METHODOLOGICAL NOTES

PACS numbers: 03.65.Bz, **05.45. + b**, 05.70.Ln, 06.20.Dk

Objects and environment

G von Oppen

Contents

Abstract. The conceptual foundations of quantum physics are discussed based on the hypothesis that physics has progressed towards the basic laws of nature by isolating objects from their environment. Observable objects are coupled to their environment by spontaneous quantum jumps and, therefore, their motion is affected by statistical laws. A completely deterministic evolution is possible only in the idealised case of isolated objects. The evolution of these unobservable idealised objects is described by the dynamical laws of quantum mechanics.

... we have to abandon the description of atomic events as happenings in space and time, we have to retreat still further from the old mechanical view.
A Einstein, L Infeld *The Evolution of Physics*

1. Introduction

The atomic hypothesis states that all physical bodies are composed of atoms. In accord with this hypothesis macroscopic matter is structured and can be decomposed in smaller and smaller parts until atomic dimensions are reached. However, at the atomic level, the material has to be described quite differently than the original macroscopic matter. Microscopic particles as atoms, ions or molecules reveal properties very different from those of macroscopic bodies. Microscopic particles have discrete energies (when confined in space) and change their states discontinuously by performing quantum jumps. They are described quantum mechanically. Macroscopic bodies, on the other hand, change and move continuously in space and time and are described using the theory of classical mechanics. Nevertheless, the physical and chemical properties of macroscopic matter can be properly understood only by resorting to quantum mechanics.

The success and fertility of the atomic hypothesis for understanding the physical world has convinced most physicists in believing that physics progressed towards the basic laws of nature by decomposing macroscopic bodies into more fundamental constituents. Based on this belief are their efforts to continue the search for the fundamental laws of physics by decomposing also the atomic particles. Various experiments on collisions of atomic and subatomic particles reveal that not only atoms, but also nuclei and their constituents, nucleons, have a composite structure constituted by more elementary particles as electrons and quarks. This search for 'the bottom of elementarity' [1] has compelled physicists to perform collision experiments at higher and higher energies in order to detect structureless, point-like particles.

Obviously, this search for the fundamental laws of physics relies on a *principle of decomposition*. In this paper an attempt is made to apprehend the success of atomic physics by looking from a different point of view. Our ideas of physical reality, in general, and the principle of decomposition, in particular, is based on the classical (or relativistic) concept of bodies moving in space and time. However, space and time can be measured only by using material bodies as, for example, scales and clocks. They are not given *a priori*, but are features of the continuously observable world. This world is the so-called macroscopic world described by classical physics. Therefore, when searching the elementary objects of physics, which do not belong to the macroscopic world but to the world of quantum physics, it may be advisable to use the concept of space and time as little as possible.

Contrary to this conclusion, objects are usually classified according to their size as macroscopic or microscopic [2]. This classification leads to various conceptual difficulties when

G von Oppen Institut für Strahlungs-und Kernphysik, Technische Universität Berlin,
TU Berlin, Sekr. PN 3-2, Hardenbergstr. 36, 10623 Berlin
Tel. (4930) 314 23021, (4930) 314 23012
Fax (4930) 314-23018
E-mail: oppen@kalium.physik.TU-Berlin.DE

Received 27 September 1995
Uspekhi Fizicheskikh Nauk **166** (6) 661 – 667 (1996)
Supplied in English by the author; edited by M S Aksent'eva

trying to understand the connection between microscopic and macroscopic physics as outlined in Section 2. A classification of objects, where the space-time aspects are of less importance, is proposed in Section 4. It is based on an analysis of the interaction between an object and its environment (Section 3). This interaction is a fundamental precondition for all physical observations and should be considered as a basic property of physical objects. By recognising the quantum properties of this interaction, one is led to the conclusion that this interaction provides a more natural basis for the classification of objects than its size or its number of atoms. Accordingly, I propose that the conceptual foundations of physics be reconsidered under the following hypothesis: The principle of decomposition has to be replaced by a *principle of isolation*. This hypothesis implies that the elementary physical objects are not prepared by decomposing material bodies but by isolating them. It implies also that the fairly fuzzy classification of objects as microscopic or macroscopic can be replaced by a better defined classification based on the interaction of an object with its environment.

This hypothesis has far-reaching consequences for the conceptual foundations of many branches of physics. Some aspects regarding, in particular, quantum mechanics and statistical physics, are outlined in this paper. This new approach to the conceptual foundations of quantum physics does not question the theories of quantum mechanics or statistical thermodynamics or any of their applications. Nevertheless, it may be revolutionary for our understanding of nature and poses new guidelines when asking for the bottom of elementarity or laws determining the phenomena of life. Though many questions arising form this new approach remain unanswered, I hope that this work will shed new light on some conceptual problems of present-day physics and initiates a new discussion on the interpretation of quantum physics.

2. Three puzzling issues of modern physics

Both quantum mechanics and statistical physics have proven impressively successful. An overwhelming variety of phenomena of microscopic, mesoscopic and macroscopic physics are explained on the basis of these theories [2]. However, in spite of their widespread and successful application, discussions on the conceptual foundations of these theories still continue [3]. Various basic questions have yet to find a satisfactory answer. Three of these fundamental issues are picked out and briefly outlined below, namely (*1*) the problem of mesophysics, (*2*) the problem of irreversibility and (*3*) the problem of quantum jumps. These problems are interrelated and all three problems are comprised in the problem of measurement [4]. These problems are embarrassing when analyzed from a point of view based on the principle of decomposition. However, they appear in a more comforting light when looking from a viewpoint based on the principle of isolation, as will be shown in the following sections.

2.1 The problem of mesophysics: the connection between microphysics and macrophysics [2]

Microscopic objects obey quantum mechanical laws. They are found in the realm of atoms and molecules and their spatial extensions are usually of the order of a few atomic units of less. On the other hand, objects are considered as macroscopic if their motion can be described by Newtonian or relativistic mechanics. Typically, they are visible, that is at least of the order of 1 μm. Between the realm of microscopic and macroscopic physics, there is a transition realm, where it is less obvious how to describe the evolution of objects theoretically. There is the 'yawning gap' of the 'mesoworld' [5]. Various objects belonging to this transition realm are investigated in the most advanced fields of present-day physics. Efforts for miniaturization of macroscopic devices lead to mesoscopic and nanoscopic physics [6, 7].

On the other hand, starting from the atomic scale, large molecules and clusters are produced to investigate the question at which degree of complexity aggregates of atoms reveal properties of macroscopic materials [8].

2.2 The problem of irreversibility

The efforts for understanding the relation between microphysics and macrophysics also confronts us with the problem of irreversibility [9]. Though the basic laws of quantum mechanics are invariant with respect to time reversal, macroscopic phenomena are irreversible. This different behaviour of microscopic and macroscopic systems is usually explained by referring to the enormous complexity of macroscopic systems [10, 11]. Once again, the conceptual difficulties of this approach become apparent when considering mesoscopic systems. Though there is a sharp distinction between the time-reversal invariant evolution of quantum systems and the irreversibility of macroscopic phenomena, the distinction between microscopic and macroscopic or simple and complex systems is vague and qualitative. In spite of these conceptual difficulties, many processes observed on mesoscopic systems can be treated theoretically by skillfully combining dynamical and statistical laws of physics. By introducing the concept of probability of states, Boltzmann and Gibbs explained the irreversibility of macroscopic phenomena and the second law of thermodynamics. However, the old problem appeared again in a new guise. Physicists are now confronted with a mysterious coexistence of dynamical and statistical laws in nature. The relation between the deterministic dynamical laws and the probabilistic statistical laws is not yet satisfactorily understood, neither on the basis of classical physics, nor on the basis of quantum physics. Nevertheless, a combination of dynamical and statistical theories can obviously be applied successfully to a vast variety of physical problems. In particular, also irreversible processes can be described.

2.3 The problem of quantum jumps

Quantum mechanical state vectors can change in two ways [4]. On the one hand, they change continuously in time according to Schrödinger's time-dependent equation of motion. But on the other hand, they change also discontinuously, when a quantum jump is detected. A problem arises when the usually accepted assumption is made that all physical systems can be closed, at least by considering the whole universe, and then can be described by state vectors evolving in time. In that case, also a state vector of the composed system consisting of object and detection device can be introduced. The process of a quantum jump should now appear as part of the evolution of the state vector of the composed system evaluated with Schrodinger's equation. However, a quantum jump cannot be described as a time-reversal invariant evolution, as was first pointed out by von Neumann [4]. This incompatibility of dynamical evolution and quantum jumps results mainly from the fact that the dynamical evolution is deterministic, whereas quantum jumps occur at random. The coexistence of dynamical evolution and quantum jumps in quantum mechanics mysteriously parallels the coexistence of dynamical and statistical laws mentioned above. This parallelism suggests that the statistical laws of thermodynamics can ultimately be reduced to the probabilistic nature of the elementary quantum jumps. Usually, however, reference is made to the complexity of macroscopic systems for introducing the concepts of statistical physics.

These three problems are encountered together when analyzing the problem of measurement [3]. Every measurement on quantum systems like atoms or molecules relies on the detection of quantum jumps which trigger an irreversible process in a macroscopic measuring apparatus. Therefore, the problem of measurement is of central significance for all discussions on the conceptual difficulties of quantum and statistical physics. It has been discussed over and over again since the early days of quantum mechanics [3]. These discussions move around the measurement paradox, the contradiction between the deterministic nature and the time-reversal invariance of the quantum-mechanical equations of motion and the probabilistic outcome and the irreversibility of a measurement [12]. The repeatedly analyzed problem of the reduction or collapse of the wave function [5, 13] arises from this paradox. Winger concludes from a discussion of the measuring process: "This situation suggests a drastic reformulation of the basic concepts of quantum mechanics. It appears that the statistical nature of the outcome of a measurement is a basic postulate, that the function of quantum mechanics is not to describe some 'reality', whatever this term means, but only to furnish statistical correlations. This assessment reduces the state vector to a calculational tool, an important and useful tool, but not a representation of 'reality'." [12]. And somewhat later in the same publication he writes: "As long as the system is isolated, its state vector is subject to the quantum-mechanical equation of motion and its behaviour is deterministic. When an observation takes place, there is a second type of change of the state vector. Its change then has a probablistic nature. It jumps discontinuously." These critical remarks of Wigner may lead the way to a better understanding of quantum mechanics. The following sections are an attempt to show that a conceptual foundation of quantum mechanics removing the difficulties of present-day concepts is possible, when focusing our attention on the isolation of quantum mechanical objects.

3. The observability of objects

The objects of classical physics are observable continuously with unlimited temporal and spatial resolution. In a typical experimental situation, objects are observed by scattering light on the object. In classical physics this light is considered to be an electromagnetic wave, which propagates continuously in space and time. In principle, there is no limitation of wavelength of frequency. Therefore, the assumption is justified that any details of the motion of objects can principally be observed. In spite of this detailed information flux, the observability of an object can be disregarded when studying its laws of motion. Though observable objects interact continuously with their environment, in particular with the observer and its measuring device, this interaction can be made arbitrarily small by reducing the light intensity. In classical physics the postulate that objects must be observable does not pose any limitations to the validity of dynamical laws. Though observable, classical objects can be considered as closed systems.

A fundamentally new situation arose with Planck's discovery of the quantum of action $\hbar$. According to quantum physics, objects cannot be observed continuously. Rather, there are discrete interaction processes between the object and the measuring device. For example, photons are emitted and absorbed. These interaction processes are quantized and occur spontaneously. Reducing the light intensity entails now that there are fewer interaction processes and, therefore, if reduces the observability of an object. Consequently, an observable object cannot be a closed system. It necessarily interacts spontaneously with its environment.

But also owing to the quantization of action, the observability of an object becomes a measurable quantity depending on the rate of spontaneous interaction processes between the object and its environment. Under suitable experimental conditions, this rate (or information coupling [5, 14]) can become arbitrarily small. In the extreme case, where this rate vanishes, the object is isolated. It does not interact spontaneously with the external world and, therefore, is unobservable. On the other hand, when the rate of spontaneous interactions is increased to extremely high values, the object becomes observable quasi-continuously and one may approach the limit of classical physics.

However, the motion of quasi-continuously observable objects cannot completely be determined by dynamical laws as in classical mechanics. Due to the spontaneous interaction with the environment, which occur at random, their motion has to be somewhat stochastic. Only so long as the spontaneous interactions are negligible, can the motion of objects be described by dynamical laws. However, the dynamical laws have to be supplemented by statistical laws, when the spontaneous interaction of the object with its environment is taken into account.

Quasi-continuously observable objects, where the influence of the spontaneous interactions on its motion can be disregarded, are found in the so-called macroscopic. However, by decomposing macroscopic bodies and advancing to smaller particles, physicists gradually depart from the realm of classical physics. The influence of the spontaneous interactions on the motion of the particles becomes more and more significant. Therefore, statistical laws can prevail as for the Brownian movements. Only in the extreme case, where an object is isolated, do dynamical laws again determine its motion. However, these laws are not the classical ones, but the laws of quantum physics.

According to these considerations, science has progressed towards the fundamental laws of physics not by decomposing macroscopic matter, but by isolating objects. Although it is true that historically it was necessary to advance to the realm of atomic particles in order to prepare completely isolated objects, the main achievement of modern physics is, nevertheless, isolation. Some consequences of this statement are considered in what follows.

4. Isolated objects and open systems

The consideration in Section 3 led to the conclusion that observability is an essential property of physical objects. Since it is measurable, it may be used for classifying objects. All physical objects are principally open systems. They must interact spontaneously with the external world to become observable. In particular, all objects of the so-called macroworld are open systems, although they may be considered as closed within the framework of classical physics, where their observability is disregarded. The isolated object is an idealised limiting case. Owing to Planck's discovery of the quantum of action, this ideal can be approached experimentally. Atoms and molecules were the first isolated objects which could be prepared for experimental investigations. The best realisation of isolated objects are single electrons of groundstate ions and atoms in a trap, where the motion of the particles is confined in space and, therefore, spontaneous interaction with the environment can be suppressed [15]. The main features of these isolated objects, by which they differ from classical objects, were recognised by Bohr, when he formulated his two famous postulates [16]:

(*1*) the existence of stationary states with discrete energy values

(*2*) the occurrence of quantum jumps accompanied by emission or absorption of photons.

The energy levels are sharp if their isolation is complete, and they are broadened if the object interacts spontaneously with the environment. The level widths Γ are determined by the transition rates γ:

$$\Gamma = \hbar\gamma\,. \tag{1}$$

Spontaneous decays as well as absorption of thermal radiation contribute to this spontaneous interaction. As long as this broadening is small compared to the energy separations, the objects can be said to be effectively isolated.

The spontaneous interaction of these objects with the environment is a purely temporal sequence of quantum jumps. The evolution between two successive quantum jumps is described by quantum dynamics. This evolution is deterministic, since the object does not interact spontaneously with the environment during this time and, therefore, random influence is absent. However, the knowledge of the evolution of the quantum state only allows a probabilistic prediction of the following quantum jump, which triggers an observable event in the environment described classically.

Isolated objects are pure quantum systems regardless of their complexity. Using the language of the traditional concept, they may be heavy nuclei consisting of many nucleons or arbitrarily large molecules or clusters consisting of many atoms. If their energy levels E are well separated, that is if

$$\Delta E \gg \Gamma\,, \tag{2}$$

they evolve according to quantum dynamics. However, experimentally it becomes increasingly difficult to isolate an object the more complex an object is, because the level density increases with its complexity.

Therefore, it can be assumed that the level structure of large aggregates of atoms is usually smeared out. That is

$$\Delta E \ll \Gamma \tag{3}$$

for all objects of classical physics. These objects have an observable spatial structure. Obviously, the inequalities (2) and (3) characterise the two extreme cases of (quasi) isolated objects which have an observable level structure and (wide-) open systems which have an observable spatial structure. By and large, they correspond to objects usually called microscopic and macroscopic, respectively.

In conclusion, the classification of objects based on their observability allows a clear distinction between the realms of quantum and classical physics. Quantum dynamics is the theory of isolated objects. These unobservable systems are not subject to spontaneous interactions and, therefore, evolve deterministically. However, because they are removed from our perceivable world, their evolution must not be describable in space and time. Deterministic evolution is perturbed by spontaneous interactions with the environment. Therefore, statistical laws have to be applied for describing observable objects. However, in the macroscopic limit, where it is possible to average over huge numbers of spontaneous interactions, the laws of evolution may again become essentially deterministic due to the laws of great numbers. In particular, the dynamical laws of classical physics appear. But classical physics do not explain all phenomena of our macroscopic world. The phenomena of life make obvious that there is a larger variety of phenomena in the macroscopic world than envisaged in classical physics. A great number of spontaneous interactions does not guarantee that the laws of macroscopic nature become deterministic in the classical sense.

5. Irreversibility

According to the conclusions of the preceding section, spontaneity is a basic feature of the physical world. It is this spontaneity which furnishes a solid foundation for the irreversibility of observable phenomena. As pointed out by von Weizsacker [9], time-reversal invariant basic laws are compatible with irreversible thermodynamics, if a statistical Ansatz for treating the observed processes is made. To illustrate compatibility, von Weizsacker refers to a game with black and white balls first discussed by P and T Ehrenfest [17].

Within the framework of the concept of isolated objects and spontaneous interactions with the environment, the irreversibility of observable phenomena arises from the spontaneity of the elementary quantum jumps of isolated objects. Here, we do not shuffle balls between two otherwise isolated ensembles as in the game of the Ehrenfests, but quanta are exchanged between an object, which may be almost isolated, and an open measuring device or the environment in general. Only the isolated object is described by time-reversal invariant quantum mechanics. But the open measuring device or the environment principally cannot be described by a quantum mechanical state vector. Therefore, it is consistent with the general concept of assuming that spontaneous interactions with the environment are irreversible and, in particular, may trigger a process of measurement.

The distinction between isolated objects and open systems paves the way not only for defining the field of quantum mechanics, but also for characterising the realm of statistical thermodynamics. While isolated objects are described by quantum mechanics, open systems are the objects of thermodynamics, in particular, those systems which are exposed to an equilibrium environment. Due to spontaneous interactions, they are not in a fixed quantum state. Rather, their state vectors fluctuate irregularly. In an equilibrium environment, this fluctuation causes the Gibbsian canonical probability distribution of quantum states $|i\rangle$ [10]

$$w(i) \propto \exp\left(-\frac{E_i}{kT}\right) \tag{4}$$

dependent on the temperature T, which appears primarily as a parameter of the environment.

Thus, the main features of thermodynamical systems, irreversibility and the stochastical fluctuation of states, are not intrinsic properties of a closed system, but result from their spontaneous coupling to the environment. It is not the 'complexity' of the system, which makes its state fluctuate. One can ascribe a temperature even to single atoms or ions in a trap [18], if they are coupled to an equilibrium environment of this temperature.

6. Demons, cats and measuring devices

In thermodynamics, primarily open systems in an equilibrium environment are considered. This is an idealization. In the real world, all objects are exposed to an environment which is not in equilibrium. Indeed, objects become observable only if they are coupled to an environment, which is not in equilibrium. This nonequilibrium condition has been emphasised first by Demers [19] and later, in particular, by Brillouin, when discussing the action of Maxwell's demon [14]. However, in these discussions the demon was assumed to be part of an isolated system. This assumption is not consistent with the present concept. Observable objects and, even more, observing subjects cannot be part of an isolated system, but are open systems.

Likewise, Schrödinger's cat [9] has to be considered as an open system within the framework of the present concept. Thus, this often discussed conceptual problem of quantum physics disappears. A cat cannot be described by a quantum-mechanical state vector, and, therefore, the transition from life to death cannot be described by the evolution of a quantum state.

All measuring devices, all living creatures as well as all observable objects, that is, the whole perceivable world of our actual life is a non-equilibrium open universe. To grasp this universe, we are striving to find or prepare approximately idealised objects, which are separated more or less from their environment. Isolated objects and open systems in an equilibrium environment are special examples, which can be understood within the framework of quantum mechanics and statistical thermodynamics, respectively. However, by idealising we disregard important features of the actual world as, for example, the observability of the objects, the main precondition for our experimental research. Therefore, these idealisations must not be identified with 'reality'. The variety of phenomena in nature can be and actually is much more manifold than expected on the basis of the idealisations of our theoretical approaches.

Thus the basic assumption of this paper, that the isolation of objects was a primary achievement of modern experimental physics, suggests that even the most basic theories of physics are strictly applicable only to well-defined idealised systems. But perturbational approaches are needed to treat more realistic physical problems. For example, the spontaneous decay of atomic particles appears as a process which cannot be treated by pure quantum dynamics. Rather it has to be considered as an interaction of an isolated object with the environment and, accordingly, is treated using the perturbation theory. It remains an open question, whether 'an alternative to quantum theory' [20] is possible where spontaneous interaction processes are included in a fundamental theory, not as a perturbational approach, but as an intrinsic part of the theory. In any case, such a theory must bring the deterministic features of quantum dynamics in line with the probabilistic features of quantum jumps, a task which may well be insolvable.

7. The bottom of elementarity

The classical idea of reality, namely the concept of bodies moving in space and time, compelled physicists to believe that the fundamental laws of nature can be found by decomposing macroscopic bodies and searching for structureless, pointlike particles. However, the physical space-time continuum is an idealisation abstracted from our experience with the physics of macroscopic, that is, continuously observable bodies. Space and time are measurable only within the framework of classical physics, where scales and clocks can be conceived. Although modern clocks rely on atomic physics, the complete device is a macroscopic system, which can be observed continuously. The concept of space and time loses its experimental basis when approaching to the realm of quantum mechanics where (quasi) isolated objects are considered. As long as an object is almost isolated, its spatial structure cannot be analyzed experimentally. Only a stochastic temporal sequence of quantum jumps can be observed.

By assuming that the isolated object, which is removed from uncontrollable and random external influences, is the ideal object of physics, the question about the bottom of elementarity assumes a meaning different from the traditional one. If the spatial structure of isolated objects is principally unobservable, the search for elementary point-like particles seems unreasonable. Rather, all (quasi) isolated objects such as electrons, nucleons, nuclei, atoms or molecules should be considered as elementary objects. However, though not having an observable *spatial* structure, these objects do have a measurable *level* structure. Therefore, the question arises: what can be the conceptual basis for the theory of this level structure and of the coupling of these objects with the environment? What is the foundation of quantum mechanics?

Present-day quantum physics — even in its most advanced version: quantum field theory — is conceived as a theory of particles moving in space and time, though this motion does not obey the laws of classical physics. This concept is not acceptable within the framework of the present approach. When conceiving a theory of isolated objects, any reference to space and time should be avoided. The concept of space and time does have an experimental basis only as long as objects are considered which are quasi-continuously observable.

Though it seems to be extremely speculative, one may suspect that there exists a fundamental mathematical structure which reflects the physical properties of isolated objects. This suspicion is in accord with the conclusions of Wigner cited in Section 2: the state vector reduces to a calculational tool, but does not represent 'reality'. The hope of finding such a mathematical structure may be justified by the fact that we are leaving the realm of the observable physical world when preparing isolated objects and, therefore, may approach pure mathematics. Nevertheless, the structural parameters of (quasi) isolated objects as masses and coupling constants can be principally measured with unlimited accuracy.

Whatever the result of a quest for a fundamental theory of isolated objects, it will not be a 'theory of everything' [21]. The goal of this quest is necessarily more modest. According to the present approach, isolated objects are idealised systems. Only these idealised systems can be described by a fundamental theory. To describe objects of the actual world, at least the perturbation of the ideal objects by their spontaneous coupling to the environment must be taken into account. However, a perturbational approach seems to be justified only if inequality (2) is valid. It remains an open question, to which extent the phenomena of our macroscopic world can be understood on the basis of a theory of isolated systems and the concept of spontaneous transitions. When considering quasi-continuously observable systems, there arises the question: How does the spatial structure of these objects become an observable feature? What is the relation of the space-time concept to the mathematical structure of isolated objects? Provided a fundamental theory of isolated objects exists, it should be possible to understand at least the concepts of space and time and classical mechanics as an idealisation of the physics of wide-open systems. However, when trying to understand the concepts of classical physics in terms of a more elementary theory of isolated objects and spontaneous couplings, one may also hope to discover ways of better understanding the phenomena of life, which are so foreign to present-day concepts of physics.

8. Conclusions

Guided by the hypothesis tat physicists approached the fundamental laws of physics by isolating objects from the environment, I have tentatively reconsidered the conceptual foundations of quantum mechanics. Instead of distinguishing microscopic and macroscopic objects, a classification of objects based on their spontaneous coupling to the environment is introduced. This coupling is a measurable quantity owing to the quantization of action. According to this classification, there are extreme cases of isolated objects and wide-open systems and in-between a transition realm well defined by a measurable quantity. Within this scheme, the irreversibility of observable phenomena result from the spontaneity of quantum jumps. Thus statistical physics attains a new conceptual basis. On the other hand, quantum mechanics should be considered as a theory of idealised objects, namely objects completely isolated from the environment. This is probably the most surprising conclusion of the present approach. Not only classical mechanics, but also quantum mechanics should be considered as a theory of idealised systems. Neither of them is really more fundamental. They are theories of two different idealised situations. This approach also suggests that statistical thermodynamics primarily applies to objects in an equilibrium environment, that is to another idealised situation. Though these results may seem unsatisfactory at first sight, they may lead the way to a better understanding of the relationship between physics and biology. At any rate, by recognising that even the most fundamental theories of modern physics are strictly applicable only to idealised objects, many of the conceptual difficulties in modern physics, especially those mentioned in Section 2, disappear.

In spite of the revolutionary change regarding the conceptual foundation of quantum mechanics and statistical thermodynamics, the application of these well-established theories to actual physical problems is unaffected. However, this change does alter the frame of reference for assessing the value of modern physics vis-a-vis our understanding of nature and, therefore, should influence future scientific research.

Acknowledgments. I am grateful to my co-workers Y Kriescher, O Reusch and B Skogvall for their many elucidating discussions. Yu L Sokolov and V G Pal'chikov revived my interest in the basic problems of quantum physics during a joint project supported by the Volkswagen (VW) Stiftung. I thank them for this stimulating cooperation and the VW Stiftung for its support.

References

1. Weisskopf V F "What is an elementary particle?", in *Physics 50 Years Later* (Ed. S C Brown) (Washington D C: National Academy of Sciences, 1973)
2. Balian R *From Microphysics to Macrophysics* (Berlin, Heidelberg: Springer Verlag, 1991)
3. Wheeler J A, Zurek W H (Eds) *Quantum Theory and Measurement* (Princeton: Princeton Univ. Press, 1983)
4. Von Neumann J *Grundlagen der Quantenphysik* (Berlin: Springer-Verlag, 1932)
5. Kadomtsev B B *Usp. Fiz. Nauk* **164** 449 (1994) [*Phys. Usp.* **37** 425 (1994)]
6. Feynman R *Journ. of Microelectromech. Syst.* **2** 4 (1993)
7. Kastner M A *Atomic Physics* **13** 573 (1992)
8. Benedek G, Martin T P, Pacchioni G *Elemental and Molecular Clusters* (Springer Series in Material Science Vol. 6) (Berlin Heidelberger: Springer Verlag, 1988)
9. Von Weizsacker C F *Der Autbau der Physik* (Munchen: Carl Hanser Verlag, 1985)
10. Reif F *Statistical and Thermal Physics* (New York: McGraw Hill, 1965)
11. Landau L D, Lifschitz E M *Lehrbuch der Theoretischen Physik*, Bd. V und IX (Berlin: Akademie-Verlag, 1979)
12. Wigner E P, in Ref. [3] p. 260
13. Garstens M A, in *Quantum Theory and Beyond* (Ed. T Bastin) (Cambridge: Cambridge Univ. Press, 1971) p. 85
14. Brillouin L *Science and Information Theory* (New York: Academic Press, 1956)
15. Neuhauser W, Hohenstatt M, Toschek P, Dehmelt H G *Phys. Rev. A* **22** 1137 (1980)
16. Bohr N *Philos. Mag.* **26** 1, 467, 857 (1913)
17. Ehrenfest P, Ehrenfest T *Math.-Naturwiss. Blatter* **11** 12 (1906)
18. Nagourney W, Sandberg J, Dehmelt H G *Phys. Rev. Lett.* **56** 2797 (1986)
19. Demers P *Can. J. Research* **22** 27 (1944); **23** 47 (1945)
20. Prigogine I, Petrosky Y *Physica A* **147** 461 (1988)
21. Salam A, in *The New Physics* (Ed. P Davies) (Cambridge: Cambridge Univ. Press, 1989) p. 481