Quantum physics ≠ quantum physics. A survey of researchers’ associations

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Abstract
No consensus has been reached so far concerning the key topics on quantum physics suitable for secondary school teaching, despite comprehensive research. We identified the variety of associations with quantum physics among professionals as a potential cause. From an explorative mind map study with $N = 29$ physics researchers, we derive six subject-specific focal points in the associations that researchers have with quantum physics.

Keywords: quantum physics, mind map, associations, exploratory study

1. Key topics in secondary school teaching on quantum physics
Quantum physics is an integral part of secondary school curricula, due to the importance of quantum physics for current research in general [1] and the modern understanding of science in particular [2]. However, the development of teaching sequences for quantum physics at secondary school level is characterized by various difficulties because ‘more than in other fields, decisions have to be made about the focus of teaching […]’ (translated from [3, p. 6]).

The foci of the various teaching concepts for quantum physics range from historical aspects [4], technological applications [5] and interpretations of quantum physics [6] to the sum over paths approach [7] or experiment-based approaches to quantum physics that are in line with quantum electrodynamics [8]. In physics education research, there still does not appear to be a conclusive consensus on the content to be taught in lessons on quantum physics. For example, McKagan et al [9] interviewed eight university lecturers about ‘standard topics’ for quantum physics courses, but in this survey, no
A consensus was reached among the lecturers. However, the results by Krijtenburg-Lewerissa et al [10] suggest that such a consensus might exist: The authors report on a Delphi study to determine the key topics on quantum mechanics at secondary schools from an expert perspective.

Three key topics were particularly important to the experts: dualism (e.g. particle character of light), wave functions (e.g. one-dimensional potential well), and atoms (e.g. energy levels). These key items are also part of the international core curriculum on quantum physics which was extracted by the analysis of curricula from 15 nations [2]. Empirical research on the students’ learning processes can provide arguments for or against the use of a respective teaching proposal [11–14]. Establishing a proposal as a valid school curriculum requires the support of physicists on school boards, in professional associations, and in academic teaching. However, the opinion about the essence of quantum physics is richly diverse.

We present the results of an explorative study to approach the clarification of two research questions:

(a) Which terms do researchers from different physics disciplines associate with quantum physics?
(b) How can these terms be categorized to find foci in the associations of researchers from the different disciplines in terms of content?

In section 2, we present the methodology by detailing the study design, sample, and data analysis. The study results are presented in section 3, and in section 4, we discuss the results of this study.

2. Methods

2.1. Data collection and study design

An association is an experience-based mental connection between different concepts according to reference [15]. Associations can be analysed with interview studies, but the interviewer’s questions can awaken mental connections in the respondent that would not have been expressed without prior input. The same problem applies to all survey procedures in closed format.

Therefore, we have chosen the mind map method in this study. Mind maps represent ideas grouped around a central theme [16]. The lack of predetermined rules makes the creation of mind maps a natural method for organizing and visualizing a cohort’s associations with complex topics, such as quantum physics [17, p. 1494]. For this reason, eliciting associations with mind maps is also more edifying than having subjects create lists of terms. Even with small samples, the procedure promises a large number of heterogeneous mind maps, and thus a comprehensive insight into the associations that exist with a topic within a cohort [16].

In our study, researchers from different physics disciplines were asked to prepare mind maps on quantum physics on prepared answer sheets to ensure the standardization of the implementation and the anonymization of the procedure.

2.2. Participants

$N = 29$ professors and postdocs from the Department of Physics at the University of Erlangen (Germany) participated in the study. Each researcher in the Department of Physics at the University of Erlangen works in one of the four fields astro- and astroparticle physics (6 participants), condensed matter (9 participants), optics (3 participants) or theoretical physics (11 participants). The researchers in these four pillars deal with thematically different physics subfields (cf table 1). All participants have worked in their area for many years. Therefore, it is reasonable to assume that they are accustomed to a specific subject culture.

2.3. Data analysis

A frequency analysis of the terms mentioned in all mind maps was carried out to identify the terms mentioned most frequently in order to clarify research question 1. Mind map terms that cover the same content were counted together: For example, since the term photoelectric effect addresses the same content as the term photo effect, both terms are included in the count under the title photoelectric effect. In contrast, the term light–matter interaction, for example, is counted separately, since more than just the photoelectric
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Table 1. The branches of the department of physics at the university of Erlangen [18–20].

| Sub field                                      | Description                                                                 |
|-----------------------------------------------|-----------------------------------------------------------------------------|
| Astro- and astroparticle physics (AP)         | Expertise in the fields of neutrino, x-ray and gamma-ray astronomy; research on the origin of cosmic rays; properties of neutrinos; research on dark matter |
| Condensed matter (CP)                         | Solid and liquid state of aggregation; topological properties in solids; research on molecules on the surface; research on synthetic allotropes. |
| Optics (OP)                                   | The science of light; Classical optics to quantum optics; Optical metrology; Optical design; Microstructuring |
| Theoretical physics (TP)                     | Exploration of the fundamental structural principles of matter; quantum dynamic descriptions of space and time; development of new mathematical concepts and methods |

A deductive-inductive procedure was chosen to categorize the mind map terms. Theory-based categories were established first, which were then inductively completed based on the data material in a second step [21]. For deductive category building, we referred to McKagan et al [9], Krijtenburg-Lewerissa et al [10], and Stadermann et al [2]. All mind map terms were first assigned to the deductively formed categories one after the other. If a term did not fit into one of the deductively formed categories, a new category was opened. In total, this procedure led to a category system with eight main categories including several sub-categories. The category system is presented in section 3.2. The final categorisation was carried out by independent raters. As a measure of their agreement, we report Cohen’s Kappa and interpret the values according to [22].

3. Results

3.1. Frequency analysis

An initial analysis of the 29 mind maps shows that a total of 577 terms were used. On average, this results in about 20 terms per person for each mind map (cf table 2).

Figure 1 shows the 18 terms that appeared in the mind maps of more than 20% of the respondents. These terms are thus often part of the associations with quantum physics of researchers from physics.

Table 2. Overview of the number of terms used by researchers to prepare their mind maps, broken down by field (AP: astro- and astroparticle physics, CM: condensed matter, OP: optics or TP: theoretical physics).

| Subfield | # Terms | # Terms/participant |
|----------|---------|---------------------|
| AP       | 126     | 21.0                |
| CM       | 124     | 13.8                |
| OP       | 59      | 19.7                |
| TP       | 268     | 24.4                |

The distribution of the most frequently used terms among the four disciplines shown in figure 2 does not reveal any structure. A categorization of the terms is necessary in order to identify focal points in terms of content.

3.2. Categorization

The categorization allows an insight into the content-related associations that the surveyed researchers have with quantum physics. In this section, we present the category system on quantum physics based on the researchers’ mind maps. Following on from this, we discuss whether there are clusters of terms among the respondents in the respective subject areas (astro-astroparticle physics, condensed matter, optics and theoretical physics), and in this way conclude subject-specific differences or commonalities between the associations that researchers have with quantum physics.

Figure 3 provides a graphical overview of the entire category system, which was designed
Figure 1. Overview of the terms most frequently mentioned in the mind maps on quantum physics.

The terms of the category Q8—associations will not be included in the evaluation below, due to the purely personal character. A total of 29 different terms (44 terms in total) fall into this category, which accounts for 7.6% of all mind map terms. Therefore, only categories Q1 to Q7 are included in the further evaluation of the mind maps on quantum physics. In the course of an extended frequency analysis, the terms regarding quantum physics mentioned by the respondents in the mind maps were assigned to the respective categories, divided according to the respondents’ subject areas. This makes it possible to record whether different content items (i.e. categories) are given different importance in the associations with quantum physics among the participants from the different subject areas of physics, although the four disciplines are not equally represented in the survey cohort (cf section 2.2).

The results of this extended frequency analysis can be found in Table 3: there, the number of terms mentioned in the mind maps is noted, collected for the individual categories (column Total) and for the individual physics disciplines (row \( \sum \)) of the respondents. Thus, the column Total contains the number of terms from the mind maps of the entire survey cohort that could be assigned to the respective category. For example, 94 of all terms relating to quantum physics fell into the category mathematical terms (Q1). Of these 94 terms for the category Q1, 13 terms came from respondents from astrophysics, 4 terms from respondents from condensed matter, 14 terms from optics, and 63 terms from theoretical physics. These entries can be found in the columns marked with \# words. The relative frequency column indicates in each case which percentage of all terms from the respective subject area (value from row \( \sum \)) was assigned to the respective category (values from
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Figure 2. Overview of the 18 terms most frequently used in mind maps on quantum physics. The bars show which percentage of the test persons in a subject area included the respective term in their mind maps, thus providing an initial subject-specific insight.

We illustrate this with an example: the subject area astro- and astroparticle physics contributed 13 terms to category Q1 (column # words). In total, astro- and astroparticle physics has contributed 120 terms in the mind maps on quantum physics (row \(\sum\)). This shows that \(\frac{13}{120} = 10.83\%\) of the terms contributed by participants from astrophysics fitted into category Q1 (relative frequency column). In comparison, 63 of the 238 terms on quantum physics contributed by subjects from theoretical physics fell into category Q1. This means that \(\frac{63}{238} = 26.47\%\) of the terms contributed by subjects from the field of theoretical physics fall into category Q1—a larger proportion than among the subjects from astrophysics.
Hiding the subcategories and looking only at the main categories Q1–Q7 reveals significant differences, as shown in Table 4. To identify a discipline’s focus of content, we speak of an accumulation of the terms of a subject area in a category Qn, if more than 15% of all terms from the mind maps of the subjects of this subject area could be assigned to category Qn.

In this way, we find that different subject areas actually place different emphases in the development of their mind maps: for example, more than a quarter of all terms from scientists from optics or theoretical physics can be assigned to category Q1—mathematical terms (OP: 25.00%, TP: 26.47%), while only 10.83% of the terms from the mind maps of astrophysicists, and indeed only 3.36% of all terms from the mind maps of scientists from condensed matter could be assigned to this category. A very similar picture emerges for the category Q4—phenomena and applications; while about one-fifth of the mind-map terms of the astrophysicists and the physicists from optics belong to this category (AP: 20.83%, OP: 19.64%), this only applies to less than 10% of all terms mentioned in the case of condensed matter and theoretical physics (CM: 9.24%, TP: 8.82%). A sole focus on the terms of category Q6—mathematical representations can be found for the subjects from condensed matter, and category Q3—experiments only plays a subordinate role in all subject areas. An evident accumulation is found in category Q2—fundamental principles of quantum physics, and this is visible at a similar level for all subject areas (AP: 30.00%, CM: 34.45%, OP: 26.79%, TP: 23.11%). The content focus on optics in category Q7 is an artefact

**Figure 3.** Category system for quantum physics. A detailed description of the individual categories including anchor examples can be found in the appendix.
### Table 3. Overview of the results of the frequency analysis, divided by category (cf figure 3) and subject area (cf table 1).

| Category | AP # Words | Relative frequency [%] | CM # Words | Relative frequency [%] | OP # Words | Relative frequency [%] | TP # Words | Relative frequency [%] | Total |
|----------|------------|-------------------------|------------|-------------------------|------------|-------------------------|------------|-------------------------|-------|
| Q1       | 13         | 10.83                   | 4          | 3.36                    | 14         | 25.00                   | 63         | 26.47                   | 94    |
| Q2.1     | 4          | 3.33                    | 1          | 0.84                    | 5          | 8.93                    | 6          | 2.52                    | 16    |
| Q2.2     | 5          | 4.17                    | 0          | 0.00                    | 0          | 0.00                    | 6          | 2.52                    | 11    |
| Q2.3     | 3          | 2.50                    | 1          | 0.84                    | 2          | 3.57                    | 5          | 2.10                    | 11    |
| Q2.4     | 3          | 2.50                    | 4          | 3.36                    | 1          | 1.79                    | 8          | 3.36                    | 16    |
| Q2.5     | 8          | 6.67                    | 24         | 20.17                   | 1          | 1.79                    | 9          | 3.78                    | 42    |
| Q2.6     | 6          | 5.00                    | 4          | 3.36                    | 0          | 0.00                    | 9          | 3.78                    | 19    |
| Q2.7     | 3          | 2.50                    | 3          | 2.52                    | 0          | 0.00                    | 6          | 2.52                    | 12    |
| Q2.8     | 4          | 3.33                    | 4          | 3.36                    | 6          | 10.71                   | 6          | 2.52                    | 20    |
| Q3       | 6          | 5.00                    | 7          | 5.88                    | 0          | 0.00                    | 9          | 3.78                    | 22    |
| Q4.1     | 7          | 5.83                    | 4          | 3.36                    | 2          | 3.57                    | 12         | 5.04                    | 25    |
| Q4.2     | 18         | 15.00                   | 7          | 5.88                    | 9          | 16.07                   | 9          | 3.78                    | 43    |
| Q5.1     | 5          | 4.17                    | 3          | 2.52                    | 0          | 0.00                    | 7          | 2.94                    | 15    |
| Q5.2     | 3          | 2.50                    | 1          | 0.84                    | 0          | 0.00                    | 2          | 0.84                    | 6     |
| Q5.3     | 4          | 3.33                    | 14         | 11.76                   | 4          | 7.14                    | 16         | 6.72                    | 38    |
| Q5.4     | 6          | 5.00                    | 4          | 3.36                    | 0          | 0.00                    | 13         | 5.46                    | 23    |
| Q5.5     | 3          | 2.50                    | 0          | 0.00                    | 0          | 0.00                    | 3          | 1.26                    | 6     |
| Q6.1     | 0          | 0.00                    | 1          | 0.84                    | 0          | 0.00                    | 6          | 2.52                    | 7     |
| Q6.2     | 1          | 0.83                    | 2          | 1.68                    | 0          | 0.00                    | 1          | 0.42                    | 4     |
| Q6.3     | 10         | 8.33                    | 18         | 15.13                   | 1          | 1.179                   | 19         | 7.98                    | 48    |
| Q7.1     | 5          | 4.17                    | 5          | 4.20                    | 1          | 1.79                    | 9          | 3.78                    | 20    |
| Q7.2     | 3          | 2.50                    | 8          | 6.72                    | 2          | 3.57                    | 12         | 5.04                    | 25    |
| Q7.3     | 0          | 0.00                    | 0          | 0.00                    | 8          | 14.29                   | 2          | 0.84                    | 10    |
| ∑        | 120        | 100                     | 119        | 100                     | 56         | 100                     | 238        | 100                     | 533   |
attributed to one single respondent, who noted a large number of physicists, and thus unwittingly distorted the scoring at this point. A graphical representation of these results is shown in figure 4.

4. Discussion
This section discusses the results of this mind-map study presented in section 3 with reference to the research questions.

4.1. Research question 1
Research question 1 was: what terms do researchers from different physics disciplines associate with quantum physics? The 29 subjects used a total of almost 600 terms to create their mind maps on quantum physics. Eighteen of these terms were used by at least 20% of all subjects. The most frequently used term is Schrödinger equation, which is included in the mind map by 17 of all 29 subjects. Several terms, such as double-slit, wave-particle dualism, uncertainty principle or entanglement, appeared in 11 of the 29 mind maps. The terms photoelectric effect and photon were also noted by six respondents in their mind map on quantum physics. The 18 terms most frequently represented in the respondents’ mind maps originate from six categories of the category system presented in figure 3.

In the study presented here, however, we are not merely interested in the isolated terms in the subjects’ mind maps. Moreover, we want to identify clusters of researchers’ associations that belong together in terms of content. In this way, we wanted to determine the extent to which certain thematic foci characterize the associations of scientists with quantum physics from different disciplines in terms of content. This requires a categorization of the associated terms beyond a mere frequency analysis (cf section 3.2).

4.2. Research question 2
Research question 2 was: how can these terms be categorized to find foci in the associations of researchers from the different disciplines in terms of content? We developed a category system (cf figure 3) by means of a deductive-inductive procedure in order to be able to structure the researchers’ associations with quantum physics. On the one hand, we used categories from technical literature (cf section 2.3) and, on the other hand, inductively supplemented these with new categories based on the data material. We then determined that a subject area (astrophysics, condensed matter, optics, theoretical physics) had a content focus on a respective category if at least 15% of all terms in the mind maps from the disciplines’ participants fell into the corresponding category.

This procedure revealed the following: the mind maps on quantum physics are heterogeneous between the disciplines, and one finds defined characteristics, i.e. focal points in terms of content, in the associations that the scientists

| Category | AP  | CM  | OP  | TP  | Total number of terms |
|----------|-----|-----|-----|-----|-----------------------|
| Q1       | 10.38 | 3.36 | 25.00 | 26.47 | 94                     |
| Q2       | 30.00 | 34.45 | 26.79 | 23.11 | 147                    |
| Q3       | 5.00  | 5.88  | 0.00  | 3.78  | 22                     |
| Q4       | 20.83 | 9.24  | 19.64 | 8.82  | 68                     |
| Q5       | 17.50 | 18.49 | 7.14  | 17.23 | 88                     |
| Q6       | 9.17  | 17.65 | 1.79  | 10.92 | 59                     |
| Q7       | 6.67  | 10.92 | 19.65 | 9.66  | 55                     |
| ∑        | 100   | 100   | 100   | 100   | 533                    |
Figure 4. The mind maps on quantum physics indicate subject-specific focal points in the associations that researchers have with quantum physics. Although there is an interdisciplinary focus on terms related to the principles of quantum physics (Q2), the individual disciplines have separable foci in their associations with quantum physics otherwise.

From the various disciplines have with quantum physics (cf figure 4). For example, over 25% of all the terms used by the scientists from theoretical physics and optics fall into the category Q1—mathematical terms, and around 20% of the terms from optics and astrophysics correspond to the category Q4—phenomena and applications. An overlap in terms of content between theoretical physics, astrophysics, and solid-state physics can be found in category Q5 related to atomic theory; this is just as plausible as the focus of the participants from condensed matter on category Q6—mathematical representations (mainly wave functions). The only category for which respondents from all subject areas frequently named terms is category Q2, in which the fundamental principles of quantum physics were subsumed.

5. Conclusion
This exploratory study shows that scientist have different concepts of quantum physics depending on their field of research. These differences are not individual, but typical concepts are found in specific fields. This result is relevant for physics education researchers, e.g. for developing concept tests to investigate students’ understandings of quantum physics but it is also of importance for physics teachers who want to evaluate their quantum physics lessons, because without further clarification it is not self-evident, what learning of quantum physics means. There are similar findings with regard to the diverse interpretations of quantum physics [23]. This uncertainty is also a chance: if there is no standard of quantum physics essentials, new curricula can put more emphasis on how well a new concept is learned rather than how well it represents a teaching tradition. Last but not least the present result independently confirms the necessity of asking a variety of experts such as in [10]. Further research will include larger test groups and a broader range of scientific fields ranging from philosophers to engineers.
Ethical statement
The study was conducted in accordance with IOP Publishing’s Ethical policy. Authors acknowledge that the research was conducted anonymously, that consent was obtained from all participants, and that all participants are informed about the publication of the results of this study.

Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

Appendix A.
In the following, the main categories and the associated sub-categories for quantum physics are described.

- Category Q1—Mathematical terms: this category includes all terms that refer to mathematical content in the narrower sense. Examples are the terms Lie algebra or differential geometry.
- Category Q2—Fundamental principles of quantum physics: terms relating to the fundamental principles of quantum physics are listed in the sub-categories axioms of quantum physics (anchor examples: operator, observable), statistical behavior (anchor examples: randomness, indeterminism), measurements (anchor examples: observer, collapse of the wave function), Heisenberg uncertainty principle (anchor example: Place-momentum uncertainty), wave-particle duality (anchor examples: DeBroglie wavelength, light particles), quantization (anchor examples: Planck’s quantum of action, energy quantization), state (anchor examples: coherent state, quantum numbers) and entanglement (anchor examples: non-locality, EPR paradox).
- Category Q3—Experiments: this category subsumes experiments in quantum physics, such as the Stern–Gerlach experiment and others.
- Category Q4—Phenomena and applications: this category on the one hand contains technical applications of quantum physics (anchor examples: quantum computing, lasers) and on the other hand phenomena of quantum physics (anchor examples: tunnel effect, Aharonov-Bohm effect).
- Category Q5—Atomic theory: this category is divided into the sub-categories atom (anchor examples: hydrogen atom, orbitals), spectral properties (anchor examples: emission spectrum, energy-time uncertainty), particles (anchor examples: electrons, protons), spin (anchor examples: spin-orbit interaction, Pauli principle) and interactions (anchor examples: weak interaction, electromagnetic interaction).
- Category Q6—Mathematical representations: terms that refer to concrete quantum physical aspects have been assigned to this category. The sub-categories are Feynman diagrams (anchor examples: Feynman diagrams, path integrals), potential (anchor examples: potential well, particles in a box) and wave function (anchor examples: Schrödinger equation, probability ketis amplitudes).
- Category Q7—About quantum physics: this category was subdivided into the sub-categories philosophical aspects (anchor examples: Born’s interpretation, many-worlds interpretation), distinction from classical physics (anchor examples: Correspondence principle, Decoherence) and physicists (anchor examples: Dirac, von Neumann).
- Category Q8—Associations: this category consists of named terms that do not have to be assigned to quantum physics per se, for example, the terms force, bond, lattice, or subsumes terms to designate subfields of physics, such as statistical physics or molecular physics.

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References
[1] Acín A et al 2018 New J. Phys. 20 080201
[2] Stadermann K, Van Den Berg E and Goedhart M 2019 Phys. Rev. Phys. Educ. Res. 15 010130
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[3] Müller R 2005 Qualitative Quantenphysik: Eine Handreichung für die Sekundarstufe I (Kiel: IPN Kiel)
[4] Unver A O and Arabacioglu S 2015 J. Balt. Sci. Educ. 14 65–84
[5] Zollman D, Rebello S and Hogg K 2002 Am. J. Phys. 70 252
[6] Müller R and Mishina O 2021 arXiv:2012.15162
[7] Malgieri M, Onorato P and De Ambrosio A 2014 Eur. J. Phys. 35 055024
[8] Bitzenbauer P and Meyn J P 2020 Phys. Educ. 55 055031
[9] McKagan S B, Perkins K K and Wieman C E 2010 Phys. Rev. ST - Phys. Educ. Res. 6 020121
[10] Krijtenburg-Lewerissa K, Pol H, Brinkmann A and van Joolingen W 2018 Int. J. Sci. Educ. 41 349–66
[11] Müller R and Wiesner H 2002 Am. J. Phys. 70 200
[12] Bitzenbauer P 2020 Quantenoptik an Schulen – Studie im Mixed-Methods Design zur Evaluation des Erlanger Unterrichtskonzepts zur Quantenoptik (Berlin: Logos Verlag)
[13] Bitzenbauer P and Meyn J P 2021 Prog. Sci. Educ. 4 40–51
[14] Bitzenbauer P 2021 Phys. Rev. Phys. Educ. Res. 17 020103
[15] Klein S 2012 Learning: Principles and Application Learning: Principles and Application 6th edn (Thousand Oaks, CA: SAGE Publications)
[16] Crowe M and Sheppard L 2011 Qual. Quantity 46 1493–504
[17] Crowe M and Sheppard L 2011 Qual. Quantity 46 1493–504
[18] (Available at: www.fkp.physik.nat.fau.eu/)
[19] (Available at: www.optik.nat.fau.de/forschung/odem/optische-messtechnik/)
[20] (Available at: www.physik.nat.fau.de/forschung/themenschwerpunkte/#collapse_1)