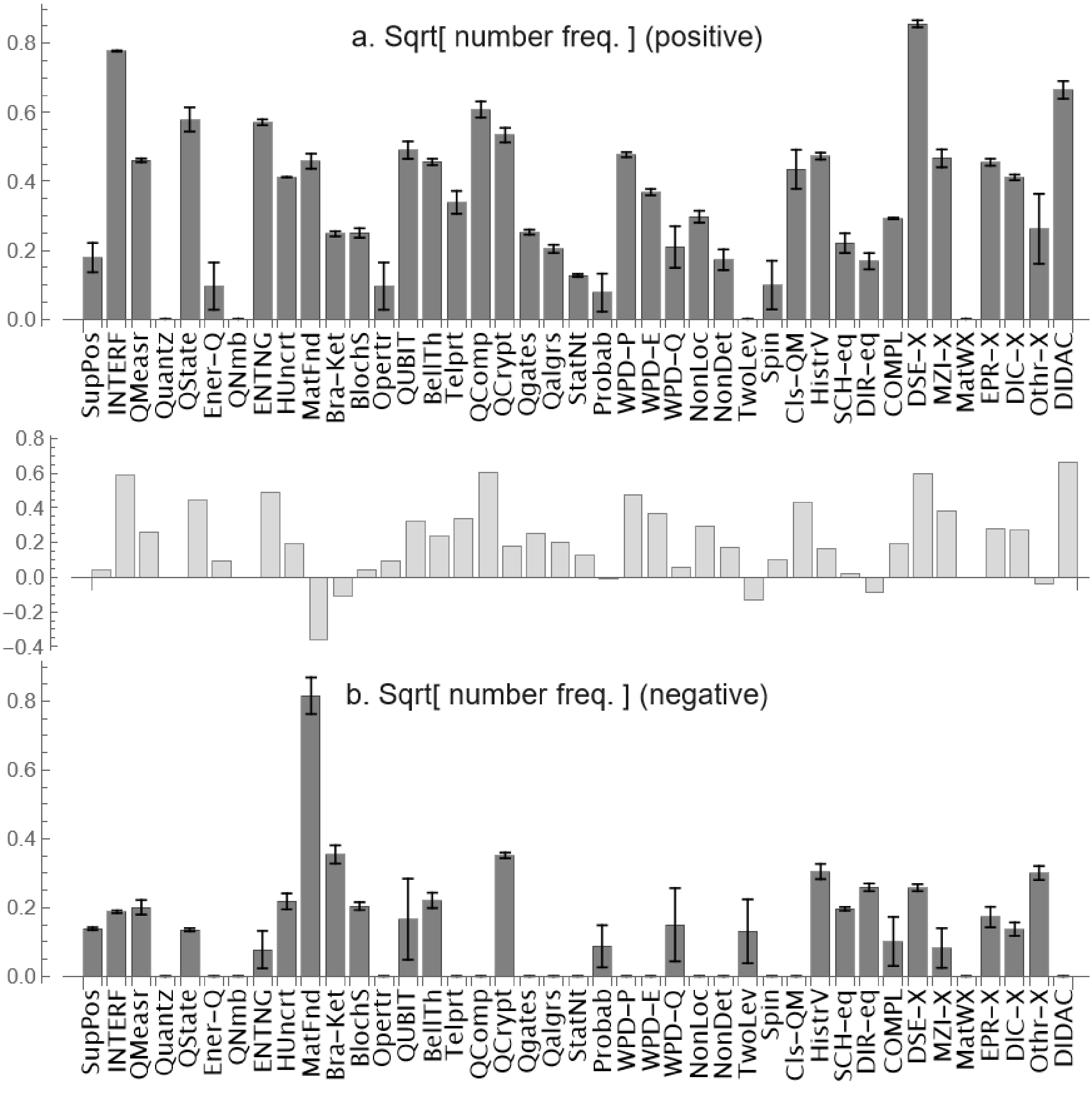
The key items and concepts as listed in Table 2 were identified in pre-service teachers’ feedback, to find out how they appear and whether the attitude is “positive” or “negative” (in sense defined above). The classification of items and concepts in feedback was mostly rather straightforward because most often pre-service teachers use the terms and concepts normatively correctly, identical to expressions as listed in Table 2. In some cases, interpretation is needed, for example when a pre-service teacher mentions e.g. “Wheeler experiment” it is taken to be the delayed choice experiment. Some terms, however, were more difficult to classify, for example expression of “photon state” and “quantized state” were taken to mean “quantum state” but sometime, when only “state” was mentioned, it was not classified as quantum state if it was not clear form the context of its use. Similar ambiguity prevailed in cases of “classical models vs. quantum models” (item 30).

Identification and classification of key items and concepts was done by two researchers. The agreement in classifications was checked by calculating the fraction of agreement A as ratio A=(number of agreed identified occurrences) /(number of all identified occurrences) in case of each of 1-41 items. The agreement A ranged from .73 to .98. Given the simplicity of the task and the irrelevance of generalizing or making predictions renders more sophisticated statistical methods (e.g. trying to take account the by chance agreement and sample size-effects) irrelevant.

## 3 Results

In interpreting the results, it should be noted that they are based on responses, where questions asked to mention three topics that: 1) were the most interesting or important for own learning; 2) one would like to learn more; 3) were too difficult to be useful for own learning or uninteresting. In the analysis, responses to cases 1 and 2 were collated, taken to indicate “positive” attitude to given topic. Items mentioned as responses to case 3 were taken to indicate “negative” attitude. The distribution of such “positive” and “negative” attitudes is shown in Figure 1 as a bar chart.

**Figure 1.** Distribution of key items. The negative and positive attitudes are shown at left (a). Only those items that were mentioned more than once are shown. Note that for better readability the square root of averages (over results by two classifiers) of number frequency of occurrence of an item in feedback is shown. Error bars correspond to max-min variation of results obtained by two classifiers. The difference between positive to negative attitudes is shown in light grey, in the middle. A value one would mean on expected response in each of the 1-8 surveys in a (reference) group of 20 pre-service teacher per each item (i.e. unanimous "positive" attitude). For abbreviations, see Table 2.



In the bar chart, the relative frequency of occurrence of a given item is normalized to 20 answers, in each feedback (the number of responses varied from 18 to 25). This means, that in bar-chart a value 1 would mean that the item appears once per feedback of a single pre-service techer, i.e. always and unanimously. Note that in Figure 1 square root of relative frequencies are shown, to moderate the visual dominance of the most favored items. It is satisfying to see that many key items and concepts listed in Table 2 were received by pre-service teachers with a "positive" attitude. In Table 3 is listed 14 most positively received items. Note that in Table 3, comparative figure (CF) of pre-service teachers having positive attitudes is scaled to reference group of 20 pre-service teachers. The most often mentioned topic of importance was double-slit experiment (normalized to average number of 20 responses, it is comparison figure of positive mentions would be 14). Didactics (item 41, omitted from Table 3, but with comparison figure 1) was the third most often mentioned positively received topic. This is as expected because the attendants of the course were pre-service teachers. Although in the feedback didactic aspects and views were not specifically asked, this viewpoint was spontaneously raised in many responses.

**Table 3.** Summary of 12 key items receiving positive attitude (important or interesting) ranking order from 1 to 14 from most positively received to lesser positively received in decreasing order. In last column is given comparative figure (CF) corresponding to number of occurrences normalized to 20 responses (the average on each feedback). The percentage of agreement (column A) of classifications by two classifiers is reported.

| R | Key-item | CF | A | | R | Key-item | CF | A |
|---|---|---|---|---|---|---|---|---|
| 1. | 35. Double-slit exp. | 14 | .98 | | 8. | 14. Qubit | 4 | .89 |
| 2. | 2. Interference | 11 | .98 | | 9. | 30. Classic vs Q. Mech | 4 | .74 |
| 3. | 17. Q. computing | 7 | .92 | | 10. | 18. Q. cryptography | 4 | .92 |
| 4. | 8. Entanglement | 7 | .97 | | 11. | 39. Deld. ch & QEr exp | 3 | .96 |
| 5. | 5. Quantum state. | 7 | .88 | | 12. | 38. EPR paradox exp. | 3 | .95 |
| 6. | 23. WPD of photon | 5 | .97 | | 13. | 15. Bell's theorem | 3 | .96 |
| 7. | 36. MZ interf. exp. | 4 | .89 | | 14. | 3. Quantum measurm. | 3 | .98 |

Given the dominance of double-slit experiment it is not unexpected to find that Interference (item 2), Wave-particle duality, WPD of photons (23) and Mach-Zehnder interferometric experiment of single photons (36) have high rankings. These topics and concepts related them are apparently felt to be of importance and interesting. The result that Quantum state (item 5) features as "positively" received is an encouraging finding. One goal it the course was to promote thinking through quantum states, to understand photons as concepts describing quantized states of electromagnetic field.

Another set of items that have attracted positive attitudes consists of Qubit (14), Quantum computing (5) and Quantum cryptography (18), all desired items for getting familiarity with quantum technology and quantum information. In addition, it is noteworthy that Entanglement (8) comes quite highly ranked with rank 4. However, in this group, Quantum cryptography (18) has received a divided attitude; also, plenty of “negative” ones, owing to its mathematical complexity.

Items which were central in the course but scored high “negative” attitudes (nearly without exception as too difficult to be useful) included: Mathematical foundations (10), Dirac’s bra-ket notation (11) and Quantum cryptography (18). Of these, the latter two received also nearly equally much “positive” attitudes, and thus, divided opinions. Only the first item of mathematical foundational details and derivations was clearly gathering dominantly “negative” attitudes.

Finally, some other remarks are of interest. Superposition (item 1), although having important role in all lectures, was mentioned only few times. It was perhaps too obvious concept to receive any specific attention. This is in line with Merzel et al. (2024) where similar lack of attention on superposition was found. The lack of occurrence of topics “quantization” (4), “energy quantization” (6) and “quantum numbers” (7) is as expected, because as mentioned, these were not explicitly discussed topics, but topics assumed to be pre-requisites.

## 4 Discussion and conclusions

The results of the survey encourage to think that Finnish pre-service teachers’ attitudes to the key items of quantum optics, information and computation are positive, and the collection of key items they have the most positive attitudes match well key items recognized in recent European-wide multi-stakeholder survey. This is promising starting point to renovate the Finnish physics teacher education for secondary level teaching, with promises to eventually lead to visibility of the key topics in national secondary level curriculum in Finland. Attempts to bring the modern quantum physics topics as part of national curriculum has been slow. Still, the high school curriculum in Finland is too much driven by history driven introduction to topics of quantum physics, it misses many relevant core concepts and key topics o understand the basis of modern quantum technologies. This is far from the optimal if the goal is to keep up with leading European countries, where modern quantum physics has already been adopted as part of the high school curricula.

If in near future the role of modern quantum physics, especially as it is related to quantum technologies, remains in Finnish curriculum as limited as it is now, the goals to educate competent “quantum workforce” the advancing quantum technologies need will be seriously hampered, when high school physics education does not properly support the future needs. An obvious starting point to facilitate change and where teacher education can affect the change, is to implement special courses for teachers to raise their awareness of the importance and possibilities of the modern topic in quantum physics. Quantum optics, information and computation provide an excellent platform for such initiatives.

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