Students' conceptions in quantum physics

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Abstract

Research studies on students' conceptions in the area of quantum physics are, in contrast to other areas of physics, rather rare. The present study gives results from quantitative and qualitative data with grade 13 students (age 19) in German high schools, taken before and after instruction as well as from transcripts during instruction. Only students from classes, which used a Schroedinger approach to understand atoms and electron orbitals, were taken. As a first result, we describe students' beliefs about models. Students tend to use "model" in a variety of meanings, ranging from "true pictures" to "tools of thinking" and "visualization". Second, we describe their conceptions about orbits, trajectories, and motion, mainly related to their interpretations of orbitals, after teaching. The findings suggest, that roughly 25% of the students use conceptions near to modern physics, another 25% use some typical intermediate conceptions such as "smeared orbits", and 50% stick to classical orbits ("Bohr model"), even after teaching. Third, we give results about their understanding of "stability" of the atom, "probability", and "energy". The problem of stability brings nearly all students back to classical thinking in terms of orbit and centrifugal force. Probability, again, has different meanings related to the algorithm or to a causal explanation of a probability distribution or to inaccuracy. The quantization of energy is readily accepted, even without a conception related to orbitals of the atom.

I. Introduction

Research studies on students' preconceptions in the area of quantum physics are, in contrast to other areas of physics, rather rare [1]. This may be taken as a hint to the different character of the issues in such studies. In contrast to mechanics, for example, the area of atomic physics in high school has little relation to likely experiences of students in every day life. Knowledge of and dealing with elements from atomic physics is not required for students to manage their everyday lives. In spite of this fact students do not start learning quantum physics with a "tabula rasa", with an empty mind. Our investigations[2] - carried out in German high schools in grade 13 - therefore focus on students' classroom discussions related to physical ideas about this subject. Our results show preferred ways of thinking about atoms and quantum physics, which we present as students' conceptions in this paper.

II. Aim of investigation: typical conceptions of groups of students ("Thematic conceptions")

The overall goal of studies on students' ideas about quantum physics is to help teachers to better understand students' ideas during instruction. Not only students, "teachers, too, construct their own meanings"[3], especially when constructing meaning for students' contributions. "Science teaching also involves the understanding of students' views of science concepts"[4]. The results of those studies thus will have to contribute to reduce the "deficit in technology"[5] observed by Luhmann and Schorr in education. To meet this demand means that knowledge of constructs on students' ideas combined with an improvement of "causal plans applied" by teachers[6] may lead to better and more flexible reactions of teachers to students' behavior. Particularly in phases of instruction determined by students' own ideas teachers must be able to give sense to students' statements, even those seeming strange, in order to be able to adequately react on their behavior.

For communication between teacher and students during instruction - and in general for the process of communication between individuals everywhere - the construction of mutual "representative constructs of objects of thinking"[7] of the partners of communication is a necessary basis for communication. In classrooms communication does not take place in a situation where students face each other as totally unique individuals, and thus also understanding is not related to individual students, but rather relates to a situation determined by the existence of a whole group of students. That means that there is some "commonsense" binding this group of students together. So our aim is to describe conceptions of students in quantum physics as "representations for groups of learners"[8]. We call those conceptions "thematic conceptions" to distinguish them from individual conceptions held by single students.

By formulating results about students' thematic conceptions we do not claim to causally explain their behavior in different situations. Not *laws* of causality for interaction in instruction have to be set up, but rather *ideas* about causality on students' actions will have to be developed. The formation of such ideas can be based on formulating propositional elements of pre-conceptions. The empirical data on the characteristics of students' ideas about atomic physics should help to support such "plans of causality"[9] and to empirically confirm them.

When investigating students' conceptions in quantum physics the different relation of this content area to everyday life mentioned above has to be noted. Everyday life experiences gained in dealing with physical phenomena out of the area of mechanics directly serve to master everyday life situations. This is knowledge "relating to everyday realities" and serves "to master *all* 'normal' situations of life"[10]. For managing everyday life it is, for example, necessary to have knowledge on the cause of motion and the acting of forces (e.g. for cycling, driving, and climbing). Such experiences impose real world knowledge on the subject of mechanics. In this content area there are many possibilities and necessities for people to develop theories for everyday life, to act accordingly, and to construct appropriate meanings. In the area of atomic physics the situation is different. Knowledge attributed to this content area is not needed to act in everyday situations. The knowledge in atomic physics refers to derived experiences. This does not mean however that the ideas of students in the area of atomic physics do not depend on experiences gained from everyday life. Constructing meaning and developing ideas when confronted with new phenomena - e.g. of atomic physics - is always based on already existing ideas. In this case they often are taken from other content areas of physics, especially from mechanics. But there tends to be a special selection related to atoms or quanta, giving special meaning to issues and solutions in this area.

III. Methods of Investigation

All data for this investigation of students' ideas were collected in grade 13 (age 19), near the end of German high school. There were four different qualitative and quantitative data sources:

(1) Audio recordings of current physics lessons [11] were our main data source. Four classes were recorded and transcribed totally. Sections from a further six classes were also used. This resulted in about 900 pages of transcripts. Especially fruitful for our qualitative interpretation process were the following parts of transcripts:

- Short open questions of teachers, followed by students' responses in more detail.
- Dialogues between several students, without contributions from the teacher.
- Spontaneous contributions of students, e.g. when students interrupted the teacher' s statements or made contradicting statements.

The following three additional methods were used complementary to test the hypotheses about the students' preconceptions on the basis of a larger number of students involved:

(2) A pair-relation questionnaire with associative elements. In this type of questionnaire students were asked to make statements using two given concepts, for example:

wave	-	energy level
wave function	-	trajectory
trajectory	-	energy level
position	-	wave function
electron	-	wave
trajectory	-	probability

(3) A questionnaire with seven "thinking type" tasks, i.e. tasks requesting qualitative descriptions rather than quantitative calculations (see below for examples).

(4) Interviews with nine pairs of students on selected statements made by students in the two questionnaires. Especially useful were the following types of interview situations:

- the interviewer gives a questionnaire statement of one student; the students in the interview develop a somewhat different viewpoint
- open interview with extensive answers of students
- the interviewer gives a picture (e.g. of an electron distribution) and the students discuss it
- the interviewer asks narrow questions and the students start with following the question but afterwards develop some personal viewpoint or differentiation.

Data in (1) were gathered during the teaching process, the methods in (2), (3) and (4) were used after students had finished the course.

From a first analysis of the transcripts, hypotheses (constructs) were established about the basic students' ideas. Afterwards, they were explored with the quantitative methods. These constructs claim to enable a better understanding of students' actions. Repeated interpretations of those dialogues during instruction, using the already formulated elements of pre-conceptions, is a methodological procedure by which better explanatory power and higher differentiation of the constructs is achieved. Such constructs shall enable the teacher to act adequately in teaching situations and to react to students' behavior. This aim combines method and goals of the study. Fig. 1 shows the procedure of data collection and evaluation including all different methods.

As discussed above, it is not the aim to describe ideas of *single* students but to describe the *type of preconceptions* of various students in similar situations.

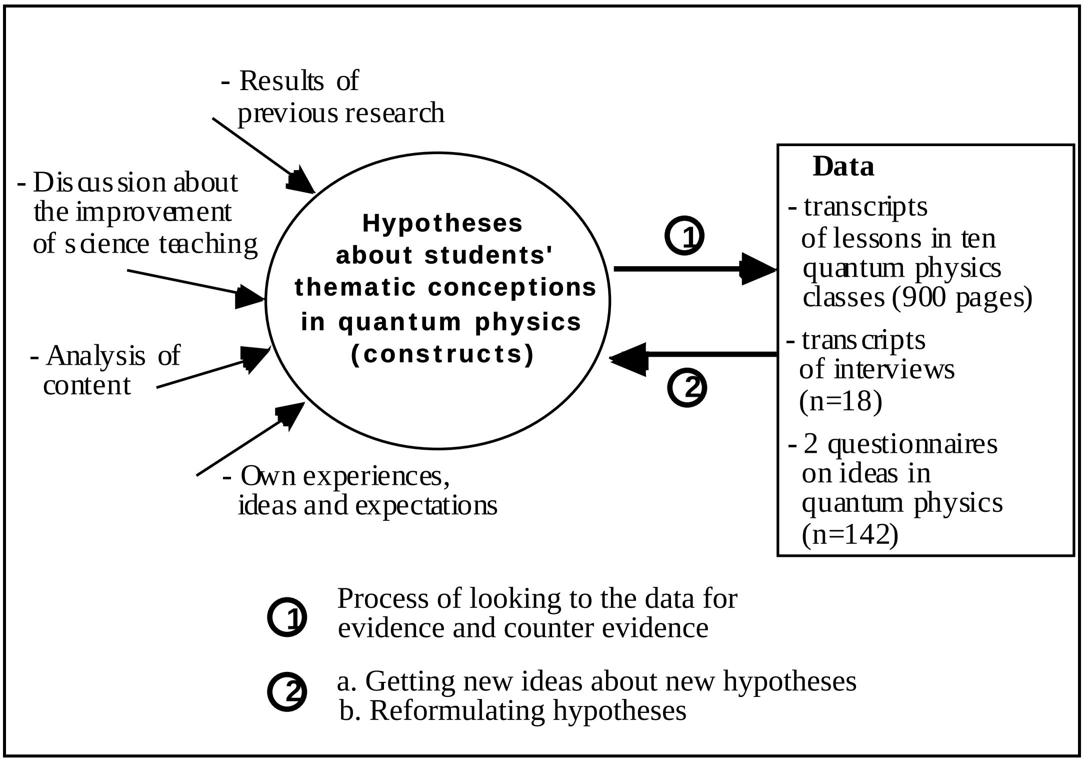


Fig. 1: Method of qualitative interpretive research

IV. Results of the study

The results of the study are presented in two different domains. On the one hand they tell something about a rather general approach of students to physics, in particular to quantum physics, and their ideas about it (e.g. ideas about the role of models in physics); on the other hand we describe students' conceptions related to central concepts of quantum physics, such as stability of atoms, orbit and motion, probability, and the use of the concept of energy.

Accordingly, the results are described in two parts:

- students' beliefs about models and their use in quantum physics
- students' conceptions in the area of quantum physics

A. Students' Beliefs about Models

In quantum physics instruction is based on assumptions about atoms and electrons being particles or waves or something else. Beliefs about models play an important metacognitive role in such discussions.

- What is the character of a "model of the atom" in students' minds?
- What kind of statements are made on models of atoms, electrons etc.? What ideas are linked to these concepts?
- With what expectations do students approach the subject of atomic models? What requirements do they attribute to models to be satisfactory?

In physics the concept of a model has gone through a change from a pictorial representation ("image") to a "structural similarity with respect to relations"[12]. This modified version of the concept of a model becomes crucial for teaching when dealing with atomic processes. Students, on the other hand, try to continue to think of reality on the basis of their known concept of model adequate to the real world. Here, "model" has a meaning close to "image". To what extent could students be expected to agree at all to a different meaning?

These issues are rarely discussed explicitly during teaching. Here is an example of an original dialogue:

L: *What else should be accomplished by an atomic model?*
S1: *I would like an enlargement of the atom. An intuitive model of the atom!*
L: *What kind of model should this be?*
S1: *Well, of wood or metal, or it should be possible to draw it.*
S2: *That it (the atom) cannot be seen or drawn - that's awful.*
L: *What should be made visible by the model?*
S2: *The shape.*
S3: *The orbit on which the electrons are moving.*

Here students ask for a clear explanation of the atomic processes. This aspect of students dealing with models is emphasized also in other investigations on the concept of model.[13] Their handling of the concept of models is ambivalent: on the one hand they ask for illustrations of atoms, on the other hand these models are not requested to be real. They are, as students like to say, "anyway only models of thinking". For students - and similar for physicists - it seems to be no contradiction to use the "Bohr orbit" for describing some phenomena and later on in a different context use the statistical distribution as an explanation.

From analyzing many similar dialogues we hypothetically formulated the following three tendencies in students' metacognitive beliefs about models:

Beliefs related to models in quantum physics after teaching [14]

(M1) True picture of an atom.
In spite of the second belief formulated below, students are still very interested in the question: what does the atom really look like? Models should be as close as possible to reality. Students would prefer models showing the "true picture" of an atom.

(M2) Models of thinking
To students, models do not represent the "true picture" of atoms. They use different models of electrons and atoms in different contexts and for different purposes - even if the models contradict each other. These contradictions are seen and accepted by students.

(M3) Models for visualization
Students take models as visualizations and explanations in a macroscopic scale of reality. They aim at a high amount of exactness and plausibility for a model.

The illustrative models are not requested to be consistent for the whole area of quantum physics. They may be only bound to a certain situation, and therefore need not be free of contradictions. Models are ideas of an unofficial, private nature, which need not have much in common with measurable and observable behavior of the objects to be described.

The simultaneous emphasizing of several aspects of 'models', that is to be a concrete illustration and a mere construct of thinking, enables students to maintain an illustrative idea of the atom when, at the same time, they stress that this idea is not conform to 'reality'. This withdrawal from 'reality' may be considered a concession of students to physics. For students the aspect of illustration is crucial. By separating the three beliefs on models students beat the difficulty teachers have when they try, on the one hand, to impart illustrative ideas to students in atomic physics and, at the same time, are obliged to and wish to make sure that this illustrative idea will not be considered as a 'mechanical truth'.

B. Students' conceptions about central concepts in quantum physics

The descriptions of the results of the study focus mainly on the ideas relating to the concepts of orbit and probability. In these two concepts the distinction between quantum physics and classical mechanics becomes clear in a particular way. Results from the other content areas of the study are only considered in passing.

1. Orbit (Trajectory) and Motion

The concept of orbit is used by all students. Two groups are to be distinguished as to their use of this concept. For the first group of students the concept serves to mark the difference between classical and quantum mechanical descriptions of phenomena. In the second group the concept of orbit is used directly for describing phenomena from quantum physics. As a common aspect, all students' statements describing different stationary states of an atom include some idea of electron motion. This motion is either seen to be necessary to create a probability distribution in accordance with the _^{2}-function or it is associated directly to the idea of electrons on orbits.

The following two statements of students, after instruction, show their ideas related to the distribution of electrons in the atom (Fig. 2). These statements also show that students' thinking in some sense is not so far away from fundamental ideas in physics on the generation and annihilation of particles explaining statistical distributions [15].

The first student denies the concept of orbit. However he requires motion - using its everyday life meaning - to explain the distribution of density. He is aware of the contradiction in his arguments relating to the two aspects. This is unsatisfactory for him, as he is not able to solve it. The second student also shows a discrepancy between the description of a distribution and the idea of its generation. In contrast to the understanding of physics the concept of motion in this context is crucial for her.

Uli: Well, actually I completely put aside the concept of trajectory in the area of atomic physics. The function you have is nothing but the probability of presence of an electron. ... you can't say it moves on an orbit. To explain - well, the motion cannot really be explained anymore ... It's however, not an orbit any more. .. The electron must move somehow - very strange, it is now here and then there .. That gets crazy .. Damned, it could theoretically move in between. Just that it moves in a strange zigzag, but that would mean again something like an orbit. And that's crazy again. Well, somehow I can't get that clear.

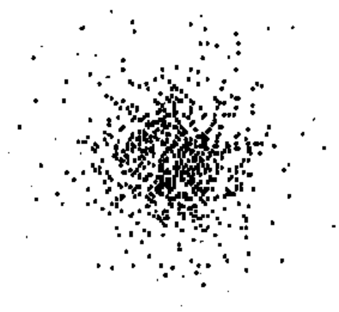


Fig. 2: Diagram of probability distribution shown during interview

Elke: If they didn't move, a probability distribution would make no sense at all. The electron would stay in one position - that's all ... As it shows up at different places it must move! Otherwise, it would be present always at only one point.

Gaby: The electron is in no position, its position can be described approximately by psi.

To test these interpretive and qualitative investigations on students' concepts in a larger scale we show quantitative results from a corresponding "thinking type" task from the questionnaire about motion versus statistical distribution.

In this task (Figure 3) the students were asked to draw possible locations of the electron at different times relating to a wave function in square well potential. They were asked to explain their diagrams.

Students' drawings were classified, most of them fitting in one of the following categories (Figure 4).

Task

The figure shows a wave function psi of an electron, which is in a square well potential. Where might the electron be found in a localization?

At time t_0 a <u>possible</u> point of the electron is already drawn. You are expected to draw possible points at further times t_1, t_2, ... to t_{10}.

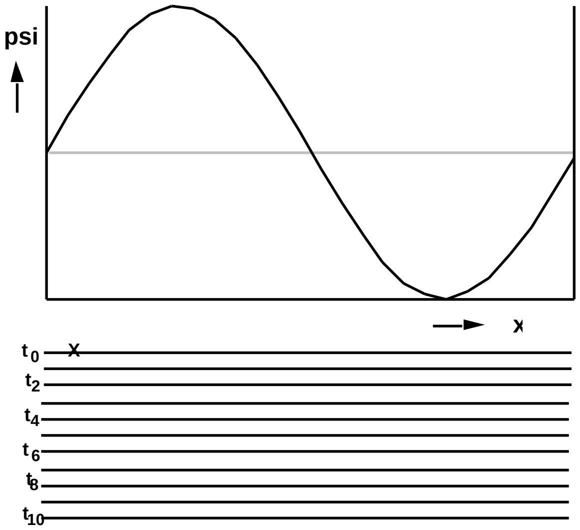


Fig. 3: Task given in the questionnaire ("thinking type question")

Students' drawings

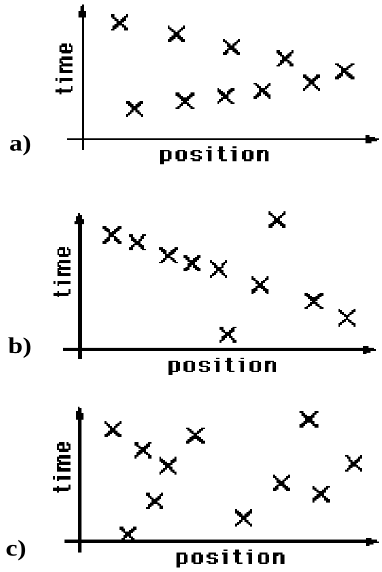


Fig. 4: The types of students' diagrams found a) Locations along a line (orbit) (≈50%), b) Similar locations, but with 'runaways' (≈15%), c) Locations with statistical distribution (≈25%)

This task together with other results allows a rough quantitative estimation of students' conceptions: about 25% of them use a conception according to quantum physics in this context. The others use either a purely classical orbit conception (50 %) or some intermediate conception with elements of orbit <u>and</u> statistics (25%).

From a physics point of view, the concept of orbit is not an adequate mode of description in a quantum physics model of the atom. It is, however, of great significance for the pre-conceptions of students in quantum physics, i.e. for understanding their statements and actions. There are two groups to be distinguished in various learning groups as to their way of orientation on the concept of orbit. One group strictly refuses the concept of orbit as a possibility of description. For them it is significant, however, in its negation. The refusal of illustrative ideas of orbits of electrons becomes a criterion of distinction between classical physics and quantum physics. The non-existence of orbits of electrons becomes the test for the existence of a quantum physics way of thinking. As we already mentioned above, this concept is held by about a quarter of the students.

Another group of students sticks to the idea of motion of electrons on defined "orbits". During instruction about the atomic shell or the one-dimensional potential well this group establishes distinguishable concrete concepts based on the general view of electrons moving on an orbit. Related to these two situations there are observably different ways of clinging to the concept of orbit, having in common that the electrons are described with orbits somehow and that a motion is attributed to them. With the atomic shell the concept of orbit is related to the notions of "probability" or "wave function", the orbit as a result seems "blurred" or "smeared", or a probability for a specific radius of the orbit is noted. The notion is adapted to the different contexts during instruction. In the description of a one-dimensional potential well the concept of "probability" recedes into the background, the electron is regarded as an oscillating particle, moving between the walls of the potential well [16].

We finally come to the following summary of conceptions related to the concept of orbit:

Conceptions related to orbits (trajectories) in quantum physics after teaching[14]

(O1) Classical orbits

Electrons move along in orbits or in oscillations. The classical notion of trajectories is conserved.

(O2) Only special orbits allowed

Specific cases of "trajectories" are "regular orbits", such as circles or ellipses. These orbits do not exist in quantum physics - which does not mean that "trajectories" are generally forbidden.

(O3) Smeared orbits

The concept of "trajectory" is combined with notions of "probability" and "wave function" from wave mechanics in several ways to form a new "intermediate" conception:

- the orbits are "smeared", not exactly determined, "fuzzy"
- the probability for a special orbit is given
- the probability of parts of the orbit is given

(O4) Trajectories do not exist in quantum physics

Students strongly express the non-existence of "trajectories" as a major postulate of quantum physics. Nevertheless they still refer to the "motion" of electrons when they think about probability distributions.

2. Stability of atoms

Students' arguments for the stability of atoms mostly refer to mechanical and everyday life ideas. They try to name activities or processes of electrons preventing them from falling into the nucleus. Such ideas are stated by the vast majority of students. A quantitative estimation was possible by introducing a corresponding question in the test, according to which about 90 % of the students after being taught quantum physics give reasons for the stability of atoms related to centrifugal forces or circular motion of the electrons on an orbit, respectively. Only few students make any remarks on the problem of electrodynamic stability in the sense of the second Bohr Postulate.

In their concepts of stability of atoms students chose a different approach than for explaining processes in the atomic shell. Even students who make use of probability distributions when describing atomic shells turn to pure mechanical concepts when explaining stability. We show one example from an interview:

Karl: *I used to think of stability in such a way that Coulomb force and centrifugal force are exactly equal and balance each other. ... Of course, that doesn't fit at all to quantum mechanics.*

I: *Do you see any connection between your ideas about probabilities we just discussed, and the stability of atoms?*

Karl: *No, I don't. For me there is, on the one hand, this idea of stability and, on the other hand, the matter of probability. I completely keep them apart. For me these are two different things. ... I have two completely different ideas. With respect to stability, I should say, it moves on an orbit. In the other case I would speak of probability of finding.*

This student makes a clear distinction between his idea of stability, which he explains by the mechanical stability in the frame of the Bohr atomic model, and wave mechanics. For students the formulation of their ideas is bound to the situation, they do not aim at a consistent theory for all different contexts.

In general, even after quantum physics instruction, the idea of electron orbits round the nucleus prevails.

3. Probability

Three aspects characterize students' approaches to the concept of probability:

Conceptions related to probability in quantum physics after teaching [14]

(P1) Probability as an algorithm
The concept of probability is used by the students as an instrument to handle and solve physical problems and tasks in a satisfactory way. Linking the term probability to the term possibility permits to interpret the mathematical formalism of wave mechanics. Students readily use an interpretation or translation algorithm from instruction.

(P2) Probability as a causal description
For better understanding of the given probability distributions some students request a causal explanation for the generation of these distributions on the basis of single events. Students require an understanding of the development of the distribution step by step.

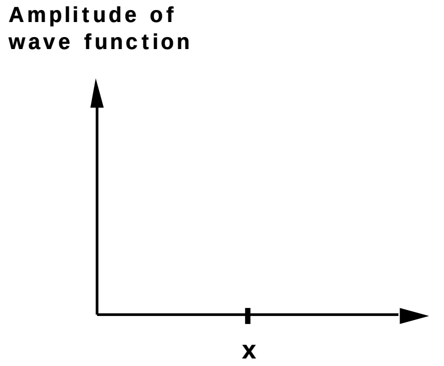
(P3) Probability as inaccuracy
Some students attach the idea of inaccuracy to the term probability. These ideas point to the everyday meaning of the term. By using the term probability, exact and definite statements are excluded.

The aspects of students' opinions relating to the term probability listed in points P2 and P3 show their dissatisfaction with the meaning of quantum physics' formalism offered during instruction. For quantum physics instruction the usage of the term "probability" is of some significance.

We therefore revert to point P1 in more detail.

Classroom tape recordings show that students are able to manage physical situations with the assistance of the term probability. They use the term in the sense of an interpretation or translation calculus.

One task of the questionnaire (Figure 5) reveals more details of the application of the interpretation of probability. In this task a wave function of a quantum located in the interval around point X has to be found. A wave function corresponding to the given physical situation is to be drawn and explained.



Task

Draw the amplitude of the wave function into the given diagram, such that it is describing an electron which stays in a small space interval around x. Give a short explanation of your drawing.

Fig. 5:
Task given in the questionnaire ("thinking type question")

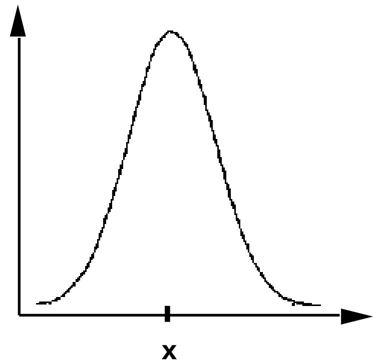


Fig. 6a: Type 1 answers of students

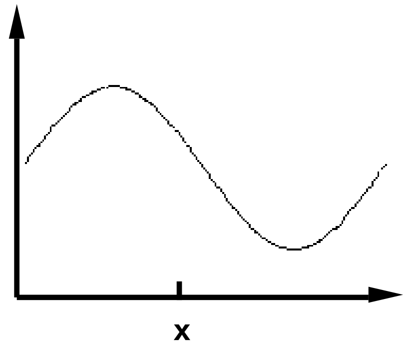


Fig. 6b: Type 2 answers of students

In **students' diagrams** we found only two types (Fig. 6a and 6b). In type 1, the wave function has an amplitude noticeably different from zero only in the area of a location interval around point x. (80 %). In type 2, the wave function is one period of a sinus wave over the whole range of the x-axis, similar to a standing wave in the square well potential. (12 %)

In **students' explanations** given for the diagrams we found the following three categories:

Type 1: The likelihood of a localization is defined by the amplitude of the wave function or its square.

Type 2: A sinusoidal standing wave is determined within a defined area. Outside of this area the amplitude is zero.

Type 3: The drawing is explained by using the Heisenberg uncertainty relation

The relation between the categories of text and diagram as well as the quantitative results are shown in table 1.

Table 1: Answers about the concept of probability

N= 142; total number of answers: 109; no answer (neither diagram nor explanation): 33					
Diagram / **Explanation**	**Type 1**	**Type 2**	**others**	**no Diagram**	**Total**
Statistical Explanation	55	0	0	1	**56**
Explanation with standing wave	2	4	0	0	**6**
Explanation with HU	7	0	0	0	**7**
Various explanations	2	4	0	1	**7**
No explanation	22	6	5		**33**
Total	**88**	**14**	**5**	**2**	**109**

Out of all students, 50 % have drawn a wave function whose amplitude is essentially different from zero only in the area of the location interval around point x, and they based their drawing on the statistical interpretation of probability of wave functions. This answer is physically correct in the frame of wave mechanics. Altogether, 80 % produced a correct drawing (type 1). Many students are able to solve the type of problems described in the task with an algorithmic conception of probability (P1) and to apply the meaning of the quantum physical formalism on probability also in a modified context. For some students the association of periodical processes with wave functions prevails so that they do not produce a solution adequate to the problem.

To illustrate the other aspects of handling the term probability one example shall be sufficient. During instruction the interpretation of probability of the _-function had been used to explain the double slit experiment with electrons. One student (Olaf) states his dissatisfaction with the interpretation of the interference picture. He misses the reasons for the kind of distribution and also the reasons for the behavior of the single quantum.

Olaf: *... How the quantum knows it is not allowed to go there? - They are, you see, quite clever that they turn round and change, at times a wave, at times a particle.*

Andreas: *We have areas of certain probabilities of the electrons.*

Olaf: *When they (physicists) don't know what to do they talk of probabilities. (...) What's the reason for the quanta for the actual distribution?*

Andreas: *Natural law!*

Olaf: *I mean, if you drop a coin the probability for each side be up is 1:2, and the probability is such because both sides have equal chances. - So, for what reasons the quanta shall distribute themselves as they do?*

For Olaf the use of the term probability in physics means only an excuse, a not knowing. He expects an explanation plausible even for himself for the probability distribution. The mathematical formalism of the explanation of probability waves offered by the teacher is insufficient for him. For him explanation means that some illustration must be possible, such as the example of the coin given by himself where he uses the equal "rights" of the two sides of the coin to explain the probability distribution. The other student accepts the teaching approach, he does not ask for causal explanations. It's just what it is - a natural law.

The interpretation of the _-function through statement of probabilities is accepted and applied by students as a calculus. A rough quantitative estimation of the spreading of this element of pre-understanding is possible on the basis of the tasks. About four fifths of the students questioned could make good use of the term probability as a calculus of interpretation. For students, however, the realization of probability distributions requires further explanations, otherwise some dissatisfaction with this way of description will remain. The explanations for probability distributions considered necessary by students are rarely explicitly asked for in instruction; most important for them is the (correct) application of the calculus. The lack of explanation is related to the idea of "inaccuracy" linked to the term probability. Students' dissatisfaction with the - in their eyes - insufficient possibilities to describe phenomena of quantum physics emerges in discussions on learning atomic physics. With the idea about generation of a probability distribution students create a link to their ideas about motion of electrons on orbits.

4. Energy

Quantization of energy is readily accepted for bound electrons, students use this concept spontaneously in their own reasoning.

The term energy is not only used in the context of discrete energy levels; students revert to the concept of energy for balancing of processes. Students then do not start from the physical term - energy as an abstract balancing quantity - they rather comprise the balancing of concrete material objects (e.g. mass, number of particles, number of photons) under the term "conservation of energy ". The term energy as a generic term for such balancing is suitable for students as different ideas may be linked together. The term energy is easily accepted by teachers in students' physical statements. The term energy therefore represents a possibility for teachers and students to come to terms on phenomena in the area of abstract quantum physics, as different ideas may coexist under this term. It is because of this particular function of the term energy that it is often used by students in statements of their own.

Conceptions related to energy in quantum physics after teaching [14]

(E1) Quantization of energy
The quantization of energy is readily accepted by students. They soon start to use it as a basis for their own reasoning. They do not ask for a physical explanation of this fact. Students seem to have no "need" for a more sophisticated atomic model. To the contrary: A simpler "model" can be based on this assumption.

(E2) Energy levels
"Energy levels" can be explained by any model of the atom. In different situations students use different models to explain energy levels. "Energy levels" are lines in an energy level diagram

(E3) Reasoning with "energy"
Students use the concept of energy actively in their own reasoning. The conservation of energy plays an especially important role in students' own explanations, e.g. related to emission and absorption of light in atoms or molecules.

V. Conclusions

The resulting conceptions of this study are formulated to describe students' views of central concepts being taught in quantum physics. They are meant to have a status "as if": students are thinking and acting as if they have cognitive representations like those having been described in this study. From the viewpoint of physics they are not coherent concepts. Their meaning varies in different contexts. One example: on the one hand, students to a large extent accept a probability view when talking about the position of an electron, and on the other they use a purely classical view of orbits when explaining the stability of atoms like that of planetary motion. This seems to be no contradiction for students; they use different structures in different contexts. We discussed that while talking about students’ conceptions with models (M2).

With respect to consequences for teaching we believe that students difficulties could be reduced using "state" and "orbital" as central concepts instead of "orbit" and "trajectory". This could help them to construct meaning of concepts and phenomena in a less mechanistic way. The concept of a quantum state can be connected to the idea of energy levels, which as a result of our study are readily accepted and easily used by students. Different states of systems are also well known from everyday life and thus already have an intuitive meaning. The states then can be described more precisely as "orbitals", using probabilities and charge densities. With a concept of state students could come to a conception of stability of atoms which is nearer to quantum physics.

Endnotes

[1] The bibliography of Helga Pfundt and Reinders Duit, *Bibliography: Students' Alternative Frameworks and Science Education* (IPN, Kiel, 1994), 4th ed., contains 34 papers in atomic physics, compared to over 500 in mechanics. Some more recent research results are: Helmut Fischler, Michael Lichtfeldt, "Modern physics and students' conceptions," International Journal of Science Education, **14**, 181-190 (1992); Michael Lichtfeldt, *Schuelervorstellungen in der Quantenphysik und ihre moeglichen Veraenderungen durch Unterricht (Students' conceptions in quantum physics and their possible change during instruction)* (Westarp Wissenschaften, Essen 1992) (Doctoral dissertation, Free University of Berlin); A. Mashhadi, "What is the nature of the understanding of the concept of 'wave-particle duality' among pre university physics students?," in *Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics* edited by J. Novak (Ithaca, New York: Cornell University 1993) (distributed electronically); Hartmut Wiesner, "Ergebnisse von schriftlichen Befragungen zum Kenntnisstand von Schuelern ueber Quantenphysik (Results of surveys about knowledge of students in quantum physics)", in *Didaktik der Physik. Vortraege Physikertagung 1993*, edited by G. Kurz (Bad Honnef: Deutsche Physikalische Gesellschaft, 1993), pp. 565-570

[2] Thomas Bethge, *Aspekte des Schuelervorverstaendnisses zu grundlegenden Begriffen der Atomphysik (Aspects of students' matrix of understanding with basic concepts in atomic physics)*, (Doctoral dissertation, University of Bremen, 1988)

[3] P. Fensham, R. Gunstone, R. White (Eds), "Indroduction," in *The content of science*. (The Falmer Press, London, 1994), pp. 1-8

[4] Merlin C. Wittrock, "Generative science teaching," in *The content of science,* edited by P. Fensham, R. Gunstone and R. White (The Falmer Press, London, 1994), pp. 32-38

[5] By 'technology' Luhmann means "the science of those causal conditions forming the base of practical intentions and to which action will have to be directed to be successful.", Niklas Luhmann and Karl E. Schorr, "Das Technologiedefizit der Erziehung und die Paedagogik," Zeitschrift fuer Paedagogik **25**, 345-365 (1979)

[6] Ref. 4, p 353

[7] Alfred Schuetz, "Symbol, Reality and Society," in *Collected Papers I*, (Martinus Nijhoff, The Hague, 1967), 2nd ed., pp. 287-356

[8] Leo H.T. West, Peter J. Fensham and Janice E. Garrard, "Describing the cognitive structures of learners following instruction in chemistry," in *Cognitive structure and conceptual change,* edited by L. West, and L. Pines (Academic Press, Orlando, 1985), pp. 29-49

[9] Ref. 4, p. 351

[10] Thomas Luckmann, "Einige Ueberlegungen zu Alltagswissen und Wissenschaft," Paedagogische Rundschau, **35**, 91-109 (1981)

[11]Basis for the teaching concept in these courses was an approach to quantum mechanics similar to that described by Hans J. Niedderer, Thomas Bethge, and Hanna Cassens, "A Simplified Quantum Model: A Teaching Approach and Evaluation of Understanding," in *Relating Macroscopic Phenomena to Microscopic Particles - A Central Problem in Secondary Science Education*, edited by P. L. Lijnse, P. Licht, W. de Vos, and A.J. Waarlo (CD-ß Press, Utrecht 1990), pp. 67-80

[12] Max Jammer, "Die Entwicklung des Modellbegriffes in den physikalischen Wissenschaften," Studium Generale, **18**, 166-173, (1965)

[13] In the investigation of L. Grosslight, C. Unger, E. Jay, and C. Smith, "Understanding Models and their Use in Science: Conceptions of Middle and High School Students and Experts," Journal of Research in Science Teaching, **28**, 799-822, (1991) the students saw the models of concrete objects as the most important form of a model.

[14]Alternative conceptions referring to different groups of students or different states of the learning process or different context.

[15] See, for example, Max Jammer, *The Philosophy of Quantum Mechanics - The Interpretation of Quantum Mechanics in Historical Perspective* (Wiley, New York, 1974, p. 429) and Fritz Bopp, "Elementarvorgaenge der Quantenmechanik in stochastischer Sicht," Annalen der Physik 17 (7.Folge), 407-414 (1966).

[16] The one-dimensional potential in our earlier approach served as a simple example for the application of the Schroedinger equation in teaching concepts on quantum physics *(e.g. Hans J. Niedderer et al. Ref. 11)* illustrating the structure of the solutions of the Schroedinger equation, with applications to colours of dyes. As students construct meaning in these examples drawing on an intuitive picture of an electron moving as a particle between two walls, the idea to introduce the potential well as a basis for teaching an atomic model based on quantum physics was abandoned in later versions of our curriculum.