Quantum Theory
and the Division of the World

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Abstract

We discuss an ontological model suggested by quantum physics, in which the notion of events is of central significance. The conventional objects are considered as causal links between events. Localization in space-time refers primarily to events, not to objects. The intrinsic indeterminacy forces us to consider both possibilities and facts, corresponding to the distinction between future and past. In presently existing theories, the definition of individual events and their localization properties depends on asymptotic arguments adapted to prevailing situations.

1. Introduction

In the early 1950s, my mentor Fritz Bopp pondered the question as to why the probabilities in quantum mechanics appear as absolute squares of complex amplitudes. This led to a series of papers with titles such as “Dice Games Whose Tokens Move Quantum Mechanically”.

In 1953, I had the great chance to spend a year in Copenhagen. One day Niels Bohr came to me saying: “I received again a manuscript by Professor Bopp. I do not understand why people occupy themselves with questions which have been clarified for decades while there are so many unsolved interesting new problems around.” My imprudent answer: “Maybe things are not so clear”, prompted a series of discussions. Comment of one listener: “You talked in different languages about different things.” Indeed. Many discussions about the status and interpretation of quantum theory create this impression.

For Niels Bohr the term quantum theory was tied to the formative experience of the almost miraculous breakthrough of the years 1925–1930. Initiated by the invention of novel mathematical structures for the treatment of the enigma of discrete stable states of atoms, it took only a few years to develop a language and a full-fledged theory capable of ordering and predicting an enormous wealth of phenomena. This required a radical break with the traditional understanding of physics. It apparently implied
the need to abandon the search for an ontology of an outside world and required the inclusion of the observer in the description.

Bohr derived the inevitability of this break as a consequence of his epistemological reflections. On the one hand there is “our incapability to assign conventional attributes to atomic objects”. On the other hand there is the necessity “to be able to tell our friends what we have done and what we have learnt” (Bohr 1960). This requires a description of the experimental setup and its results in the language of a naïve ontology related to everyday language in a unique way.\(^2\) Thus, the analysis of any kind of experiment requires a threefold division of the world into an “observer”, a “physical system”, i.e. a part of nature selected by the experimental setup, and finally the rest of the universe insofar as it is relevant for the experiment. The choice of the cut between these parts is a matter of expediency. The knowledge that we gain is the final event, the “observational result”, a unit which cannot be further decomposed.

This is a clear description of the basic conditions underlying every experiment, and it indicates our limited possibilities to gather knowledge. Nonetheless, there remains a wide-spread uneasiness. The purpose of experiments does not end in themselves. Traditionally, their goal was “to unveil the mysteries of nature”. What does this mean? The goal was an ontological model consistent with experience as far as possible. This was how Einstein understood the character of a theory. Theory is not confined by epistemology; it always represents an extrapolation beyond what we can know. It cannot be read off from experiments but requires a “free invention of the mind”. Nobody will expect that such a model presents a complete and ultimate description of the world. Each theory has a limited domain. There are phenomena which cannot be correctly described within it. It is unlikely that a “Theory of Everything” will ever be developed.

The division between observer and observed system plays an essential role in the abstraction of the principles of quantum mechanics due to Dirac and von Neumann. It is canonized by the term “observable” as a central concept in the mathematical formalism. Does this mean that quantum theory is far from an ontological model, and that the possibility of such a model is ruled out in principle? A poll among physicists would probably result in a clear majority of positive votes for both questions.

\(^2\)Bohr calls this “the language of classical physics”. I feel somewhat uncomfortable with the term “classical” in this context. It suggests that quantum theory cannot be formulated without a classical (deterministic? ontological?) theory, connected to it by a correspondence principle and a formal “quantization” rule. In the historical development, these analogies were crucial. However, I cannot ascribe fundamental significance to them. Describing an experiment simply and focusing on its essential features, we use terms established by previous work of other physicists, which can be related to everyday language in a unique operational manner. This applies to a beam of H-atoms in a highly excited metastable state as well as to an electromagnetic field.
I consider this judgement as too narrow. There is nothing like “the” quantum theory. We have the non-relativistic quantum theory of material particles and electromagnetic fields. This is a complete theory (if we consider atomic nuclei as given and exclude nuclear physics) and, if we do not define ontology in a too restricted fashion, it can be interpreted as an ontological model with a particular domain, within which it corresponds with experience exceedingly well. This will be described below. In high-energy physics we have fragments of a theory indicating an essential shift of perspective, but we are far from a complete theory. Some remarks in this regard will be made in the third section.

Let me return to the question of what is meant by the word “observer”. The two sides of the cut are distinguished by their different descriptions and not (or at least not yet) by an intrinsic distinction. Heisenberg mentions as an example that a photographic plate could be considered as “the observer”, but equally well as part of the system. In the first case, the result of an observation is the formation of a small silver crystal at some place on the plate at a more or less well-defined time. This is considered as a fact, neither depending on recognition by a spectator nor depending on its being fixed as a permanent document. It is the prototype of an event. In the second case, we need an observer of the photographic plate. Normally his task will only be to register the fact mentioned above.

The formalism of quantum theory admits, however, a different way of observing the photographic plate, complementary, as it were, to the determination of the position of the silver crystal in the emulsion. There are good reasons to expect that such an observational instrument could never be realized, even with unlimited financial funds of an institute founded exclusively for this purpose, because of the effective decoherence of systems with many degrees of freedom.

But if we nevertheless insist on the existence of such a complementary observable, then we are obliged to conclude that the photo plate cannot be regarded as an observer: It does not generate facts. The same argument applies to an extended observational instrument. It cannot generate facts either. So we come to a chain of observers. Where does it end? Several eminent scientists (von Neumann 1932, London and Bauer 1939, Wigner 1967) proposed that it terminates when an event becomes consciously perceived. Consciousness is regarded as the ultimate agency: “If one formulates the laws of quantum mechanics in terms of probabilities of impressions, these are ipso facto the primary concepts with which one deals” (Wigner 1967, p. 176). One will not dispute that “our knowledge of the external world is the content of our consciousness” (Wigner 1967, p. 177). But impressions on human consciousness are not what quantum theory is about. The empirical material that it orders consists of reproducible phenomena, identifiable without any doubt by any research group. Only then can they be considered as facts in an imagined external world.
In this sense it is irrelevant whether or not a phenomenon corresponds to an impression on consciousness.

Observation results are coarse phenomena. They are assigned to the interaction between two objects which are regarded as real, the “physical system” and the “measuring instrument”. The coarseness reflects the asymmetry between the two objects. The measuring instrument is large, the observed system can be small. This quantitative difference is reflected in different descriptions of the two objects. However, we may use the theory in order to refine the description toward more elementary objects and processes. The fundamental problem in this regard is the division of nature into individual, specifiable elements, without which no physical conclusions can be drawn.

The non-relativistic quantum theory offers a range of possible components. These are “objects” on the one hand and “events” on the other, i.e. undivided processes of mutual interactions among objects. Examples for such objects, to be regarded as wholes, are atoms, molecules, crystals. Events have to be regarded as wholes, too. An example for an undivided event could be an atomic ionization process caused by a collision with electrons. Bohr has emphasized that a quantum process should not be understood as a continuous change of properties but constitutes an inseparable whole (Bohr 1949).

The theory assigns to each object, even to “atomic” objects, attributes in terms of an internal structure described by the internal wave function (after separating the motion of their center of mass). Every Na-atom in its ground state has the same structure. The classification of stable objects and the determination of their internal structure is one of the triumphs of quantum theory. The object does not possess conventional attributes such as the position of its center of mass at a given time. Born’s probability interpretation of the wave function cannot be understood as the probability of a position of an object that is simply unknown to us. The Copenhagen viewpoint that the attribute “position” only emerges in a position measurement is well established. The measurement of the position of an object, however, means an interaction with another object, thus an event. The attribute of position in space and time refers to events, not to objects.

Moreover, the intrinsic indeterminism of the theory means that any ontological picture has to include both possibilities and facts. Such a distinction enforces the distinction between past and future. The future is open, the realization of facts belongs to the past. This has often been emphasized by von Weizsäcker (1985).

Quantum theory makes statements about probabilities. Probabilities for what? We talk about the probability for the emergence of new facts given past facts. Every fact is unique in the universe. In an ontological model the notion of probability must therefore refer to individual facts.
(as it is the case in risk assessments, for instance). This probability must be endowed with an ontological meaning referring to the configuration of past facts and representing, as a state in a quantum theoretical sense, an attribute of future possibilities. Such an interpretation of the probability statements of quantum theory has often been proposed, e.g. by Popper (1957) with the notion of “propensity”, or by Mermin (1998) as “objective probability”. This does not introduce conceptual difficulties, but it cannot be empirically verified in a direct manner. We can test it only by counting relative frequencies in an ensemble of cases (that are identical to the best of our knowledge). But this is no relevant objection. Every ambitious theory contains terms which cannot be verified in a direct manner.

A collision process between stable objects has some features that are analogous to an observational process. A basic attribute of such an event is its localization. In order to fix the idea in a somewhat simplistic way, we are talking about the position of a collision center within an established reference system. The theory allows us to claim\(^3\) that each individual event has such a position with an accuracy of the order of \(\sum (\lambda_i d_i)^{-1}\)^\(-1/2\), where \(\lambda_i\) are the de Broglie wavelengths of the colliding objects and \(d_i\) are their distances from the preceding event (Haag 1999). This will in general be much sharper than the overlap of the wave functions and does not depend on any future measurements.

This implies that we can postulate a decision for the realization of a position of a single event among many events, in analogy to the alternatives of an observation. The propensity for the choice of this position can be calculated from the configuration of previous events.

The resulting ontological picture differs drastically from a classical one. It sketches a world which is continuously evolving, where new facts are permanently emerging. Facts of the past determine only probabilities of future possibilities. While an individual event is considered as a real fact, the correlations between events due to quantum mechanical entanglement imply that an individual object can be regarded as real only insofar as it carries a causal link between two events. The object remains an element of potentiality as long as the target result has not become a completed fact.

The described attributes of stable objects and of events (in particular their localization) are mental constructs within the theory. However, they yield an ontological picture which, in its domain of application, corresponds well with experience. This domain is restricted by the fact that we can speak about a division of the world into single stable objects and corresponding events only in the limiting case of sufficient isolation. We deal with asymptotic notions adapted to a particular idealization.

\(^3\)This requires to exclude formal observables not corresponding to a realizable experimental setup.
In more complex situations the extraction of elements to which individuality can be assigned in an ontological picture is more difficult. Quantum theory begs the question of what is an elementary object or an elementary event. When we reconstruct a possible “history”, which implies a division of a whole into distinct individual parts, we do currently depend on idealizations using large quantitative differences in order to derive an “effective decoherence”. In complex situations we have a large number of degrees of freedom, in the simple situation described above we have large distances.

It should be emphasized, though, that this problem cannot be mitigated by shifting decisions into the domain of consciousness. Nor does it change the necessity to include facts as well as probabilities in the description. This leads to an evolutionary picture with decisions in nature, comprising the transition from possibilities to facts. A similar ontological picture was already outlined by Whitehead in 1929 in his book *Process and Reality* (Whitehead 1978; see also Stapp 1979). The answer to the question for the limits of divisibility in nature will presumably change with the further development of the theory.

2. Non-Relativistic Quantum Theory

2.1 Mathematical Structure

The systems considered are constituted by a number of basic material components (we restrict ourselves to electrons and atomic nuclei) and an electromagnetic component. Following Fermi’s decomposition, we split this component into a transversal part, described as a system with an indefinite number of photons, and a longitudinal part producing the Coulomb interaction between charged particles. In addition, there may be an external field resulting from external sources, which we consider as a classical field rather than a part of the system considered. A Hilbert space is assigned to each system. The Hilbert space of the system as a whole is the tensor product of the Hilbert spaces of its subsystems (antisymmetric or symmetric, respectively, for several components of the same kind).

A state of the system (summarizing our knowledge about its previous history) is represented by a positive operator $\rho$ with trace 1 in the Hilbert space, called “statistical operator”. This operator can be represented as

$$\rho = \sum \lambda_i P_i ,$$

where the weights $\lambda_i$ are positive numbers with $\sum \lambda_i = 1$, and the $P_i$ are orthogonal, one-dimensional projectors. If only one single weight $\lambda$ is different from zero, the state is called “pure”. In this case the state can
be more conveniently characterized by a unit vector $\Psi$, a “state vector”, in the one-dimensional subspace into which $P$ projects. A non-pure state can be decomposed in many ways by

$$\rho = \sum \mu_i \rho_i,$$

where the $\mu_i$ again are positive weights and the $\rho_i$ are other (purer) statistical operators. If one imagines that the notion of a state is not assigned to a single system but to a statistical ensemble, prepared by a source designed by specific instructions, then Eq. (2) can be interpreted as an ensemble $\rho$ generated by a mixture of ensembles $\rho_i$. The probabilities for arbitrary future observational results depend only on $\rho$. At first it appears quite strange that it makes no difference how $\rho$, as a mixture of other ensembles, was prepared. The particular form of Eq. (1), which corresponds to the spectral decomposition of $\rho$, seems to be mathematically preferred. In Sect. 2.3 we will see that it is physically significant, too.

An observation is represented by a set of orthogonal projectors $\{P_k\}$, where $P_k = P_k^*; P_k^2 = P_k; P_k P_k = 0$ for $k \neq 1$. They can project onto subspaces of any dimension. Each of these projectors corresponds to one of the possible observational results. The probability for the result $k$ in state $\rho$ is given by

$$\omega_k = tr \rho P_k.$$  

The symbol $tr$ means the trace of the operator. The positivity of $\rho$ guarantees the positivity of the number $\omega_k$. If we assign real numbers $a_k$ as “measured values” to the different alternatives $k$, the self-adjoint operator

$$A = \sum a_k P_k$$

is identified as the observable associated with the so calibrated measuring instrument.

2.2 Relation to Space and Time

For the application of the general formalism to physical problems we need a bridge from the naive description of experimental setups to specific mathematical objects ($\rho, P_k$). Historically, this was achieved by the formal correspondence of the variables of classical mechanics with quantum theoretical operators. In textbook literature, the description of these rules takes a significant position. Another approach, avoiding any reference to classical mechanics, starts with the geometric symmetry group. It consists of translations in space and time, rotations, and the transition to a uniformly moving reference frame.
In the usual space-time representation, this 10-parameter group – in the non-relativistic case it is the inhomogeneous Galilei group, in the relativistic case the Poincaré group – acts on the components of the experimental setup by changing their position and velocity. As Wigner found, one can assign a unitary operator, fixed up to a phase factor, in the Hilbert space of the considered system to each of those operations. All these operators together form a representation of the symmetry group (up to a phase factor), a so-called ray representation.\footnote{The indeterminacy of the phase factor results from the fact that a “pure state” corresponds to a ray rather than a vector in Hilbert space.}

All such representations can be constructed from irreducible representations. Wigner classified the irreducible ray representations of the Poincaré group long ago (Wigner 1939). The corresponding analysis for the Galilei group was carried out later (Hamermesh 1964). In simplified words, the result is that in both cases an irreducible ray representation is determined by two parameters, one of which must be interpreted as the mass, the other as the spin of a particle. Irreducible representations are assigned to individual particles, no matter whether they are elementary components or stable objects in the sense of Sect. 1.

It is now important that in an irreducible representation all operators in Hilbert space can be expressed as functions of operators representing group elements. This allows us, in the framework of the non-relativistic theory of a massive particle, to specify that projector in Hilbert space which describes the localization in a selected space region at a given time. This leads to a “position operator”, and we obtain Heisenberg’s commutation relation for position and momentum (the generator of space translations). The material component of systems considered in the theory can be obtained from elementary components (electrons and nuclei) by the tensor-product construction mentioned above. For the kinematic quantities (position, momentum, spin orientation at a given time) this corresponds to the transition to configuration space and establishes the relation between vectors in Hilbert space and the naive view.

A photon system requires an entirely different discussion for two reasons. First, there is no position operator due to the vanishing rest mass of photons.\footnote{The physical interpretation of an irreducible representation of the Poincaré group (Newton and Wigner 1949) shows that the notion of a localized state of a particle becomes increasingly blurred with decreasing rest mass.} Second, photons do not possess charge quantum numbers. This implies that the “number of photons” is in general no physically relevant notion.

For the description of the “dynamics” (time translation) we still need the form of the mutual interaction among the basic components of the system as well as their interaction with the photon system. Within the chosen limits of the theory, the interaction is of exclusively electromagnetic...
nature and can be derived (almost) uniquely from the classical Maxwell theory. A fundamental understanding of this structure and its generalization exceeds the scope of the present exposition. As a keyword one might refer to the (not yet completely clear) “principle of local gauge invariance”.

2.3 Entanglement

In the Hilbert space $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$ there is a special class of vectors, the “product states” of the form $\Psi = \Psi^{(1)} \otimes \Psi^{(2)}$. This set of states would correspond to the Cartesian product of the state vectors of subsystems. The tensor product contains, in addition, linear combinations of such product states. Choosing orthonormal systems $\Psi^{(1)}_k, \Psi^{(2)}_\alpha$ in $\mathcal{H}_1$ and $\mathcal{H}_2$, the general vector

$$\Psi = \sum c_{k\alpha} \Psi^{(1)}_k \otimes \Psi^{(2)}_\alpha,$$

(5)

in $\mathcal{H}$ is not reducible to the form of a simple product. This indicates a holistic feature of quantum theory: The whole is more than the sum of its parts. The state vector $\Psi$ of Eq. (5) characterizes a pure state for the total system composed of objects (1) and (2). If we restrict attention to measurements on object (1) alone, the probabilities for the outcome will be governed by an effective statistical operator $\rho^{(1)}$ whose matrix elements are

$$\rho^{(1)}_{k1} = \sum_\alpha c_{k\alpha} \overline{c}_{1\alpha}.$$

(6)

Let us call $\rho^{(1)}$ the “partial state” of system (1). This makes sense since $\rho^{(1)}$ determines the probability for an event caused by system (1) even if we have influenced system (2) somehow in between, e.g. by an observation. However, it is essential that the partial states $\rho^{(1)}$ and $\rho^{(2)}$ are not sufficient to describe the probability of pairs of events. The entanglement implies a correlation between events at the two subsystems which can be observed by coincidence measurements. If the correlation refers to a conserved quantity (spin orientation, energy, momentum, charge) of the subsystems, it is preserved over long periods and long distances. It is further essential that these correlations cannot be reduced to correlations between (hypothetical) “states” of some kind ascribed to the subsystems

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6This often ignored fact is ultimately a consequence of a property of relativistic quantum theory that is called “locality” or “Einstein causality”. We can speak of an observation of system (1) or (2) alone only if they are sufficiently separated in space. The probability of an event at system (1) is independent of the fate of system (2) in the region which is spacelike with respect to the event. Correlations in the coincidence rate of events at the two objects are a different matter. Their causal origin lies in the previous history.
before the events actually occurred. Such correlations, well-known in classical physics, would have to satisfy inequalities first pointed out by Bell (1964).

The experimental verification of the statements of quantum theory have revived the discussion about “elements of reality” as initiated by Einstein, Podolsky and Rosen (1935). The existence of particular quantum theoretical correlations certainly means that the notion of a “state of an individual object” concerns only the probabilities for events exclusively caused by “this” object, disregarding any possible coupling of such events with others. More precisely, we can assign ontological significance to an individual object only insofar as we understand it as a causal link between two events considered as facts. An entanglement of all electrons in the universe is already implied by the Pauli principle; nevertheless it makes sense to speak of “that” electron which was released from a metallic surface by a radiation pulse and then caused a latent image in a photo emulsion. This interpretation of the notion of an object (or subsystem) relates to the evolutionary ontological picture sketched in Section 1.

Let us finally turn to another question. Given the partial states $\rho^{(1)}$ and $\rho^{(2)}$, under which conditions are they restrictions of a pure state of the system as a whole, and how uniquely is this state defined? Writing Eq. (5) as

$$\Psi = \sum \Psi_k^{(1)} \otimes \Phi_k^{(2)} ; \quad \Phi_k^{(2)} = \sum c_{k\alpha} \Psi_\alpha^{(2)},$$

we have:

$$\rho_{k1}^{(1)} = (\Psi_1^{(2)} \Phi_k^{(2)}).$$

If we choose for the $\Psi_k^{(1)}$ an orthonormal system in which $\rho^{(1)}$ is diagonal, thus

$$\rho_{k1}^{(1)} = \lambda_k \delta_{k1},$$

then it follows for $\lambda_k \neq 0$ that $\Psi_k^{(2)} = \lambda^{-1/2} \Phi_k^{(2)}$ is a (possibly incomplete) orthonormal system in $\mathcal{H}^{(2)}$, and we have

$$\Psi = \sum \lambda_k \Psi_k^{(1)} \otimes \Psi_k^{(2)}.$$

The $\lambda_k$ and $\Psi_k^{(r)}$ are obtained from the spectral analysis of $\rho^{(r)}$. The two partial states $\rho^{(r)}$, $r = 1, 2$, are restrictions of a pure state of the system as a whole only if their eigenvalues (including multiplicity) are identical. The spectral decomposition of $\rho^{(1)}$ is physically distinguished from other decompositions of the form of Eq. (2) by the fact that it allows us to interpret $\rho^{(1)}$ as a restriction of a pure state of a larger system.
2.4 Coherence

The consequences of entanglement enforced a revision of the naive understanding of “objects” or “systems”, respectively. An ontological picture can only be accomplished by referring to the notion of an “event”, understood as a definite, free (within certain restrictions) decision in nature. The question for the status of events and their separability is itself obscured by coherence, the capability of interference of additive terms of a state vector. The orthodox view assigns decisions only to the interaction with an observational instrument. The description of the dynamical evolution within a closed system (Schrödinger equation or time translation operator) excludes events. Nevertheless, it can ascribe an approximate meaning to this notion. For instance, if we characterize an event by a projector $P$, then the statement that within an ensemble in state $\rho$ a decision took place as to whether or not this event occurred means that for all future observations the state

$$\rho' = P \rho P + (1 - P) \rho (1 - P)$$

is undistinguishable from $\rho$. As a consequence, since

$$\sigma = \rho - \rho' = (1 - 2P) [\rho, P],$$

all projectors $P_f$ corresponding to possible future observations would have to satisfy

$$\text{tr} \sigma P_f = 0.$$  

(9)

Dropping the restriction “possible future” and admitting all projectors in Hilbert space as candidates for $P_f$ implies that Eq. (9) holds only in the trivial case $[\rho, P] = 0$. As a matter of fact, however, there are both practical and fundamental restrictions for $P_f$. The former are concerned with the realizability of hypothetical observational instruments. They lead to the “effective decoherence” mentioned above, which has often been discussed for typical examples. Regarding fundamental restrictions, we do not know much. It is certainly not plausible to assume that (in the sense of Section 2.1) any projector $P_f$ (as an observation) can be applied to every statistical operator $\rho$ (as a state). This idealization does not take into account the self-consistency of a description of the whole. Any deeper justification of a “fundamental decoherence” exceeds the scope of this contribution. It might have to do with a presently unsatisfactory understanding of the local gauge principle in quantum physics, referring to the question of the local significance of charge quantum numbers and, related to this, a local version of superselection rules.

Decoherence is necessary for the assumption of individual events. An “effective decoherence” means that the notion of an event, and thus the ontological picture outlined here, is to be understood as an idealization...
that transfers large quantitative differences into qualities. By contrast, a “fundamental decoherence” would permit a precise definition of the notion of an event.

3. Remarks on Relativistic Local Quantum Physics

In high-energy physics, one observes the creation and annihilation of particles, and we do not know any basic distinction between elementary particles and other stable objects (apart from a hierarchy of particular charge quantum numbers). If we want to talk about systems and subsystems as parts of nature, we can no longer connect this with a particular number of basic components. Instead, an organisation according to space-time regions suggests itself. In local quantum physics, which can be considered as an integrative framework for models of quantum field theory and their generalizations, an algebra is assigned to each space-time region. The union of two spacelike separated regions corresponds to the tensor product of the algebras of these subregions.

The connection to Hilbert spaces is not immediate. To begin with, the elements of the algebras are not operators in a Hilbert space. They can be represented as such, but there are infinitely many inequivalent representations and, thus, an infinite amount of possible states. For the selection of a particular representation, a global reference state (e.g. the global vacuum) is required. A space-time region can be interpreted as an (open) subsystem and a “partial state” can be assigned to it. But no Hilbert space is associated with this region, and the discussion of entanglement changes slightly as compared to Section 2.3. For a more detailed presentation of this framework see Haag (1996). Here we have to confine ourselves to a few remarks.

Superficially considered, the problem of the “division of the world” is answered by reference to a given space-time continuum that is unrestrictedly divisible. However, Bohr’s epistemological warning is particularly important here. We need macroscopic bodies (idealized as rigid objects) and light rays (idealized as straight lines) in order to establish a space-time reference frame and to describe the position of any physical object or event in it. The assumption of a space-time continuum as an ordering scheme independent of physical occurrences is a classical picture, a last classical anchor which we use in local quantum physics.

As a starting point for the interpretation, a Bohr-Heisenberg cut must then be introduced between macroscopic observational instruments and the rest of the universe. The space-time attributes refer to the former. When the cut is shifted, including the instruments in the “state of the world” and substituting the observational results by events, the situation is similar to that described in Section 2. In simple situations, i.e. if the
partial states differ only in a few space-time regions from those of the global vacuum, a separation of single events can be specified.

But we do not have a precise and general definition of the concept of events as long as we do not know of limitations of the superposition principle which are much stronger than the presently known superselection rules. This difficulty is tightly connected with the status of space-time in a future theory. If one wants to understand space-time propositions as relations between physical elements rather than as embeddings of these elements in a given continuum, the concept of an event appears to be essential. This also concerns the distinction of the direction of time in the world we live in. Is such an arrow of time anchored in natural laws, as it is assumed in an evolutionary picture, or is it a consequence of the global situation, traced back to accidental initial conditions in the cosmological model of an expanding universe? A satisfactory answer (within a completed theory) should endow the concept of an event with precise meaning.

References


