



The Karlsruhe Physics Course

for the secondary school A-level

The Teacher's Manual

Atomic physics
Nuclear Physics
Particle Physics

The Karlsruhe Physics Cours – *The Teacher’s Manual*

A textbook for the secondary school A-level

- Electrodynamics
- Thermodynamics
- Oscillations, Waves, Data
- Mechanics
- Atomic Physics, Nuclear Physics, Particle Physics**

Herrmann

The Karlsruhe Physics Course

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Edited by Prof. Dr. *Friedrich Herrmann* and Dr. *Holger Hauptmann*

Translation: *F. Herrmann*

Figures: *F. Herrmann*

Computed Figures with density distributions: *Patrick Bronner* and *Sebastian Kretz*



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Physical Foundations

1. Reality, theory and model

In physics, we are dealing with three areas, Fig. 1:

A. With the real world. In it, the phenomena that we want to describe take place.

B. With a theory. It consists of mathematical objects and relationships between these objects. The theory, including the objects of which it consists, i.e. Variables, operators and arithmetic operations are human inventions.

C. With models. A model is also a system of the real world. Unlike A, this system is familiar to us. The terms used to describe it are familiar to us, and the relationships between the parts that make it up are plausible.

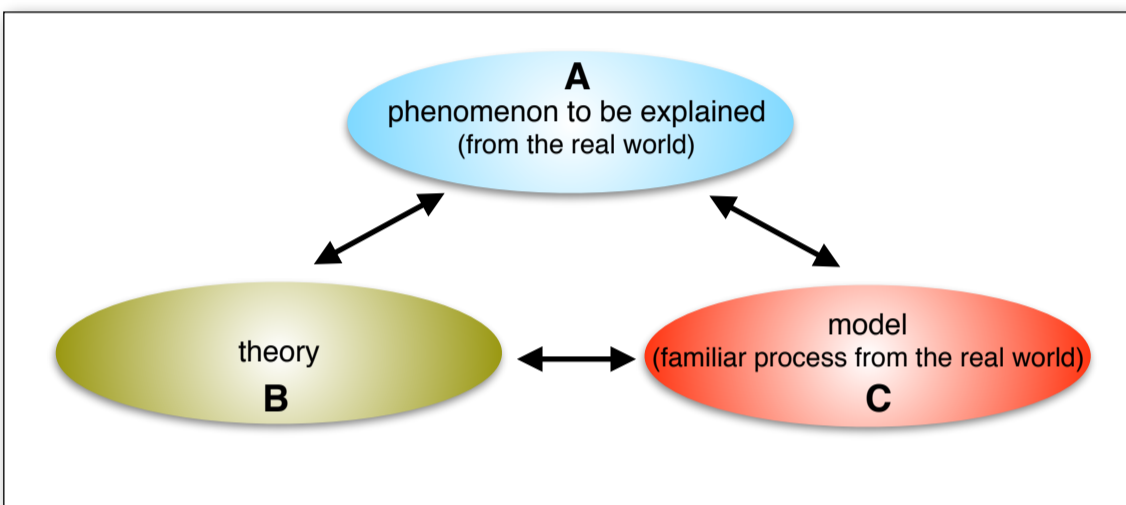


Fig. 1

A group of phenomena, that is described by physics, the corresponding theory and an appropriate model all have the same structure.

These three areas have a common structure. Elements of one of them can be imaged onto each of the others and the relationship between them within one area is the same as that between the corresponding elements in the other areas. So there is a homomorphism between A, B and C.

However, this common structure only relates to a few aspects of the systems considered.

A theory always describes only a small part of the system under consideration and a model does not match the original system in most of the properties. If the theory maps the considered range of phenomena with great accuracy, it is a good theory. If there is much agreement between the phenomenal area and the model that is used, the model is a good model. There are no correct and incorrect theories; there are only more or less good ones,. And there are no correct and incorrect models; there are only more or less appropriate ones.

The language we use when we teach physics sometimes belongs to area A, sometimes to B and sometimes to C. What we perceive as „understood“ is based on the language, which refers to C, i.e. the model area. We understand something that seems abstract at first, when we can say, „It’s similar to ...“ and then follows the description of the behavior of our model. Every understanding goes back to a „it’s similar to...“.

2. Difficulties in learning quantum physics

With quantum physics we mean in the following the quantum theory and the description of the real world with the help of this theory. The difficulties we encounter in teaching are twofold: some are of a mathematical nature and have to do with area B. The others are of a conceptual nature and belong to C.

Mathematical difficulties

First, it should be noted that there is no problem here that distinguishes quantum physics. We have a well-functioning theory, and this is no more difficult than, say, Maxwell theory, Hamiltonian mechanics, or statistical thermodynamics.

A problem arises only because the corresponding mathematics is not available to us at school – just as in the case of Maxwell's theory, that is, electrodynamics. In the case of electrodynamics we lack the vector analysis, in the case of quantum physics we lack complex numbers and partial differential equations. As with electrodynamics, a didactic reduction must be made. One way to get around the complex numbers is to use the pointer formalism. We do not go this way, because we think the pointer calculus has the same difficulties as the complex numbers themselves.

Conceptual difficulties

Everyone knows the conceptual difficulties from his own experience. It is often said that they disappear by getting used to it. But it can be said that even older physicists, who had enough time to get used to it, still discuss it passionately. So it looks more like we're dealing with problems not found in classical physics. Here are some of the statements that make us feel that we have not understood the matter correctly:

- An electron is both particle and wave.
- Two particles are basically indistinguishable.
- An electron moves around the nucleus but does not move on a trajectory.
- Particles fly through a single or two slits, but still produce a double-slit interference pattern.
- The angular momentum of particle A is basically indefinite. However, if one measures the angular momentum of a particle B 100 km away, that of A is also determined.

The difficulties associated with these sentences have to do only with the choice of the model, that is with our area C.

3. The status quo

Atomic and quantum physics as a story

It is noticeable that in both school and university books the history of quantum physics is described in many details. Numerous contributions by individual researchers are listed, and their experiments are described as if this was the only way to understand. This path was laborious and rich in detours. Much of this effort is now required of the learners, and the detours are pursued again. It's all too easy to lose sight of one question: what do students, or pupils at school, know after one year or five years? Yet everyone knows the answer to the question: they remember the Bohr atomic model, i.e. a model that was only intended as a stage on the way to the actual learning objective. The motto „The way is the goal“ certainly should not be applied here.

So we are wasting time that we would so badly need for more important subjects.

And what does the result of such lessons look like? What idea of an electron, a photon and an atom do the students end up with?

The current ideas about the electron, the photon, and the atom

The electron

One imagines the electron as a body, with the following characteristics: it is small, perhaps punctiform, it is an individual, that is, one can follow it in space and time. That an electron is considered as an individual can be recognized from every statement that speaks of the motion of an electron. First *it* is here, then *it* is emitted, then *it* flies from the cathode to the anode, *it* is deflected, etc. *It* always remains the same.

Even though it is said that the electron does not have some of these properties, by our way of speaking about the electron we support the expectation that it is an individual. One chooses an inappropriate model, then says that it does not fit to the model, but one still does not abandon the model. The idea of the individual small body remains in the minds of the learners.

The photon

Also the photon is thought of as a small body flying around on well-defined paths. One does so for example when one says that a photon moves or flies from the sun to the earth.

It is interesting that hardly anyone can be persuaded to say what size a photon has. Nevertheless, it is easy to find out something about what people think about the size of a photon: in many sentences pronounced about photons, an upper limit of this size is clearly assumed. For example, if one says that a photon is emitted by one body and then absorbed by another, it is assumed that the photon is shorter than the distance between the emitting and the absorbing body. If one says that the photon passes through an aperture, it is assumed that it is smaller than the aperture in its transverse dimension. Of course, one could also imagine that it is wider before and after, and contracts to get through the aperture. But this view does not seem to prevail. Even if one does not formulate these ideas openly – with the language that one applies to the photons, such images are evoked and strengthened.

The atom

It is essentially empty. The shell is empty anyway, because the electron is point-like. The core was initially considered not empty. Since we know the quarks, which we also imagine point-like, also the core became empty. Thus, the whole world is empty. This emptiness is somewhat relativized by the fact that the electron, which is said to move around the nucleus, does not have a specific orbit and with a certain probability lingers a bit everywhere.

„For small quantum numbers, however, the concept of the trajectory obviously has to lose its meaning both in phase space and in the real space“, says Heisenberg [1]. But how can the concept of the trajectory lose its meaning without losing its meaning the point-like individual corpse?

One talks about phenomena in such a way that the logic inherent in our language no longer allows for a control.

That the model does not fit, one tries to mitigate with several other words and phrases. The particle becomes a *quantum object*, the trajectory to the *path*. These and other terms really only express our helplessness. The same holds for expressions like „complementarity“, „dualism“ and „quantum possibility“.

A sentence like: „The particle moves around the core, but has no trajectory“ simply does not make sense if you deal with the language as you have to deal with it, if you want to communicate at all.

So let us conclude that the idea of the electron and the photon as point-like individuals is not a good model, and above all that it leads to „it's similar to...“ conclusions in cases where actually it is not similar to anything.

Two ways out are possible:

1. Choose a better model.
2. Completely renounce a model.

In the following, we want to address both possibilities.

4. An alternative model

We propose a model, in which one imagines the electron as a portion of a negatively charged substance distributed in space. This model is as old as quantum mechanics itself. It comes from Schrödinger and was further elaborated by Madelung [2]. Although it reproduces several phenomena very satisfactorily, it is only occasionally mentioned in general textbooks of atomic physics, as in Döring [3]: „[...] Bohr's postulates are easily obtained from known laws of physics, if one applies the wave model instead of the particle model, i.e. if one assumes that the electron matter is continuously distributed with a density proportional to the square of the absolute value $|\psi|^2$ of a complex wave function ... ” The model has survived only in the special literature about quantum hydrodynamics and the density functional theory.

We consider the Schrödinger equation for a one-electron system:

$$i\hbar \frac{\partial}{\partial t} \psi(\mathbf{r}, t) = \left(-\frac{\hbar^2}{2m} \Delta + V(\mathbf{r}) \right) \psi(\mathbf{r}, t)$$

The solutions are called wave functions. By means of the wave function $\psi(\mathbf{r}, t)$, i.e. a solution to the Schrödinger equation, we define two expressions. First:

$$\rho := \psi^* \psi \quad (1)$$

and second:

$$\mathbf{j} := \frac{\hbar}{2mi} (\psi^* \nabla \psi - \psi \nabla \psi^*) \quad (2)$$

In a one-electron system the knowledge of the two functions $\rho(\mathbf{r}, t)$ and $\mathbf{j}(\mathbf{r}, t)$ is equivalent to the knowledge of the wave function. Any statement that follows from the wave function also follows from $\rho(\mathbf{r}, t)$ and $\mathbf{j}(\mathbf{r}, t)$.

Using the Schrödinger equation and the expressions (1) and (2) one gets:

$$\frac{\partial \rho}{\partial t} + \operatorname{div} \mathbf{j} = 0 \quad (3)$$

This equation has the structure of a continuity equation. Multiplying the quantities ρ and \mathbf{j} with the elementary charge e

$$\rho_e = e \cdot \rho$$

$$\mathbf{j}_e = e \cdot \mathbf{j}$$

one can write the continuity equation in the form:

$$\frac{\partial \rho_e}{\partial t} + \operatorname{div} \mathbf{j}_e = 0 \quad (4)$$

By multiplication with the mass m of the electron

$$\rho_m = m \cdot \rho$$

$$\mathbf{j}_m = m \cdot \mathbf{j}$$

one gets from (3):

$$\frac{\partial \rho_m}{\partial t} + \operatorname{div} \mathbf{j}_m = 0 \quad (5)$$

Equation (4) can now be read as a continuity equation of the electric charge and equation (5) as a continuity equation of the mass. Equations (4) and (5) express the conservation of electrical charge and mass, respectively.

This interpretation means that one imagines the shell of the atom to consist of a substance which is distributed continuously around the nucleus, and which in general also flows. Döring [3] calls this imaginary material as „electron matter“. In our student text we call it „electronium“ for short.

The electron in this model is made up of electronium such as a lake consists of water or a coin of metal.

We want to investigate how density and current density behave for different types of solution of the Schrödinger equation. The Schrödinger equation has special solutions of the form:

$$\psi_k(\mathbf{r}, t) = u_k(\mathbf{r}) e^{-\frac{i}{\hbar} E_k t} \quad (6)$$

The associated states are called eigenstates. The solutions and the corresponding states are numbered with the index k . To each such solution belongs a certain value E_k of energy, the energy eigenvalue. Note that in (6) the position and time dependencies are separated. The position dependence is only in the first factor $u_k(\mathbf{r})$, the time dependence only in the exponential function.

Also every linear combination of these eigenstate solutions is a solution of the Schrödinger equation:

$$\psi(\mathbf{r}, t) = \sum_k a_k u_k(\mathbf{r}) e^{-\frac{i}{\hbar} E_k t}$$

A state described by such a sum is called a superposition state. The superposition states differ in an important property from the eigenstates: For the eigenstates density and current density are time-independent, for the superposition states not. We want to show that.

In an eigenstate the density of the electronium is:

$$\rho_k(\mathbf{r}, t) = u_k^*(\mathbf{r}) e^{+\frac{i}{\hbar} E_k t} \cdot u_k(\mathbf{r}) e^{-\frac{i}{\hbar} E_k t} = u_k^*(\mathbf{r}) \cdot u_k(\mathbf{r})$$

The product of the two exponential functions is equal to one, so the time dependence disappears, or in other words: the density is constant over time. The calculation of the current density gives a similar result. It too is constant in time (but not necessarily zero). The eigenstates are therefore also called stationary states.

We now consider a superposition state. We take the simplest case imaginable: the superposition of only two eigenstates. So the sum consists of two summands:

$$\psi(\mathbf{r}, t) = c_A \psi_A(\mathbf{r}, t) + c_B \psi_B(\mathbf{r}, t)$$

with

$$\psi_A(\mathbf{r}, t) = u_A(\mathbf{r}) e^{-\frac{i}{\hbar} E_A t} \text{ and } \psi_B(\mathbf{r}, t) = u_B(\mathbf{r}) e^{-\frac{i}{\hbar} E_B t}$$

Since the calculation of ρ is cumbersome, we do not execute it here, but only give the result. It is an expression of form:

$$\rho(\mathbf{r}, t) = C_0(\mathbf{r}) + C_1(\mathbf{r}) \cos(\omega t) + C_2(\mathbf{r}) \sin(\omega t)$$

It can be seen that now the density depends on the time. We have:

$$\omega = (E_A - E_B) / \hbar$$

One can also see: The density is composed of a term that only depends on the position and a remainder that vibrates harmonically. Again, the corresponding applies to the current density. These states are non-stationary.

Compared to the point-particle model, our „substance model“ has the following advantages:

1. The electron distribution corresponds to the charge distribution in atoms and solids, which is determined by scattering experiments. The substance model therefore makes statements about what one might call the shape of atoms and molecules.
2. The substance model correctly states that an electron does not radiate in a stationary state.
3. The substance model correctly reproduces the orbital angular momentum and the magnetic moment.
4. The substance model predicts which transitions are fast, which are slow and which do not take place at all (which transitions are allowed and which are forbidden).
5. The substance model predicts how the radiation emitted by an atom or molecule or a lattice defect is polarized.

5. Physics without any model – the new insight

The phenomena that worry us most are those you cannot find a model for. The particles have properties that can be mathematically modeled, but for which we do not find any „it’s similar to...“ in the realm of our experience. This has to do with the fact that physical quantities are no longer represented simply by variables but by operators or matrices. And it has to do with the fact that a many-body wave function is a function in a high-dimensional space, the configuration space. Thus, the wave function of the electron shell of a sodium atom (atomic number 11) is a function in a 33-dimensional space. How can we deal with such problems in the physics lessons of the school?

Often one addresses these questions with a certain fatalism: Because we all make our experiences in the macroscopic lifeworld, we basically can not understand the phenomena of quantum physics. So there is a limit to our understanding. It all too easily results in the impression that we are finished with our wisdom.

We propose to see the positive side of these difficulties. Let us have another look at Fig. 1. Humans make the theory, and humans choose a model. The more important of these two activities is the invention of the theory [4]. Models are helpful in inventing new theories and make it easier to deal with physics. But basically we can do without them, especially when it comes to applying physics. The insight that we sometimes have to do without a model is something like the end of a beautiful dream, or even like growing up. The comfortable physics of simple models is over. We try to convey this message carefully to the pupils.

6. Physics and enlightenment

There are topics that particularly fascinate and motivate teachers and students. These are themes that shake our metaphysical core beliefs: our idea of space and time, or of cause and effect. Apparently, quantum physics is particularly rich in such topics. The fact that one can not simultaneously specify the position and momentum of a particle, which one imagines point-like,; the entanglement of two mutually distant particles; the so-called teleportation. These facts or phenomena teach us that something that was considered impossible or unlikely is possible. We try to disenchant these effects. We try to present quantum physics in a way that does not give the impression that miracles happen. Because otherwise all too easily it will move in the vicinity of real miracles, i.e. meaningless statements. We try to expose the fascination emanating from such phenomena as an all-too-human tendency to believe the unbelievable or improbable; a fascination that many people succumb even when the miracle is no longer supported by science.

So we do not put those phenomena in the foreground where something very incredible happens. Entanglement of particles already exists in the single atom, and nobody has a problem with it. Only when one brings a system into extreme states, which can often only be realized in the thought experiment, does the phenomenon seem fascinating to us, and unfamiliar. One might just as well present thermodynamics or classical electrodynamics in a way that wonderful things happen. Gibbs' paradox, Maxwell's demon, and energy flows in static electromagnetic fields are examples. We do not do it, and we do not have to do it in quantum physics either. Physics is interesting enough anyway.

[1] HEISENBERG, W.: *Physikalische Prinzipien der Quantentheorie*, Bibliographisches Institut Mannheim 1958, S. 27.

[2] MADELUNG, E.: *Quantentheorie in hydrodynamischer Form*, *Zeitschr. f. Physik* 40, 322-326 (1926).

[3] DÖRING, W.: *Atomphysik und Quantenmechanik, II. Die allgemeinen Gesetze*, Walter de Gruyter, Berlin 1976, S. 20.

[4] FALK, G.: *Physik – Zahl und Realität*, Birkhäuser Verlag, Basel 1990.: „A mathematical and scientific image of the world that is logically mandatory is not possible ... Only an abstract structure of relations between concepts is mandatory, concepts that are free inventions of the human mind and not, as was once believed, pictures of realities that exists also without the human mind – just as living things, stones, earth, moon, sun are realities that exist without the human mind. Our experience of reality is reflected scientifically and quantitatively only in relationships that exist between invented concepts – or rather are determined by us to reflect the real experiences – but not in pictures that we make of these concepts.“



Remarks

1. Models in physics

Quantum physics is suitable for addressing a topic in the classroom that one might call epistemology. Actually, in every science teaching process one has to deal with questions of epistemology from the beginning. An overview of the possibilities for this is given by Leisen [1].

However, it is not easy to learn a subject while at the same time thinking about process of learning. Now, in physics, the time comes where thinking about the process of learning is no longer avoidable, that is, when dealing with quantum physics. If this reflection about epistemological issues is not done, the students might get the impression that nature is full of contradictions.

2. Photons and electrons

The wave-particle duality

The problem that in the traditional interpretation of quantum mechanics, a „micro-object“ sometimes appears as a wave and sometimes as a particle, does not arise with us. By way of explanation, we consider the electron, since it is the particle most familiar to physicists. But the same applies to photons and other particles as well.

According to quantum mechanics, the wave character of an electron manifests itself most clearly when it is in a state with a well-defined value of its momentum (and that means with a certain wave number). The position is then extremely uncertain. The particle character manifests itself most clearly when the system is in a state of a certain position and with a very uncertain momentum.

However, particle and wave are two model concepts.

The perfect particle is thought to be point-like. Its location in space is defined by a single point. (This is different from macroscopic bodies, whose location can not be determined by a point because they occupy an entire space area.)

In contrast, the perfect wave is imagined to be sinusoidal and infinitely extended. Thus its momentum is given by a single k vector, i.e. a single point in momentum space.

In any state of the electron, neither one nor the other model fits. And if the electron also undergoes a process of changing its state, moving from a state of certain momentum to a state of certain position, of course, there is a problem in trying to apply one of the extremes models, i.e. that of a particle (point in the space) or that of a wave (point in the momentum space). One clads the conflict into the somewhat obscuring words „wave-particle dualism“ or „complementarity“.

Such designations suggest a somewhat mystical principle. But if we look at the associated mathematics, things look a bit simpler. The uncertainty principle tell us that the extension of a particle in space, multiplied by that in momentum space, has a certain minimum value. We can only change one at the expense of the other, but we cannot change their product. A comparison: We consider a portion of water flowing through a pipe. As the tube narrows, the portion of water becomes thinner and longer. Diameter and length of the water portion are in a certain ratio to each other. Here one would certainly not say that diameter and length follow a principle of complementarity, because the phenomenon has nothing surprising about it. The only reason the electron needs to have such a description is because with an inappropriate model one creates the expectation that an electron that was once small must also remain small, or an electron that once had a sharp momentum value, must always have it. With our water portion we do not have the corresponding expectation.

The problem disappears if one does not apply the models „point-like particle“ and „infinitely extended sine wave“, but admits from the very beginning that a particle has a variable extension, namely the space occupied by the wave function.

We use the word „particle“ no matter what state the electron or photon is in.

Light as a substance

In the context of light and its elementary portions, the photons, it is sometimes said that light is an energy form and that photons are energy quanta. When saying that, two concepts are confused: that of a physical quantity, energy, and that of a physical system, the electromagnetic field. A physical system is always described by a set of physical quantities and the relationships between them. The statement that light or electromagnetic radiation is energy is just as inappropriate as the statement that an ideal gas is energy or that electrons are energy. Just like an ideal gas or any other system, besides energy light has momentum, angular momentum, entropy, and mass, and it has a pressure, a temperature, and a chemical potential.

It is important to make clear in the classroom that light is something that is very similar to a substance, indeed, it can be said to be a substance. Just as the elementary portions of the substance helium are the helium atoms, or those of the water are the water molecules, so the elementary portions of the substance light are the photons. To make that clear, we introduce the photons via photochemical reactions. Here it should become clear that light appears as a reaction partner very similar to any material substance. In a reaction equation we designate it with the symbol γ .

When setting up a reaction equation γ does not necessarily appear on both sides of the equation, as the chemical elements do. This should not bother us. The reason is that in the reaction light can be produced or destroyed. In the case of nuclear reactions, the students will have to get used anyway to the fact that there are not the same numbers of each species of atoms on the right and the left side of a reaction equation.

In order to avoid the misconception that photons are energy quanta, it is important that in a reaction equation the light is not represented by the symbol $h\nu$, because $h\nu$ is not the name of a substance but stands for an energy value.

The size of photons

What is the size of an object? The answer seems simple: the distance between its beginning and its end. The question can be further generalized: What is meant by the shape of an object? The answer to this question is: It is the shape of its surface. In the following, when we speak about the size of an object, we always mean it in that sense.

So, what shape does a photon have? To answer the question, we need to know where are the beginning and end of the photon, or we need to know where its surface is. One might object that the beginning and the end of a photon can not be defined, let alone its surface. So a photon wouldn't have any size. The term size in the sense of extension comes from our experience in the macroscopic world. It can not be used in microphysics and especially in quantum physics, would be argument. The question of the size of a photon is therefore as meaningless, just as the question for the color of an atomic nucleus.

However, if we agree with this view, we must abandon a whole series of other statements. Whenever we talk about photons, we use a model. For example, we say that the photon is emitted by a light source and later absorbed by some other body. The model used here is the model of the little objects moving through space. Now, we do not want give up this model. But if we use it, we have to attribute a certain size to the photon.

The statement that a photon moves from a light source to an absorber only makes sense if the photon is smaller than the distance between the source and the absorber. If the source and the absorber are at a distance of 10 cm, it follows that the photon is shorter than 10 cm. However, the source and absorber can also be located at a distance of 1 mm or 1 μm . So, by saying that the photon is first emitted and then absorbed by an absorber 1 μm away from the source, we presume that the photon is shorter than 1 μm .

In some textbooks one can read that elementary particles are point-like. This statement is awkward. Even if we should prove in a measurement that the diameter of an electron is smaller than 10^{-30}m – a structure with a diameter of 10^{-30}m is far from a point. The point is a metaphysical concept, it is a product of our mind. That a particle is point-like can neither be verified nor falsified.

Here's our conclusion: Even if one does not admit it – one is spreading the idea that the photons are very small. In any case one speaks in such a way that the pupils have to believe it. Because if you use the model of the flying individual, the question for its form and its size is legitimate. And if we do not answer them, the students will answer themselves. So we are relinquishing control over the learning process in an important context. If we let the photons fly around, we also have to say what shape and size they have.

But what is their size? Or better: Does the model allow to attribute a size to the photons?

For the physicist this question is not difficult to answer. Even if we are embarrassed we asked to define the beginning and the end of a photon, or the surface of the photon in the sense of our macroscopic experience, we can give an answer that does justice to the question. Does the theory of the photon provide any characteristic with the dimension of a length? Yes it does. Actually there are two candidates: the wavelength and the coherence length.

We can exclude the wavelength from the outset. According to our model, the photon is an entity extended in the three spatial dimensions. The wavelength however refers to only one dimension.

On the other hand the coherence length, or more precisely, the three-dimensional coherence region, is a suitable measure of the extension of the photon. It has a well-defined, measurable shape. That is why we interpret the coherence range of a particle as the space the particle occupies. The shape of the coherence region is the shape of the particle. Later, we apply this definition to electrons.

This interpretation of the particle size is quite common among experts – although it is rarely expressed as explicitly as we do, see, for example, [2].

Another way of saying the same is: The shape of a particle, a photon or an electron, is given by the uncertainty relation. The area of the positional uncertainty is interpreted as the area of space occupied by the particle.

A consequence of this definition is that the size (and the shape) of a photon (or an electron) depends on its state.

Here are some examples of the form of photons in our interpretation. The photons of sunlight on the Earth when the sky is not cloudy have a length of about 1 micron and an extension transverse to the direction of motion of about 40 microns. On the other hand, the photons of light coming from a laser are long and thin: as wide as the laser beam, say about 1 mm, and as long as the coherence length, e.g. 10 centimeters. The photons of the electromagnetic waves emitted by a radio station are much larger: they cover the entire transmission area.

Measuring the Planck constant

The Planck constant is often regarded as a constant responsible for the fundamental difference between classical physics and quantum physics and indeed, its discovery has contributed significantly to the development of quantum physics. However, the quantization of certain physical quantities, i.e. the fact that nature prefers particular values for some extensive quantities, was already known before the advent of quantum physics. Its consequence has more to do with the advent of atomism, i.e. the discovery of the laws of the constant and multiple proportions, because these laws are based on the fact that a particular physical quantity is quantized: the amount of substance. Its quantum is equal to the reciprocal of the Avogadro constant. Two other quantities that have a universal quantum are the electric charge with the elementary charge and the entropy with the Boltzmann constant. One should see the Planck constant in this context.

Also its measurement in the classroom, in our opinion, is no more important than that of the measurement of the elementary charge, the Avogadro constant or the Boltzmann constant. If one have the time to deal with these technically complicated measurements, one can do it. But it certainly does not lead to a better understanding of quantum physics.

The two experiments that are usually made in school are quite treacherous and are sometimes misinterpreted.

The photoelectric effect is a nice experiment in that it shows that the voltage at which the photocurrent starts does not depend on the light intensity, but rather on the current strength. But that's actually all we can deduce from it. We cannot determine the work function of the cathode, as long as we do not know the contact voltage between the anode and cathode. But this latter one is difficult to measure.

When determining h by means of light-emitting diodes, another problem occurs. It is often described as determining a threshold voltage at which the diode begins to shine. But there is no such threshold voltage. One can shift the apparent threshold back and forth by an appropriate choice of the calibration of the current intensity axis. To determine the value of h , it is necessary to read the voltage values for the same current for two LEDs emitting at different wavelengths, assuming that the p-n junction surfaces of the LEDs have the same area. The procedure is actually too complicated for the school, because the necessary understanding of the semiconductor diode can not be assumed.

One should therefore ask oneself whether the measurement of h should be attempted at this point. Finally, the tabular values of h were also not determined with such experiments.

3. Quantum mechanics

The time dependence of the wave function

The time dependence of the wave function of stationary states is given by a factor $e^{-\frac{i}{\hbar}Et}$. Since at school we do not yet have complex numbers, we ignore this time dependence and mention only that part of the wave function that depends on the position.

The square of the wave function for stationary states, which we will use later, is actually time-independent.

Probability density

As we imagine the electron to be extended in space, we do not use this term. Nevertheless some remarks about these designations. So we better see which problems we avoid by the introduction of the electronium.

In the traditional interpretation the square of the wave function (given as a function of position) tells us about the result of measuring the position of a particle. If we understand this a statement in a sense that our normal use of the language suggests, it tells us that the particle under consideration is found at a given location with a certain probability. It is logical to conclude that the particle is somewhere even we do not make a measurement and the word part „probability“ only expresses our ignorance about the location of the particle. If you say someone is now probably in his office, you are sure that he is in some place but you do not know that place. However, that is not meant in the case of the probability density of an electron. One does not want to say that the electron definitely is somewhere.

Therefore it is more cautious to look at the square of the wave-function in another way. Actually, when measuring the position of a particle the system makes a transition from a state in which the position of the particle is very uncertain into a state in which it is less uncertain, or localized as we re used to say. If, after the measurement, the particle is in a state whose wave function is limited to a small space area with the volume $d\tau$, then $|\psi(r)|^2 d\tau$ is the probability for the transition to this state, where $\psi(r)$ is the wave function of the initial state. One finds the electron after the position measurement preferably in places where the square of the wave function before the measurement has a large value. Thus, $|\psi(r)|^2 d\tau$ is the transition probability into a state characterized by r . It is the transition probability from the initial state into a state with the sharp location r . If one adopts this interpretation, one is almost with the electronium model.

In the electronium model, the process that we just considered is not the measurement of a position, but rather a transition from a state in which the electron is large to a state in which it is small. In the transition, it contracts to a small region of space. Repeating the process very often, one finds that the electron contracts to the most various places. The probability of the various positions where the small electron is located after the transition is described by $\psi(r)$, i.e. by the density of the electronium before the transition.

Pure and mixed states, decoherence

We do not deal with an area related to quantum mechanics: the boundary to classical physics. Traditionally, this is done in a way that differentiates between the quantum-mechanical system under consideration and the classical measuring apparatus. It is assumed that the quantum mechanical system is small or „microscopic“, the measuring apparatus large or „macroscopic“. For some time now, the systems that obey the laws of quantum physics, are getting bigger and bigger and it is becoming increasingly obvious that the distinction microscopic - macroscopic is no longer important. The important difference is rather that between systems that can be described by a wave function and those that do not, or in other words, between pure and mixed states.

However, the relationship between quantum mechanical and classical systems is more difficult than either of the two system classes individually. We know a similar situation from other areas of physics: Geometric optics is simple, wave optics is also quite simple. However, the relation between the two is complicated. How does geometric optics (where there is no interference) come out of wave optics (interference occurs)? The relationship between quantum mechanics (there is interference) and classical particle mechanics (there is no interference) is similar. In a way, the situation also resembles the relationship between statistical and phenomenological thermodynamics. Entropy and temperature are simple quantities in phenomenological thermodynamics. In statistical physics they are a bit more complicated, but still relatively understandable. However, it is difficult to show that the concepts from both areas are the same. We exclude all these questions from the classroom.

Entangled systems

They are a popular topic because they lead to strange statements, such as: A „particle“ A is in a state with an uncertain, i.e. a basically unknown spin. If one now makes a measurement of the spin on a distant „particle“ B, then the spin of A is determined at the same moment. The fact that this is so, is usually shown by using the compressed Bra and Ket notation for quantum mechanical states.

An aspect that is responsible for the incredible statements is hidden a bit: kinematics, i.e. the position and the time. It is better to see what happens when you write the wave function in the good old way with a wave function depending on the position. It is then clearly seen that a six-dimensional space is needed to describe two particles. Now it seems less surprising that strange things can happen. Attempting to get the phenomenon into our mind which mainly operates in a three-dimensional space must fail. We do not consider the topic suitable for the school.

4. The atom – stationary states

The empty atom

The model of point-like electrons results in another discrepancy. If the electron is point-like, the atomic shell would have to be empty, and that is even sometimes emphasized. But if the electrons are point-like, it is only right that the other so-called elementary particles also be assumed to be point-like, including the quarks and the gluons of the nucleus. That would mean that not only the atomic shell, but also the nucleus is empty. In other words, the whole world is empty. The statement that something is point-like is in principle not falsifiable. Therefore it is not a scientific statement. The wave function contains everything we can ever know about an electron in a given state – and there is no indication of a pointlikeness in the wave function.

The idea that the atomic shell is empty came up after the Rutherford scattering experiments. These have only shown that the shell has a very low mass compared to the core. Although in many cases the mass of the shell can be neglected compared to that of the core, the corresponding argument does not apply to the electric charge: the amount of the charge of the shell is equal to that of the core. And with regard to the magnetic moment the situation is opposite. The magnetic moment of the electrons is just so much greater than that of the nucleus as their mass is smaller.

We are therefore a little more cautious when comparing shell and core. Instead of saying that the shell is empty space, we only say that the shell has a low mass density.

5. Transitions in the atom – non-stationary states

The semiclassical description

We describe transitions between stationary states of the electron by considering the oscillating electronium as an antenna emitting a classical electromagnetic wave in accordance with electrodynamics. Thus, the atom is described quantum mechanically, the electromagnetic wave classically. One may imagine that the wave emitted in the electronic transition is a photon. However, in this way one will not see the reason for the quantization of the electromagnetic field. This quantization will only occur if the field is described in terms of quantum physics.

Quadrupole transitions

Quadrupole transitions are so weak compared to dipole transitions that they play no role in normal spectroscopy. They are important only at very short wavelengths, i.e. in the X-ray domain and for very large principal quantum numbers, i.e. in the highly excited Rydberg atoms.

Also in the gamma emission of excited nuclei quadrupole radiation is observed.

6. Atoms with several electrons

Electronium density and wavefunction

For single-electron systems, say the hydrogen atom, the electron density (or, in our language, the electronium density) $\rho(r)$ is equal to the square of the wave function:

$$\rho(r) = \psi^*(r) \cdot \psi(r),$$

the current density is

$$j(r) = \frac{\hbar}{2mi} (\psi^*(r) \nabla \psi(r) - \psi(r) \nabla \psi^*(r)).$$

The density and the current density distribution together contain the same information as the wave function. This is different for multi-electron systems. Here the wave function depends on as many (vectorial) spatial variables as there are electrons. Electron density and current density, on the other hand, are still functions of a single spatial variable. In this case the wave function contains more information than the electron density and current density. Some properties of the atom, such as which chemical bonds it makes with other atoms, are therefore not apparent from the electron density.

The shell model

To explain the properties of the atoms, in particular the periodicity of atomic radii and ionization energies with increasing atomic number, one usually uses the shell model of the atom. If one gradually builds up a multi-electron atom by increasing the size of the nucleus step by step by one proton (and also by one or two neutrons) and adding one electron to the shell, the atom is enlarged shell by shell. Each new electron is thought of as an individual attached to the outside of the atom, and this attaching happens by filling one shell after another. Whenever a shell is full, the ionization energy reaches a maximum; Atoms with closed shells are particularly stable. One would expect the atomic radius to be at a minimum for atoms with a closed outer shell and a maximum for atoms with a single electron in the outer shell. The maxima are actually observed, but the minima are in the wrong place. Nevertheless, the model is certainly a good model.

Occasionally, pieces of evidence are cited for the shells that are not pieces of evidence. One shows that the probability of finding an electron at certain distances from the nucleus has maxima. In fact, however, the probability density is a function that monotonically decreases from the core outward. The density is therefore greatest at the core, and there is not much to see from the shells. But one can create shells by a mathematical trick. Instead of plotting the density over the radius r , the function is integrated over the full solid angle and the result is plotted over r . Since the atoms are almost always spherically symmetric, this result is simply the product $r^2 \cdot \rho(r)$. This function actually shows for atoms of higher atomic number some oscillations. In fact, it conveys a somewhat trappy idea of the density distribution.

Indistinguishability of particles

When the laws of quantum statistics are derived, it is emphasized that particles are identical and indistinguishable. This statement is not easy to understand.

Imagine two electrons, one at position r_l (left), one at r_r (right). The electrons are the same in almost every respect: same mass, same charge, same spin ... But in one feature they are different: in their position. One is in place r_l , the other is in place r_r . So we can distinguish them.

In fact, statistical physics is not concerned with the indistinguishability of particles, but with that of states. We look again at the two electrons. One is again at position r_l , the other at r_r . We now bring the left particle to the position r_r and the right one to the position r_l . The new state that we realized in this way is actually indistinguishable from the old state – it is identical to the old state. However, we can always distinguish the two particles from each other: one is on the left, the other on the right.

But is it possible that the same state arises after interchanging two particles? Is there really no way to find out that the new state has emerged from the old one by an exchange? One would not have the problem if one had not accepted the habit, through long practice in classical mechanics, of considering a particle as a small being, characterized by something else besides the values of physical quantities, something one might call its soul. Unfortunately, this bad habit is not put aside as soon as possible in quantum mechanics, but it is cherished and nurtured by the language used by quantum physics. Interestingly enough, one has the problem when it comes to the exchange of two electrons. One does not have it, if two defect electrons (holes) in a semiconductor are interchanged. The holes are intuitively not imagined in the same sense as the electrons as individuals.

In the electronium model this conflict does not occur even with electrons.

8. Solid matter

The electronium in solid materials

The electronium model can also be applied to solids. The idea that solid state physicists and crystallographers have about the microscopic structure of a solid is in good agreement with this model. Electronium density distributions of solids are measured by X-ray diffraction and tunneling microscopy and are calculated theoretically.

Let us compare the traditional image of the point-like electron with the electronium model. We refrain from the thermal movement of the atomic nuclei.

In the traditional picture, the solid looks like this: point-like electrons move around the atomic nuclei. They move in such a way that they cover the entire space in the vicinity of the core. Most likely, they are or are found in the nuclei themselves. This idea is exigent because the electrons are said to have no trajectory. From the fact that the electrons are point-like, it also follows that the solid is empty.

In the electronium model, on the other hand, nothing moves. Between the atomic nuclei is the electronium. It has its highest density in the nuclei. Going away from a nucleus, the density decreases strongly. Nevertheless, the whole interior of the solid is filled with electronium.

Band model and energy ladder

As in a single atom, also in the solid, an excitation corresponds to a change in the electron density. But while the atom can only assume very specific density distributions, solids have whole ranges of shapes that can be continuously transformed into one another. Accordingly, there are also continuous ranges of excitation energies. Such ranges of allowed energies alternate with ranges of forbidden energies: energies that the solid can not admit.

We describe a solid by its energy spectrum or its *energy ladder*, as we say. Considering the energy ladder we can make many important statements about the properties of the material, just as we did in the case of a single atom.

By „allowed energies“ of the energy ladder we mean the energies of the stationary states of the solid. We do not ask whether these states are one-electron excitations or collective excitations. The energy ladder is not model-dependent. It reflects the energies that are determined experimentally.

The energy ladder is a simpler and more limited description of the solid than the energy band representation.

Optical properties of solids

It would be desirable in the context of a chapter on solid-state physics to fully describe the optical properties of matter: everything that one perceives with the eyes when looking at the surface of a body.

To fully describe the optical properties of matter, two functions are needed: the real and the imaginary part of the complex refractive index. However, we have only one function available in our course, and this only in the rudimentary form of the energy ladder. Therefore, we cannot explain all the optical properties. In particular, we cannot explain with the energy ladder the phenomena of reflection and refraction.

But many other phenomena are well described and we took advantage of this opportunity. We can explain why metals absorb the visible light, why most non-metals are transparent, why other non-metals, such as cadmium sulfide, are transparent and colored, why semiconductors are transparent in the infrared, why black materials are black, and white materials are white.

Solids as a light sources

Like gases, solid substances can emit light when the electron system goes from a higher-excited to a lower-excited state. Excitation, as with gases, can be done in different ways:

1. by fast electrons (example: television picture tube);
2. by photons (example: phosphor on the inner surface of a fluorescent tube);
3. in a chemical reaction (example: the reaction of electrons and holes in the p-n junction of a light emitting diode);
4. by heating (example: glowing).

When time is available, it is worthwhile treating these various mechanisms and recalling that gases can be brought to emit light in the same four ways. In the students' text we have restricted ourselves to the treatment of the glowing.

Glowing bodies are among our most important sources of light: the filament of a light bulb or the glowing carbon particles of a candle flame.

This topic is usually given very little space. A high school graduate is expected to explain how a laser works. The corresponding microscopic description of glowing, however, is usually not treated in the classroom.

Electric properties of solids

The most widely used model of electrical conductivity in metals is the Drude model: one limits to the consideration of the free electrons and describes them as gas, i.e. as flying little bodies. The Drude model is very useful. Surprisingly – one can say, because it is hard to imagine why the electrons should move freely in a solid material. One of the drawbacks of the model is that one does not see how it fits with the models one uses elsewhere: for describing electrical phenomena in semiconductors and the energy band model. Since we wanted to confine ourselves to a single model, we also describe the metallic conduction in the electronium model.

In this model, charge transport is described as follows: In metals, a deformation of the electronium can be achieved with as little energy as desired, i.e. a deviation of the density distribution from that of the ground state. Such a deviation consists of a compression and a dilution (always compared with the density distribution of the ground state). Both the compression and the dilution can be pushed through the solid with the help of an electric field, and thereby electronium and thus also electrical charge is transported.

For those who have no experience in dealing with electrons and holes, the question may arise as to how our densifications and dilutions are related to the known electrons and holes of the ordinary band model.

First, some general remarks. The terms electron and hole are used to describe the transport of electrical charge. We look at a particular band that is responsible for the transport. One always has the choice to describe the transport by means of holes or by means of electrons – the result is the same. Now, however, the effective mass of the electrons depends on the energy. It has a different value at the lower edge of the band than at the top. In particular, the effective mass of the electrons at the lower edge of the band is positive and negative at the top. For the holes it is the other way round: their mass is positive at the upper edge of the band and negative at the lower edge.

The fact that the effective mass is not constant makes the description of the transport process generally complicated. But there are situations where it becomes simple.

If a band is only weakly occupied by electrons, their mass is positive and essentially constant. The electrons therefore behave like free electrons. So we describe the transport of electricity in such a band with electrons.

A description with holes would give the same result, but would be much more complicated: on the one hand, there are many more hole states whose contribution to transport must be taken into account, and in addition these holes have a variety of masses, including negative ones.

Accordingly, a charge transport in a band, that is almost completely occupied with electrons is conveniently described with holes: these are less numerous than the electrons and have a unique, positive effective mass.

It can be seen from these considerations that it is not really convenient to say that the Hall effect tells us whether we are dealing with an electron or a hole conductor. Each transport can be described either with electrons or with holes. Rather, what the Hall effect tells us is whether the band is mainly occupied with or almost free of electrons.

Now for the electronium model: One can describe the transport of electric charge not only either by electrons or by holes, but also with a mixture of both. That's what we do with our densifications and dilutions. Even so, we get the correct total current through the solid.

The naming of the charge carriers in metals

The name electron for the moving excitations in a metal suggests that it is the same particle as a free electron. In fact, it is very different from this one. Actually, a proper name would be justified. We have refrained from introducing a name of our own because we do not want to stray too far from the established technical terminology. But we always emphasize that we only mean the „mobile“ electrons.

9. Diode and transistor

The semiconductor diode

The semiconductor diode is a difficult topic. Our treatment is therefore a description rather than an explanation of what happens in the diode. A true explanation of the operation is not possible with the means of electricity alone. The current of the charge carriers in the diode is determined not only by a gradient of the electrical potential, but also by a gradient of the chemical potential: The gradient of the electrochemical potential is responsible for the current.

The functionality of the semiconductor diode is misleadingly explained in many texts. That the transmission is greater in one direction than in the other, has nothing to do with the thickness of the barrier layer.

The contacts

There is a problem that we do not address because it would go too far. Actually, it would have to be addressed: What happens at the connection contacts? What happens there is just as complicated as what happens at the p-n contact, only it does not cause a rectifier effect.

The solar cell

The solar cell cannot be explained by means of electricity theory alone, that is to say with terms such as conductivity, electric field or potential difference. The driving for the current is a chemical potential difference generated by the light. Since we have to assume that the chemical potential is not available for explanation, the driving force is explained by the concentration (from which the chemical potential depends logarithmically).

The transistor

We limit ourselves to the treatment of the field effect transistor. In many textbooks the bipolar transistor is given preference, probably because it was developed earlier and that it had prevailed in the applications before the field effect transistor appeared. For us, the field effect transistor has the advantage that it is simpler.

In contrast to the bipolar transistor and the diode, the mode of operation of the field-effect transistor is based on purely electrical phenomena; it can be understood by means of electricity alone.

To control the electrical current from source to drain, all we have to do is change the gate potential, just as one did with the old triode tube where the grid potential is changed to control the current from the cathode to the anode. The field effect transistor is, so to speak, the ideal realization of a switch, which can be opened and closed by changing a potential value.

We do not handle applications where the transistor operates in the amplifier regime. The effort would be considerably larger because we would have to discuss characteristics. In most applications, in all digital technology applications, transistors are used as switches, i. e. as binary components.

Naming the contacts of a transistor

Not without hesitation we have decided to apply the following notation: The source and drain electrode have no name of their own. In the context of our somewhat simplified explanation of how it works, we cannot distinguish the two electrodes.

11. Particle physics

Technical terms

Particle physics uses some terms that are also used in other areas of physics, but have a slightly different meaning there. Such a phenomenon is natural. A new discipline always generates its own technical language. Thereby usually there is not a real effort done to preserve the consistency of the language.

The school can try to have a moderating effect by not accepting too inappropriate terms. However, proposing a different and better wording will hardly prove to be efficient.

Scattering

In optics one speaks of scattering, when light of a certain direction is deflected by an object in the various directions. Light can therefore be reflected, refracted, absorbed or scattered by a medium.

In particle physics, every interaction of a fast particle with a stationary target particle or with another fast particle as called scattering.

Interaction

This is a dazzling term. The term interaction is a placeholder for the most diverse processes in classical physics. The only requirement is that at least two systems are involved in the process. One speaks then of the interaction between the two systems. In a narrower sense, the term is used in the case where two bodies exert forces on each other or, in other words, that they exchange momentum.

In particle physics, the word refers to processes involving two particles of matter, which are mediated by a field particle. In this sense there are four different kinds of interaction: electromagnetic, weak, strong and gravitational. One goal of particle physics is to find a theory in which all four interactions appear as special cases of a single interaction. The association of the electromagnetic and the weak interaction has already succeeded.

Force

The word force has had many different meanings in the historical development of physics; above all, it was the name of various physical quantities.

The quantity for which the term is most used today is the quantity F , i.e. the current strength of the momentum. Formerly, the term force was also used for those quantities, which today we call momentum and kinetic energy. The kinetic energy was often called *vis viva*, i.e. living force.

In the thermodynamics of irreversible processes, „drive quantities“ such as temperature, electrical potential and concentration gradients are called forces.

In electricity, the no-load voltage of an electric power source is called an electromotive force.

More recently, the term force has also been used by particle physics. The word here does not stand for a physical quantity, but for a phenomenon or process, practically synonymous with interaction (in the sense of particle physics).

So it is said that the strong force is responsible for the bond between hadrons.

Conflicts with previously treated subjects

Particle physics is a young branch of physics. We can see how new ideas, concepts and models emerge and how a language emerges that describes the new ideas.

This makes the topic interesting, but it also causes particular difficulties. One problem is that topics that were the subject of previous lessons should be treated differently from the outset given the new insights from particle physics.

For example, in the past with the term vacuum was meant empty space. Now particle physics teaches us that space is not empty at all. Formerly, fields were spatially limited entities. Now a field is everywhere, and what we used to call field, distinguishes itself from the rest only in that it is in an excited state.

Distinctions to which we have become accustomed lose their meaning. A reworking of larger areas of physics is necessary. On the one hand, it should happen as early as possible so that inconsistencies do not establish themselves. On the other hand, it is not possible as long as the area is still in formation.

Energy and wavelength

In Section 11.2 we estimate wavelengths of radiations. We are not interested in exact values. A calculation would only provide an upper limit of resolution anyway. In fact, the resolution in the electron microscope is limited by lens aberrations and not by the wavelength. In addition, we limit the calculation to relativistic particles, because only these interest us in the context of this chapter.

The particle zoo

We do not deal with the systematics of the so-called particle zoo, i.e. the many baryons and mesons. In principle, it is not much different than the chemical elements or nuclides. So we already know the principle; the practical usefulness is not great.

Virtual particles

To say that a particle is „virtual“ does not explain anything unless we define what we means by the term „virtual“. It is a way of speaking that we can hardly explain in the context of school physics. It is better to say nothing than something incomprehensible. Statements that escape the logical control of the students harm the reputation of physics.

The photon is difficult enough. What should we say to the virtual photon without using quantum electrodynamics?

If we say that photons or virtual photons are exchanged between two interacting particles, what will our students imagine? That a photon is flying from one to the other? Why non't we say it then? Because we did not mean it that way. How did we mean it?

It's not that the real particles are trivial and the virtual ones are the exotic exception, that can only be understood with quantum electrodynamics.

Field particles

In our tables one may miss the interaction particles: especially the gluon of the strong and the vector bosons of the weak interaction. It is certainly not difficult to claim that these particles exist. It is much harder to explain what is meant by „they exist“. We do not want to adopt the wording of the popular scientific literature.

Phrases such as „the vector bosons are responsible for beta decay“ are more likely to undermine confidence in the logical consistency of our physical statements.

There is no objection to saying anything in the classroom where we can not prove it. But saying something absolutely incomprehensible is not good.

Identical particles – different particles

The student text says that there are about a hundred hadrons, 12 quarks and 12 leptons. These statements must be viewed with some caution. When should we say of two particles that they are of the same kind, and when say they are different particles?

Two particles of the same mass, of the same electric, baryonic and leptonic charge, will be called the same.

Two atoms with the same number of protons and neutrons, e.g. two deuterium atoms, will be called the same. That is already expressed by their name. Both are called deuterium atom. However, they can still be rather different. One may be in the ground state, the other in a highly excited state. So one is much bigger than the other, and it has a different rest energy and angular momentum. However, the rest energies of the two particles differ only slightly. Our feeling tells us that despite the different values of some physical quantities, the two particles are still of the same kind. However, the further we get into high-energy physics, the less clear is this distinctness. The excitation energies become larger and larger as compared to the rest energies of the constituents, that is, an ever greater part of the energy comes from the interaction field. In fact, the distinction between different particles and different states of the same particle also becomes increasingly blurred. For example, baryon and meson excitation have got their own names as if they were new species of particles, see the Lambda and Rho particles. It is commonplace in particle physics to say that there are six different quarks. The associated antiparticles are only considered as other states of the six quarks. That quarks carry color charge, could also be expressed by saying that there are not twelve, but 36 different quarks. But we do not do that. There is no natural boundary between the two approaches. Basically, we already have the phenomenon on other levels of the particle hierarchy: we call all potassium isotopes potassium, but they could have been named differently and considered as different substances. With hydrogen one actually goes this way. There is protium, deuterium and tritium.

[1] LEISEN, J.: Wie kommt die Erkenntnistheorie in den Physikunterricht?, MNU-Kongress Regensburg 2009.

[2] GREENBERGER, Daniel M.: Reviews of Modern Physics 55, 898 (1983).



Solutions to problems

1. Models in physics

1.1 The description of a process with a model

We do not want to give here a „solution“ that claims liability, because the question is very large, and there are many correct answers.

1.2 The description of a process by means of a theory

The equations of mechanics form a theory, as do those of electrodynamics or thermodynamics. Relativistic mechanics is a theory that is different from Newtonian mechanics. Geometric optics is a theory and wave optics is one.

The set theory is a theory of mathematics. The theory of evolution is one of biology.

2. Photons and electrons

2.6 The size of photons

One makes an interference experiment with laser light: the light beam or photon beam is split at a semitransparent mirror, and the two sub-beams, after going through different paths, are made to hit the same point on a screen. If the light paths are the same length, we will see an interference pattern there. We now make one light path longer than the other, until the interference pattern disappears. When this happens, the path difference is equal to the coherence length of the light, or in other words, equal to the length of the photons.

2.7 The size of photons

1.

$$a) E = h \cdot f = 6.6 \cdot 10^{-34} \text{ Js} \cdot 0.984 \cdot 10^8 \text{ Hz} = 6.494 \cdot 10^{-26} \text{ J}$$

$$p = \frac{h \cdot f}{c} = \frac{E}{c} = \frac{6.494 \cdot 10^{-26} \text{ J}}{3 \cdot 10^8 \text{ m/s}} = 2.16 \cdot 10^{-34} \text{ Hy}$$

$$E = \frac{h \cdot c}{\lambda} = \frac{6.6 \cdot 10^{-34} \text{ Js} \cdot 3 \cdot 10^8 \text{ m/s}}{1.5 \cdot 10^{-10} \text{ m}} = 1.32 \cdot 10^{-15} \text{ J}$$

$$b) p = \frac{h}{\lambda} = \frac{6.6 \cdot 10^{-34} \text{ Js}}{1.5 \cdot 10^{-10} \text{ m}} = 4.4 \cdot 10^{-24} \text{ Hy}$$

$$c) E_{\text{SWF3}}/E_{\text{visible}} = p_{\text{SWF3}}/p_{\text{visible}} \approx 10^{-7}$$

$$E_{\text{X-rays}}/E_{\text{visible}} = p_{\text{X-rays}}/p_{\text{visible}} \approx 10^4$$

2. a) A current of negative momentum (positive direction downwards) flows into the ball via the water jet. The positive momentum from the gravitational field and the negative from the water jet cancel each other.

b) A current of negative momentum flows into the bead via the light beam. The positive momentum from the gravitational field and the negative from the light beam cancel each other.

$$c) p = 7 \cdot 10^{-11} \text{ Hy}$$

flow per second into the bead via the gravitational field.

One photon carries (see the student's text)

$$p_{\text{Ph}} = 8,25 \cdot 10^{-28} \text{ Hy.}$$

$$n = \frac{p}{p_{\text{Ph}}} = \frac{7 \cdot 10^{-11}}{8.25 \cdot 10^{-28}} \approx 10^{17}$$

Every second about 10^{17} photons hit the bead. (The exact value depends on how the light is reflected and refracted on the bead.)

4. The atom – stationary states

4.1 The density of the electronium

$$\frac{12\,000\text{ km}}{50\,000} = 0.24\text{ km} = 240\text{ m}$$

4.2 Size and density of the atomic shell

The radius of both atoms (from Fig. 4.3) is:

$$r = 1.6 \cdot 10^{-10}\text{ m}$$

From this we get the volume:

$$V = \frac{4}{3}\pi r^3 = 17 \cdot 10^{-30}\text{ m}^3$$

The mass of the electron is:

$$m = 0.9 \cdot 10^{-30}\text{ kg}$$

Thus the average density of the electronium in the hydrogen atom is:

$$\rho_{\text{H}} = \frac{0.9 \cdot 10^{-30}\text{ kg}}{17 \cdot 10^{-30}\text{ m}^3} = 0.05 \frac{\text{kg}}{\text{m}^3} = 0.05 \frac{\text{mg}}{\text{cm}^3}$$

The lead atom has 82 electrons. Therefore we have:

$$\rho_{\text{Pb}} = 82 \cdot \rho_{\text{H}} = 4.3 \frac{\text{mg}}{\text{cm}^3}$$

Estimation of the density of nuclear matter:

Necessary data:

Mass of the core $\approx 1000 \cdot$ mass of the shell
radius of the core $\approx 1/50\,000 \cdot$ radius of the shell
density of the shell $\approx 2\text{ mg/cm}^3$.

$$\rho_{\text{nucleus}} = \frac{1000 \cdot m_{\text{shell}}}{\frac{1}{50\,000^3} \cdot V_{\text{shell}}} = 1.25 \cdot 10^{17} \rho_{\text{shell}} \approx 2.5 \cdot 10^{14} \frac{\text{g}}{\text{cm}^3}$$

Normal matter has a density of a few grams per cubic centimeter. The density of the electron shells is thus about 1/1000 of it, that of the cores is 10^{14} times as large.

7. Spectra

7.1 The excitation of atoms with light

1.

$$E = \frac{h \cdot c}{\lambda} = \frac{6.6 \cdot 10^{-34} \text{ Js} \cdot 3 \cdot 10^8 \text{ m/s}}{2.85 \cdot 10^{-7} \text{ m}} = 6.95 \cdot 10^{-19} \text{ J}$$

2. The ionisation energy of the sodium atom is $8.8 \cdot 10^{-18} \text{ J}$ (see the student's text).

$$\lambda = \frac{h \cdot c}{E} = \frac{6.6 \cdot 10^{-34} \text{ Js} \cdot 3 \cdot 10^8 \text{ m/s}}{0.8 \cdot 10^{-18} \text{ J}} = 2.475 \cdot 10^{-7} \text{ m} = 247.5 \text{ nm}$$

It is UV light.

8. Solid matter

8.2 The distribution of the electronium in solids

$$m/n = 58.5 \text{ g/mol}$$

$$\rho = m/V = 2,16 \text{ g/cm}^3$$

$$\frac{m/V}{m/n} = \frac{n}{V} = \frac{2.16 \text{ mol}}{58.5 \text{ cm}^3} = 0.0369 \text{ mol/cm}^3 = 36.9 \cdot 10^{-6} \text{ mol/mm}^3$$

1 mol corresponds to $6.02 \cdot 10^{23}$ particles.

Z = number of particles

$$\frac{Z_{\text{NaCl}}}{V} = 2.2 \cdot 10^{19} \frac{\text{molecules}}{\text{mm}^3} = 4.4 \cdot 10^{19} \frac{\text{atoms}}{\text{mm}^3}$$

9. Diode and transistor

9.2 The semiconductor diode as a rectifier, a light source and a solar cell

1. Similar to a sine current, but firstly one half-wave is missing and secondly the other half-wave is somewhat deformed because the relationship between voltage and current is not linear.
2. In the bridge rectifier the electrical current passes at all times, no matter how the AC voltage at the output of the transformer is just poled. However, the electric current flows through the rectifier in different ways at the two half-waves. In the resistance it always flows in the same direction.

9.3 The transistor

The gate potential must be higher than that of the channel.
