Chapter 1
Introduction

Quantum physics is thought, without doubt, to be one of the greatest intellectual achievements of the 20th century. Its history began at the turn from the 19th to the 20th century. But we are confronted with its profound scientific, technological and philosophical implications today even more than ever. Not only in scientific original papers and text books but also in popular science literature and fiction more and more frequently book titles appear which contain terms as quantum theory, quantum mechanics, quantum physics, quantum world or quantum entrainment etc. Sometimes these titles are abused to supply quite questionable and esoteric treatises with a quasi-scientific background. What, therefore, is it all about with this field of quantum physics, which plays a central role in the education of physicists and, hopefully soon, also of chemists, biologists and engineers.

1.1 General and Historical Remarks

Isaac Newton created, more than 300 years ago, classical mechanics by finding the laws of motion for solids and of gravitation between masses. This theory was so successful for the deterministic description of motions, in particular for the planets in our solar system, that Newton was led to the assumption that also light has corpuscular character. On the basis of light particles, which propagate along a straight line in a light beam, he could consistently explain a number of optical phenomena including the reflection and diffraction of light. The diffraction and interference experiments of Christian Huygens living at Newton's time and a little bit later, at the beginning of the 19th century, of Thomas Young and Augustin Fresnel, however, paved the way for the wave theory of light, at that time still waves in a not understood ether.

The triumph of wave theory could not be stopped anymore when the prominent Scottish physicist James Clark Maxwell successfully described the nature of light by a wave-like propagation of electrical and magnetic fields. He, thus, unified the two classical branches of optics and electricity in one and the same theory. By the detec-

H. Lüth, *Quantum Physics in the Nanoworld*, Graduate Texts in Physics,
DOI 10.1007/978-3-642-31238-0_1,

tion of radio waves at around 1887, Heinrich Hertz finally established the familiar theoretical system of electrodynamics and electromagnetic waves.

Simultaneously, during the 19th century, an atomistic and molecular view of matter emerged and became more and more important, and this against various philosophical objections. Milestones in the development of an atomistic picture of matter were certainly the statistical kinetic gas theory of Ludwig Boltzmann around the end of the 19th century and the explanation of the Brownian motion in terms of collisions between liquid molecules and pollen particles suspended in the liquid by Einstein in 1905.

At the beginning of the 20th century, then, experimental results accumulated which contributed essentially to the emergence of a new physics, quantum physics. Among these there must be mentioned the detection of cathode rays in vacuum tubes, of X-rays and of radio activity. In particular, the Rutherford model of the atom must be emphasized, which was suggested by Ernest Rutherford in order to explain his scattering experiments of α-particles on metal foils. Rutherford's atom is already imagined to consist of a massive small nucleus containing almost the entire atomic mass and an extended electronic cloud which determines the spatial extension of the atom.

This breakthrough in the understanding of the atom might be thought of as the beginning of the era of quantum physics. In a next step, the emission of sharp spectral lines of exited atoms being in contradiction to the successful theory of electrodynamics by Maxwell was explained. In 1913 Bohr interpreted, or better made plausible, the emitted line spectrum of hydrogen atoms on the basis of heuristic postulates about stable electron orbits around the positive nucleus, the proton.

A little bit earlier, already Max Planck had broken new ground into the direction of quantum physics. Around the end of the 19th century there was the puzzle of black body radiation. A so-called black body emits a continuous spectrum of electromagnetic radiation whose shape strongly depends on the temperature of the emitter. By means of classical electromagnetic theory, the spectrum for the shortest wavelengths always was calculated to diverge into infinity, the so-called ultraviolet (UV) catastrophe. Planck, who was a quite conservative physicist, made the revolutionary assumption that a black body interacts with the electromagnetic field by exchange of energy only in small quanta rather than in a continuous way. The UV catastrophe could thus be removed and the experimental black body emission theoretically be described correctly. In a kind of desperation, he must have drawn this conclusion which was in strict contradiction to Maxwell's electromagnetic field theory of continuous electric and magnetic fields. The assumption, indeed, led back to the rejected corpuscular theory of light by Newton. Planck created the term quantum which gave the whole field its name. In his theoretical assumption, the quanta carry an energy E which is proportional to the light frequency ν. The constant $h = E/\nu$ has been named Planck's constant in honor of its inventor. A number of illuminating detections followed (Chap. 2) which finally led to the formulation of quantum mechanics in its present form. In particular, the explanation of the photoelectric effect by Einstein (Sect. 2.1) shall be mentioned.

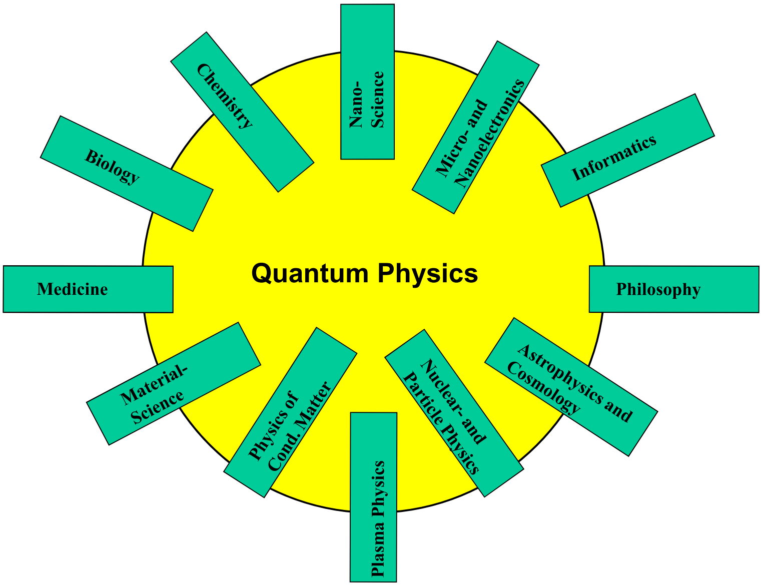

Fig. 1.1 Qualitative representation of the overlap between important science branches and the field of quantum physics. The amount of overlap with the "quantum circle" indicates how far quantum physical methods, theoretical and experimental ones, are used in the particular science disciplines

1.2 Importance for Science and Technology

While quantum theory was originally intended to explain the world of atoms, molecules and elementary particles, in particular the electron, it became clear meanwhile, that the theory has universal importance for the understanding of the whole surrounding world, up to cosmological questions. This is by no means astonishing since our world consists of atoms, elementary particles and energy fields which closely interact with matter. Thus, the stability of matter can only be understood on the basis of quantum theory (Sect. 5.7.2).

The fundamental principles of quantum theory as particle-wave duality, the uncertainty principle and the random behavior on the atomic level, therefore, have to be taken into account in almost every natural or engineering science. This is true, although, because of historical or practical reasons, models of classical physics, mechanics or chemistry are used in many of these sciences. This is shown in a somewhat qualitative way in Fig. 1.1. Each science field plotted by one of the boxes participates more or less in the general field of quantum physics. The amount by which it reaches into the quantum circle should indicate to what extent theoretical models and experimental tools of quantum physics are used in the field. A partial overlap of a science field with the quantum circle does not mean that only part of the phenomena or systems considered there obey the laws of quantum physics. According to our understanding everything in this world, matter and fields, be it in microelectronics, in medicine, in chemistry or in astrophysics is totally subject to the laws of quantum physics. A partial overlap (Fig. 1.1) only indicates qualitatively to what extent one uses typically quantum physical methods and considerations in this field. Partially, this is dependent on the degree of atomistic thinking in a particular science field.

As an example take chemistry. All what happens in a chemical laboratory or in a chemical plant is related to chemical bonds and reactions and thus obeys the laws of quantum theory. Nevertheless a chemist working in the laboratory must not always think about quantum physical laws. During the long history of chemical sciences typically chemical rules about reactivity between molecules and radicals have been established, which have to be applied in order to produce a certain product. But being confronted with novel problems of chemical bonding or reactivity a theoretical chemist using quantum mechanical calculations has to be asked for an efficient solution.

Similarly in medicine, for the interpretation of images from NMR (nuclear magnetic resonance, Sect. 6.5.3) or PET (positron emission tomography) usually the skills of the special medical education are sufficient. But in difficult cases, at the front of research, one has to dig into the basics of the quantum physical elementary processes of spin precession or decay times etc. in order to reach a certain level of understanding. The same is true for all nuclear medical methods of cancer treatment. The interaction of high energy particle radiation with biomolecules and cells can only be approached by means of quantum physical methods.

Biology presents an extremely broad field of scientific activity reaching from animal observation, evolution biology (theory), cell biology down to molecular biology. This latter branch of biology, which has an ever more growing influence on the explanation of biological phenomena on the atomic and molecular level became possible only on the basis of quantum theory. Decoding of the DNA and its function in genetics was achieved on the basis of quantum theory. The study of folding of proteins and the related biological activity requires the use of supercomputers and algorithms being based on quantum mechanics.

Astrophysics and cosmology reach into the quantum circle only halfway. In these research fields relativity theory certainly plays an equally important role as quantum physics. Similarly, in plasma-physics (nuclear fusion) magneto-hydrodynamics contributes to the understanding of problems as much as quantum physics does.

Nuclear- and elementary particle physics as well as condensed matter physics penetrate the quantum circle almost completely. Both disciplines arose on the basis of quantum physics and can only be understood within the frame of quantum theory. Classical physical models are sometimes used only for analogy reasons.

Material science, micro- and nanoelectronics and nanoscience (treats nanostructured materials) are of particular interest. These disciplines penetrate the quantum circle by a significant amount, since many theoretical models and experimental techniques stem from quantum physics. Examples are the description of the electrical resistance which is due to scattering of charge carriers on crystal defects and lattice vibrations, as well as the scanning electron tunneling microscope which allows imaging of single atoms and atomic orbitals on a solid surface. On the other hand, there exist many classical, microscopic analysis and preparation techniques in these fields, which work without using explicitly quantum physics. Probes for mechanical hardness and the design of micro- and nanoelectronic circuits shall be mentioned. In the considered disciplines, however, a clear trend to more and more atomistic thinking and to structures on the nanoscale is observed (transistors with 5–10 nm dimensions). In the near future, therefore, quantum physical techniques will be much more important and the corresponding boxes in Fig. 1.1 will move more into the quantum circle.

Informatics characterized by its historical roots, Shannon's entropy (information measure) and the Turing machine (abstract model for computer), managed without using quantum physics. This situation has changed since quantum information (Sect. 7.1) has become an interesting and growing field within information science. Superposition states being characteristic for quantum physics allow extremely parallel data processing which is by no means possible within a classical computer with von Neumann architecture. The realization of quantum computers and correspondingly adapted algorithms is meanwhile an important branch in physical and information research.

Similarly as in science the impact of quantum physics on every day life can not be estimated highly enough. Many industrial products which we use without one single thought would just not exist without quantum physics. The development of lasers, a product of quantum physics, enabled important applications in ophthalmology, material engineering and, of course, the familiar CD (compact disk) player. Our satellite antennas for TV reception contain, in the first amplifier stage, a low noise transistor (HEMT: high electron mobility transistor) which was developed by using principles of quantum physics. For the function of the navigation system (GPS) atomic clocks are essential, also products of quantum physics. This is similarly true for all imaging systems in medicine as NMR, CT, PET etc. The information age is based on integrated semiconductor circuits the development of which was possible after the electronic structure of semiconductors was understood from the laws of quantum mechanics (Sect. 8.3.4). Weather forecast with high predictive quality and climate models require calculations on supercomputers, products of modern semiconductor technology.

Quantum physics is an essential basis of our modern world. There is an estimate that almost a quarter of the gross national product in highly developed countries arises from products being directly or indirectly related to quantum physics.

1.3 Philosophical Implications

In Fig. 1.1, even philosophy penetrates into the quantum circle to some extent. No other physics theory excited philosophers, at least those with a view on natural science and epistemology, to such an extent as quantum theory did. No other theory in physics interferes so much with philosophical questions as what is real, what can we recognize, in how far is our knowledge about nature pure imagination.

Let us start with the question, what means quantum theory for the whole edifice of physical science. Its fundamental issues, random behavior on the atomic scale, particle-wave duality (Chap. 3), uncertainty relation (Sect. 3.3), and the principles of field quantization (Chap. 8) form a non-classical frame of thinking which is relevant in all sub-disciplines of physics such as elementary particle physics, physics of condensed matter, astrophysics etc. There are no experimental results in all these fields which are in contradiction to quantum theory so far. Quantum physics, in its non-relativistic Schrödinger formulation for condensed matter physics and the highly sophisticated relativistic field theories of the standard model in elementary particle physics (Sect. 5.6.4) describe nature equally well on all scales, even up to cosmology. Quantum theory must, thus, be considered as a hyper-theory, which has to be matched also by future theories about so far unsolved problems such as quantum-gravity or dark matter and energy.

Theory of relativity and Darwin's theory of biological evolution certainly also belong into this class of hyper-theories. No serious biologist or natural scientist in general would dare to make assumptions which are in contradiction to Darwin's theory, to its central statements, not to minor derivations. Similarly theory of relativity yields the general frame for our understanding of space and time as well as of gravitation. A restriction, however, has to be made. In the theory of relativity, welldefined curves in space and time do exist. The wave-particle dualism and the uncertainty principle do not exist, relativity theory is a classical theory in that sense. We therefore expect that in a future unification of quantum and relativity theory the latter one has to adapt to quantum theory. First approaches to quantum-gravity as loop or string theory point into this direction.

It is worth mentioning that in both hyper-theories, quantum theory and the theory of biological evolution, accident, that is, random behavior, plays a dominant role. Random mutations in biology enable the emergence of something new on the cellular level. ("Le hazard et la necessite" how it is expressed very accurately by Jaques Monod [1] in his famous book). Hereby, the term mutation in biology is intimately related with random behavior as it is defined in quantum physics.

The strongest interference of quantum physics with philosophy is certainly given in the field of the theory of knowledge. Two fundamental issues of quantum physics, in particular, have troubled philosophers, the inherently random, that is, non-deterministic behavior on the atomic level and the interference of the human observer with the physical measurement process, that is, the co-determination of our knowledge about nature by the observing subject. For a long time, the opinion prevailed that the collapse of a wave packet upon a measurement and the transition of the wave function into an eigenstate of the measured observable (Sect. 3.5) demonstrate the dependence of our knowledge on the measurement. Our knowledge should, thus, be determined to an essential part by the measurement and the observer rather than by an externally existing reality. The Copenhagen interpretation of quantum mechanics (Bohr, Heisenberg) sometimes shows features of a subjective and idealistic philosophy, in which a reality beyond our perception horizon is denied. Both a better understanding of the physical measurement process in terms of entanglement (Sect. 7.4) and philosophical developments as in evolutionary epistemology [2] have caused a return to a critical, realistic interpretation of quantum mechanics.

Particularly, philosophical branches as *Evolutionary Epistemology* [2] in connection with *Hypothetical Realism* [3] are appropriate to quantum mechanics and form a wider frame for quantum mechanical thinking. Popper presents a detailed analysis on realism and subjectivism in physics and concludes [4]:

> There is, therefore, no reason whatever to accept either Heisenberg's or Bohr's subjectivist interpretation of quantum mechanics. Quantum mechanics is a statistical theory because the problems it tries to solve—spectral intensities, for example—are statistical problems. There is, therefore, no need here for any philosophical defence of its non-causal character…
>
> To sum up, there is no reason whatsoever to doubt the realistic and objectivistic character of all physics. The role played by the observing subject in modern physics is in no way different from the role he played in Newton's dynamics or in Maxwell's theory of the electric field: the observer is essentially the man who tests the theory.

The statement about the statistical nature of quantum physics must be seen in connection with the fact that quantum physics is non-deterministic on the level of elementary events; but the calculation of probabilities and average measurement results for large ensembles of particles is performed in a deterministic way by means of differential equations with boundary and initial conditions (Sect. 3.5).

The problem of the measurement process in quantum physics has posed many questions and caused much discussion about perception of reality and subjectivism in the past. Meanwhile, these discussions have been eased due to recent fundamental experiments on the participation of the observer in a measurement (Sects. 2.4.2 and 8.2.4) and due to the recognition of the importance of entanglement between the system under study and the measurement apparatus (Sect. 7.2). In this modern context the human experimentalist merely plays the role of an observer rather than an integral part of the system under study. The entanglement (specific quantum correlation) between measurement apparatus and the real object being studied connects both of them and simultaneously separates the cognizing human observer from the reality of the outside world. Consequently, experiments yield an image of the externally existing reality, but we can achieve step by step an ever better image of that reality.

As is worked out in the epistemology of hypothetical realism, all statements about the world have hypothesis character. According to Popper [4], these hypotheses must be falsified to establish new improved hypotheses in a trial and error procedure. By means of ever better hypotheses, reality is described step by step more adequately. The "invention" of Schrödinger's equation or of field quantization (Sect. 3.5, Chap. 8) are good examples for the establishment of hypotheses. These hypotheses in quantum physics could not be falsified in their corresponding validity ranges (non-relativistic range for Schrödinger equation). They must be assumed to be valid for the description of realty so far.

It is essential that modern quantum physics does not deny the existence of a structured reality beyond our senses and our perception. In this context Vollmer remarks [2]:

> We assume that a real world does exist, that it has particular structures and that these structures are partially recognizable. We test how far we can come with these hypotheses (translation from the German by the author).

In this context, we always have to remember that philosophical realism can not be proven; it can neither be verified nor falsified [5]. But according to Popper [4] and other philosophical realists, it is certainly the most reasonable hypothesis to get along with the every-day environment as a human being.

In this sense of philosophical realism, the counter-intuitive character of quantum physics, for example, the particle-wave duality, does not cause difficulties. In the evolutionary epistemology, human recognition is essentially determined by limitations of our sensual perception and the structure of our brain. Both are results of the biological evolution of man who had to adapt to a macroscopic rather than to an atomic scale environment. In this sense, Shimony [6] remarks:

> Human perceptual powers are as much a result of natural selection as any feature of organisms, with selection generally favoring improved recognition of objective features of the environment in which our pre-human ancestors lived.

References

1. J. Monod, *Le Hazard et la Necessite* (Editions du Seuil, Paris, 1970)
2. G. Vollmer, *Evolutionäre Erkenntnistheorie*, 3rd edn. (S. Hirzel Verlag, Stuttgart, 1983)
3. D.T. Campbell, Inquiry **2**, 152 (1959)
4. K.R. Popper, *Objective Knowledge, An Evolutionary Approach* (Oxford at the Clarendon Press, Oxford, 1979), p. 303
5. B. Russel, *The Problems of Philosophy* (1912). German translation: Probleme der Philosophie (Suhrkamp-TB 1967)
6. A. Shimony, J. Philos. **68**, 571 (1971)

Springer

http://www.springer.com/978-3-642-31237-3

Quantum Physics in the Nanoworld
Schrödinger's Cat and the Dwarfs
Lüth, H.
2013, XII, 466 p., Hardcover
ISBN: 978-3-642-31237-3