Chapter 4
Quantum Events and Irreversibility

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Abstract It is pointed out that the conceptual structure of Quantum Physics already implies irreversibility arising from the bipartition of temporal evolution into the "Quantum State" on the one hand and real events (e.g. observation results) on the other, connected by probability assignments with intrinsic indeterminacy.

Keywords Quantum events · Time direction · Irreversibility

The topic of this conference "Direction of Time, Irreversibility" is a subject which has accompanied me for decades. I considered it again and again, sometimes changing my opinion or at least the emphasis. I had lengthy discussions with quite a number of colleagues and found this often very tedious because in these questions one is likely to meet strong convictions and even firmly entrenched prejudices. So I hold no great expectations that I can present on five pages anything that could change the previously held opinion of anyone. But I shall try to isolate essential issues, to state and partly justify the possible answers I want to suggest.

The major opinion among physicists is that

(1) within physics the appearance of irreversibility is appropriately described by the second law of thermodynamics;
(2) this law is derivable from statistical mechanics;
(3) in this derivation it is immaterial whether we use classical theory or quantum theory.

The main point I want to make here concerns item (3). It is the assertion that Quantum Theory, as we know and use it, contains a basic element of irreversibility whose relation to the second law of thermodynamics is not usually considered. But let me first, very briefly, elaborate on item (2) above.

Statistical Mechanics gives a coarse grained description which endows a macroscopic state with a thermodynamical probability, the number of microscopic states

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which have the same coarse grained appearance. This coarse graining by itself will not produce an asymmetry of the time direction. Starting from a microscopic theory which is invariant under time reflection it is logically impossible to arrive at irreversibility on the macroscopic level without further assumptions. These are well known but often glossed over.

For example, in Boltzmann's collision equation for a dilute gas, starting from classical mechanics of a large number of molecules, it is assumed that before each collision there is no correlation between the molecules engaged in it. After a collision the pair of molecules concerned are correlated. But this correlation is wiped out by subsequent collisions with different molecules and its cumulative effect will not become relevant in time intervals of interest.

More generally we may start from a macroscopic state of relatively low thermodynamic probability (entropy) and ask for its subsequent development. We can expect that it will move towards a state of higher probability. This is fine. But we should not ask then how the macrostate looked in the past. Otherwise we might conclude that also then it was a state with higher probability. In particular, if we consider a process of approach to equilibrium and start arguing from a time somewhere in the middle of this process, having only this information and using it to ask what the situation was at an earlier time then we should conclude that the entropy has been higher then. If instead we use Boltzmann's equation to calculate backward we find that the entropy decreases in the past. Miraculously this agrees with the actual history up to some specific early time t_0 but from then on it deviates from it and ultimately, in the remote past, it leads to a singularity. This special time t_0 can in laboratory experiments be attributed to the willful action of the experimenter, starting his investigation. On the cosmic scale the experimenter might be replaced by God creating the big bang.

Another type of situation is an open system such as the earth. We may distinguish the outgoing radiation (characterized by Sommerfeld's boundary condition) from the incoming radiation, originating from outside sources. The outgoing radiation escapes and the asymmetry between incoming and outgoing radiation leads to some rough flux equilibrium with entropy production and irreversibility on the small scale.

Moving now to Quantum Physics we should first clarify a few general questions concerning the scope and method of physics. This is because the advent of Quantum Mechanics has injected some doubts about what we mean by "reality" and by the conventional picture of an "outside world" as distinguished from the impressions in our consciousness. That this insecurity is serious is exemplified by a title like "Reality or Illusion?" chosen for the description of some recent experiments. I have to be very brief about this question but what I find helpful is a remark by Wolfgang Paul (not Pauli!) who distinguished the "real part of physics" from the "imaginary axis". The former consists of phenomena, but not arbitrary phenomena. To be acceptable for physics there has to be agreement between many people about its occurrence and description. So it is not dependent on the consciousness of any individual person. And it must be reproducible which means that we must be able to classify the phenomena considered and their circumstances of their appearance into equivalence classes. I shall call a phenomenon subject to these conditions an "event" in order to indicate that it may be abstracted from human cognition. All empirical material of Quantum Physics consists of such events. The prototype is the response of some detector. The imaginary axis of physics is the theory. Its concepts are mental constructs whose "reality value" is debatable.

In the formal structure of the theory there appear two basic concepts: Quantum States and Observation Results. The latter correspond to events (if you wish "individual elements of reality"). A quantum state, on the other hand, describes probabilities for the occurrence of various possible events. Whatever mental picture we associate with the term "probability", in the physical applications we have in mind it always amounts to the counting of a relatively frequency within an ensemble combining many individual cases. Thus it depends on the definition of equivalence classes of circumstances and of type of events. Events are individual facts, the quantum state relates to possibilities.

Now we must recognize that an "observation result" is a very special kind of event in two respects. In the standard formulation of the theory the picture is that an experimenter "puts a question to nature" with the help of a "measuring instrument" which determines a disjoint set of possible answers. The concept of event should, however, not depend on whether some artfully constructed instrument is installed in some place but refers to anything which can—with a high confidence level—be regarded as the appearance of a fact. Our knowledge about it may be inferred indirectly from traces in a rock or the theory of stellar evolution. The point is that in such cases the menu of alternative possibilities is not decided by an experimenter but must be inherent already in the quantum state and that we cannot use the Bohr–Heisenberg cut between an experimental arrangement and a "physical system" we want to study. Related to this is the point that an observation result such as the click of a detector is a very coarse event; otherwise it could not be a common experience of many spectators. Under what circumstances can we speak of finer events, considered as individual facts? How does the "total quantum state" determine the menu of alternative possible events if "the observer" does not focus on a particular question? Since this concerns indirect information the answer needs some extrapolation along the imaginary axis.

As a prototype of an individual finer event let us consider the interaction of a single electron with a single atom. If we can isolate this process (whatever that means precisely) we expect that after the process we shall encounter one of several alternative situations: an ion plus two electrons or an atom plus one electron and (perhaps) some photons with characteristic energies. Standard collision theory tells us that in an experiment where we determine the final reaction products by an array of detectors we shall find one of these alternatives realized in each individual case. The formal structure of the theory suggests, however, that if, instead of installing detectors, we consider other kinds of later measurements we might find interference effects between the mentioned alternatives, telling us that no decision between these alternatives has occurred. This argument is misleading. It results from an overidealization of the term "observable". In a self-consistent treatment we should not speak of an abstract observable represented by some operator in a Hilbert space but have to specify the observation procedure. This includes the positioning of hardware in space-time which may possible interact at some later time with the reaction products and this specification is part of the relevant total state. For an interference effect the obtainable contrast is essential. Given a state and a putative division of the subsequent development into alternative individual histories there is a quantitative measure for the contrast in an interference between the assumed alternatives. It is the deviation from Griffiths' "consistency condition for the histories". The qualitative demand that the process be adequately isolated means precisely that this deviation is negligible under the prevailing circumstances. There are two conclusions to be drawn. First, that there is a holistic feature in Quantum Physics. In other words, the division of "reality" into separate elements called events depends on circumstances which may involve a possibly rather wide environment. Secondly, an appropriate division is determined by the state. It leads to the enumeration of alternative histories, each composed of a sequel of events. In the example considered (given adequate isolation) the ionization or excitation with photon emission can be regarded as alternatively possible real events which cannot be revoked by a "subsequent measurement". They have become facts and a fact is irreversible. Past facts are subsumed in the "state". According to existing experience and theory they only determine possibilities for the subsequent development. The universe does not appear to be a clock work. This brings an asymmetry between past and future. "Reality" consists of past facts. The future is open. Thus we come to an evolutionary picture of reality, similar to that described by A.N. Whitehead many years ago.

I have to close now though there are many issues not addressed. Let me just briefly mention some. There are the attempts to eliminate probabilities and return to a deterministic theory with hidden variables. Personally I regard this as a wrong track. Existing proposals like Bohm's particle trajectories are no adequate tool for the description of particle transmutations (or even photon emission). Concerning the "many worlds picture" of Everett we must bear in mind that the branching of alternative histories reaches the macroscopic level (for instance by the click of one specific detector among many) and thus only one particular history becomes the common experience we call reality. Each emerging fact annihilates the other possibilities and changes the state.

Finally there is the question of localization of events. If we do not assume space-time to be an a priori given 4-dimensional continuum then events (rather than objects) play the essential role in the development of a theory of space-time. Some information concerning the sharpness of localization in space-time of simple events can be obtained from existing theory.