Pramāṇa, Vol. 3, No. 1, 1974, pp 1–9. © Printed in India.

Irreversibility and quantum measurement—The observer's role

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MS received 18 April 1974; after revision 23 May 1974

Abstract. The role of the observer in physical theories in the sense of the observer's viewpoint determining prominent features of the observed phenomena is discussed with reference to the problem of irreversibility and quantum measurement, the latter being closely related to the problem of classical behaviour of quantum systems. A completely subjective interpretation of irreversibility is proposed. It is claimed that irreversibility belongs only to phenomena as observed by a restricted observer who must project all phenomena on a restricted subset of the set of all possible states. The possibility of a completely unrestricted observer who does not see irreversibility is discussed.

Keywords. Irreversibility; entropy; quantum measurement; observer.

1. Introduction

The belief in the existence of an objective external world existing independently of any observer, following fixed laws which either have been or can be discovered, forms the basic motivating force behind all physical sciences. The fact that an observer exists who can look at the phenomena, think about them and interpret them is regarded more or less as a matter of accident and is not relevant to the main body of physical science. The evolution of a human observer in this general scheme is a highly special event that requires very specific physical conditions which have been obtained more or less by chance on our planet, failing which presumably there would be no observer to look and marvel at the whole display. The concern against such a world view has been elegantly expressed by Schrödinger in a fascinating little book called *Mind and Matter* (Schrödinger 1958).

Apart from being aesthetically unpleasing, the main objection against such a view of the objective world and the status of the observer is the underlying assumption in this view that the observer is able to observe the phenomenon in all its detail without disturbing or modifying the phenomenon in an *unaccountable* way. In the light of modern developments in physics, particularly quantum mechanics, the justification for such an assumption is rather weak. If this assumption is not made, *i.e.*, if one allows for an indeterminate influence of observation on the observed phenomenon, the concept of an objective world existing independently of observation becomes questionable, because such a world can never be accessible to observation. What is it that 'really exists' then becomes a matter of conjecture, in principle unverifiable.

One obvious reason why an observer must have an influence on the phenomenon as it is observed is a finite characteristic time-scale associated with the observer's sensory apparatus. Any phenomenon taking place over time scales short compared to the characteristic time scale of the observer's perception must be perceived in the form of an average over such time scales resulting in an inevitable loss of detail, possibly in an indeterminate manner. This could result in the appearance of new features in the observed phenomenon, not present in the actual phenomenon.

In section 2 we discuss the problem of irreversibility in classical and in quantum mechanics. In section 3 the problem of classical behaviour and the related problem of measurement in quantum mechanics is discussed. It is intended to show that a complete solution of these problems inevitably involves the role of the observer in the above mentioned sense. The special status of the electromagnetic field as a link between phenomena involving massive particles and their observation is briefly discussed. Finally in section 4 we raise some plausible conjectures regarding the solution to the philosophical dilemma mentioned in the beginning. The purpose of this paper is by no means to provide final answers but to stimulate thought and discussion along the lines suggested in the paper.

2. The problem of irreversibility

The problem we are concerned with is the following: We see irreversible phenomena all around us—by which is meant phenomena that are never seen taking place in the reverse order. If we take a motion picture of any sufficiently complex phenomenon, for example a dish falling from a person's hands and breaking into pieces or a piece of wood catching fire and burning to ashes and run it backwards, the phenomenon seen in the reverse movie is never observed in nature. It is our experience with such phenomena which include life processes like ageing and death that gives us our notion of a unidirectional time flowing from past to future. We express this unidirectionality of large scale phenomena in the second law of thermodynamics by saying that a physical quantity called entropy always increases in large-scale phenomena. The problem arises when we assume that phenomena on the macroscopic level where we find irreversible behaviour can be derived in terms of more elementary phenomena involving elementary particles or atoms and their interactions. It is recognized that each of these elementary phenomena* is perfectly reversible. In other words if we take a motion picture of any of these elementary phenomena, for example of a collision between two atoms, and run it backwards, the phenomenon seen in the reverse movie is also seen in nature equally often. The problem then is, how do we explain irreversible phenomena on a large scale, that are supposed to be derivable from a large number of perfectly reversible elementary phenomena? More exactly, how can we derive the increase in entropy of a system with time by applying microscopic laws of time evolution to the state of a system given at some initial instant of time t_0, when these laws do not show any preference for a given direction of time. This is an old problem in statistical mechanics and has been a subject of much discussion since the days of Boltzmann whose famous '*H*-theorem' proved that for a gas not in thermal equilibrium, a function H exists that increases with every collision among the

* Except perhaps weak interactions; we assume, however, that weak interactions are not relevant for irreversible behaviour of objects of our familiar experience like burning of wood.

atoms of the gas. It is well recognized, however, that Boltzmann's derivation of the H-theorem cannot be considered as a derivation of irreversibility from dynamics alone, since there is always a statistical assumption involved at some stage of the derivation involving averaging over macroscopic time scales and distances which has the character of ' destroying correlations ' between individual molecular motions (Rosenfeld 1972).

Let us consider the familiar example of a perfect gas initially confined to one half of the volume of a container by a removable partition, the other half being vacuum. Let us assume that the container is completely isolated from the environment. At some instant t_0 the partition is removed and the gas expands, eventually filling the entire volume. This is a typical example of an irreversible process and we immediately say the entropy of the gas increases in the process. In fact the concept of entropy would be of little use if it did not increase in this process. The question we wish to discuss is, whether this increase in entropy with time can be derived without any explicit or implicit reference to the abilities of the observer who observes it as an irreversible phenomenon. In statistical mechanics, the entropy of a system is defined as

$$S = -k \sum_i P_i \ln P_i \tag{1}$$

where P_i is the probability that the system is in its i-th microstate. These probabilities are determined by the macroscopic information available about the system. For example, when it is known that the gas is contained in one half of the container, $P_i = 0$ for all states in which there is gas in the other half. At thermal equilibrium, one makes the additional assumption that all microstates that are consistent with available macroscopic information about the system are equally probable, so that in our example of the gas contained in one half of the container, the entropy for $t < t_0$ is given by

$$S = k \ln W \tag{2}$$

where W is the number of microstates the system can be in, given the volume, temperature and quantity of the gas. It should be noted that a subjective element is already present in this definition of the entropy since it refers to available information about the system which is limited by the fact that an observer is able to make only macroscopic measurements on the system so that we can treat only macroscopic parameters like temperature, pressure, volume, magnetization, etc., as given information. If the states of the gas are described in terms of classical mechanics, W is replaced by a patch of volume Ω in a $6N$ dimensional phase space (configuration space) where N is the number of molecules.

Now, according to Liouville's theorem in classical mechanics, for a completely isolated system or in fact for any system whose Hamiltonian structure is preserved in time the total volume of the patch in phase space remains constant as the system evolves with time according to Hamiltonian dynamics. The shape of the volume, however, changes with time and becomes more and more complicated as time goes on. Liouville's theorem has an exact analogue in quantum mechanics. The entropy S defined by eq. (1) or eq. (2) can, therefore, not increase with time as a result of pure dynamical evolution, whether classical or quantum mechanical. There is nothing mysterious in this. The system is in one out of W states at the beginning and we know what happens to each of the W states at all later times. Hence the system must always remain in one out of W known states. In other words, our ignorance about the system cannot increase if we knew the exact time evolution of each of the states the system could be in. Something in addition to Hamiltonian dynamics must be introduced if S is to increase. In order to do this, we have to realize that our assumption that the exact time evolution of each of the microstates can be followed is not consistent with the way in which S was defined in the beginning. S was defined as a measure of our ignorance about the system determined by the fact that we are able to make only macroscopic measurements on the system. In talking about the time evolution of entropy, we should be consistent with this definition at each stage of the time evolution. Our macroscopic measurements are not able to keep track of individual molecular motions. Stated another way, when the patch of volume Ω in phase space becomes too ' filamentary ', our measurements cannot keep track of the exact shape of the volume. At this point, it is wrong to consider Ω or W as a measure of entropy of the system. Instead, one must divide the phase space into macroscopically distinguishable cells whose size is determined by the nature of the experiment and smear whatever part of the original volume Ω falls inside a given cell uniformly over the whole cell. The entropy should then be written as

$$\bar{S} = \sum_n W_n P_n \ln P_n \tag{3}$$

where n labels the macroscopically distinguishable cell in phase space, W_n is the total number of states in the n-th cell and P_n is the *a priori* probability of any microstate belonging to the n-th cell, all of them assumed to be equal. If a fraction f_n of the original phase volume or the original number of states W falls within the n-th cell at the instant considered, then

$$P_n = \frac{f_n}{W_n} \tag{4}$$

This coarse-grained entropy will increase with time and will assume a maximum value when all P_n become equal, *i.e.*, when the original volume becomes so thready that it looks as if it is uniformly smeared over the whole of the newly available phase space. The entropy increase is, therefore, a result of coarse-graining* and coarse-graining is necessary because of the observer's inability to make other than macroscopic measurements, *i.e.*, because of the observer's inability to keep track of detailed molecular motions. Putting it in a different language, entropy increase results when we ' project ' the phenomenon taking place in an exact microstate on to a set of macroscopically distinguishable states and find that in a given microstate, some macroscopic states like those of uniform density are much more probable than others corresponding to non-uniform density. A microscopic observer capable of following all molecular motions would not have to perform this coarse-grain averaging and for such an observer, there is no entropy increase. Does it mean gases don't expand for such an observer? The answer is, such an observer does not have the same attitude towards phenomena. We see the phenomenon as expansion of gas because of our macroscopic viewpoint, *i.e.*, because of our inability to follow detailed molecular motions. A microscopic observer does not adopt this viewpoint. For him, all microstates have the same significance. He does not treat the microstates corresponding to all the gas collected in one half

* The idea of a coarse-grained entropy was first introduced by Ehrenfest.

of the vessel as ' qualitatively different ' states from those corresponding to uniform density all over the vessel. He does not see the spreading of gas as an irreversible phenomenon. For him, the gas goes through a succession of equally significant microstates. There need be no contradiction in the entropy increasing for a macroscopic observer and not increasing for a microscopic observer if we realize that entropy is not a property of the physical system, but a property of the perspective we have towards the system. Isn't the microscopic observer then able to violate the second law of thermodynamics ? The answer is, if we argue consistently from the point of view of the microscopic observer, there is no second law of thermodynamics for him. So the question of violation does not arise†. This statement is, however, made with some reservation. The above discussion assumed that the atoms of the gas move classically and that a microscopic observer is able to determine the positions and velocities of all the atoms with arbitrary accuracy. It is only under these assumptions that there is no entropy increase for a microscopic observer who is able to follow all atomic motions.

If we take into account the fact that the true time evolution of atoms cannot be looked upon as a classical motion in a 3-dimensional space and that the position and velocity of an atom cannot be measured simultaneously to an arbitrary accuracy, then a microscopic observer who wishes to follow the ' motion of an atom through space ' will find a continuous entropy increase even for a single atom. This entropy increase follows from the Schrödinger equation and is a result of the fact that the observer is limited to following the time evolution of an atom as motion in a 3-d space, which is not the true time evolution of the system. We can easily see why this should be so. The observer measures the position and momentum of the atom to an accuracy allowed by the uncertainty principle and prepares the atom in a wave-packet state with the spread $\triangle p$ and $\triangle q$ in momentum and position satisfying $\triangle p \cdot \triangle q \sim h^3$. An observer following the motion of the atom in classical space-time will represent the state of the electron by a patch of volume $\triangle p \cdot \triangle q$ on a 6-dimensional phase space. It can be shown that when such a state of the atom evolves with time according to the Schrödinger equation, this product in general increases. This is the well-known phenomenon of spreading of wave-packets. See for example discussion in (Merzbacher 1961). The patch of volume $\triangle p \cdot \triangle q$ on the classical 6-dimensional phase space of the particle, which is a measure of the entropy as measured by such an observer, therefore, increases with time‡. Once again this entropy increase is a result of the fact that the observer is unable to follow the true time evolution of the system because of his being limited to a classical space-time description. We now need a super-observer who is not so limited and who is sensitive to the actual quantum evolution of the system. It is implied in this statement that the limitations of the uncertainty principle, namely the impossibility of exact specification of the state of a system, are not absolute but can be transcended. It is not implied, however, that these limitations can be transcended by introducing hidden variables in a classical 3-d

† Brillouin's 'exercising of Maxwell's Demon' (Brillouin 1951, 1960) is not applicable here, as Brillouin's argument involves assumption of a randomness in the measuring device even for the demon. This is not true of the microscopic observer under discussion.

‡ In some very special states, the uncertainty product may decrease for some time but the final result is always an increase.

space. What is probably required is transcending the concept of objects moving in a three-dimensional space. Such a superobserver will not see irreversible behaviour, provided these concepts are final. The author strongly suspects that this ideal observer has to transcend *all* concepts, before he can see complete lack of irreversibility.

3. The problem of classical behaviour

In quantum mechanics the problem of the observer determining prominent features of the observed phenomena because of his limited viewpoint becomes much more transparent when we consider the problem of ' deriving ' classical behaviour of macroscopic objects of everyday experience from the laws of quantum mechanics. It is a commonplace belief that the laws of quantum mechanics go over to those of classical mechanics in the limit of large quantum numbers. The truth, however is that the laws of quantum mechanics only 'allow' for classical behaviour in this limit and do not by themselves determine classical behaviour. Something in addition to quantum laws is necessary to ' explain ' classical behaviour of macroscopic objects. The problem of measurement in quantum mechanics is closely related to this fact.

Let us be a bit more precise about what we mean by classical behaviour. The minimum requirements for classical behaviour are, objects having well-defined positions in a three-dimensional space at every instant and fields having a well defined value at every point in this three-dimensional space at each instant. The complications due to special relativity are not important for our discussion so that we can restrict ourselves to one given frame of reference. By well-defined positions and values of the fields, we mean those quantities within the limit of experimental accuracy. We know that these properties are very well satisfied by all phenomena on our scale of perception and any phenomenon that does not satisfy these requirements is never perceived by us directly. It must be perceived by means of an, apparatus that does behave according to these requirements. We know that quantum systems like atoms and electrons do not satisfy these requirements in their behaviour. They behave neither like objects having well-defined positions at each instant, nor like fields having a well-defined value at each point of space, at each instant. An electron in a momentum eigenstate for example cannot be described as an object having a well-defined position. We therefore need a macroscopic apparatus in order to observe an electron.

The problem, however, is that macroscopic objects and measuring apparatuses are made up of atoms and electrons and are presumably supposed to obey the laws of quantum mechanics. If this is so, there must also exist states of these objects that do not satisfy the above requirements for classical behaviour. We shall call them ' non-classical ' states. An example of a non-classical state of a table would be a state in which it is in a superposition of two states, in one of which the table is in one corner of the room and in the other in another corner. A state of the pointer of a measuring instrument which is a superposition of states in which the pointer points to two different regions of the dial is another example of a non-classical state. These states are allowed by all principles of quantum mechanics, yet the exclusion of such states is necessary in order to have classical behaviour and in order to have measuring instruments in the usual sense of the term.

How is this exclusion of a large infinity of allowed states of macroscopic objects from the class of observable states to be explained ? One point of view holds that macroscopic objects should never be treated as isolated objects. This is due to the fact that their energy levels are so closely spaced that the smallest interaction with the environment can give rise to off-diagonal matrix elements between their stationary states. The interaction with the environment is then said to be responsible for these objects being always found in classical states which are in fact non-stationary states. This, however, does not solve the problem. The reason is that the environment has to be in a classical state in order that interaction of an object with the environment can result in a classical state of the object. For example a ferromagnet with a large total spin $S = N$ can be in any arbitrary superposition of $(2N + 1)$ degenerate states corresponding to $S_z = N, N - 1, \cdots - N$. But for a sufficiently large N, any small magnetic field H in the z-direction can select the classical state $S_z = N$. A real magnet is always found in such a state corresponding to some direction z and never in an arbitrary superposition of these states. It is important, however, that the magnetic field should be in a classical state before it can ' pin-down ' the magnet. One could argue that the field is produced by a classical current source but then we must explain the classical states of the current source. One could continue in this way and include the entire universe, but the problem still remains. Eventually we have to explain the classical states of the entire observed universe. The final solution can only lie in the observer who observes the universe selecting the classical states out of all possible states.

There is no escape from the conclusion that when an observation is made on a macroscopic system which is not in a classical state, the observer must force the system into one of the classical states. The exact state into which the system is forced is indeterminate, the probabilities for various states alone being determined by the original state. This is commonly known as the ' collapse of the wave-function ' or ' wave-reduction '. Such non-classical states of macroscopic instruments must be produced in any measurement interaction between a measuring instrument and a quantum system which is not in an eigenstate of the observable the instrument is designed to measure (d'Espagnat 1971). The wave collapse must therefore be associated with every observation on a general state of a quantum system.

It is worth emphasizing at this point the important role played by the electromagnetic field in bringing about the wave-reduction (Chew 1971). The final instrument on which the observer makes the observation is always the electromagnetic field. At the end of the chain of physical processes leading to the complete observation is the entry of an electromagnetic signal into the observer's brain. This signal would also in general be a non-classical state of the electromagnetic field. Before the measurement is complete, however, the signal must be interpreted. The phenomenon of wave reduction could well be associated with this stage of interpretation where the observer's concepts limit the possible interpretations. The limitations of the observer's mind, namely the necessity of interpreting every signal in terms of a fixed set of concepts, then appears to be the cause of the wave-reduction and of the inability to make other than classical measurements.

The phenomenon of wave reduction associated with observation on quantum systems also introduces irreversibility in their observed behaviour. This is due to the fact that there is a contingent or indeterminate element involved in the process.

The exact state to which the system collapses is determined by chance; hence the process cannot be reversed. Another way of looking at it is the following: Let a quantum system be prepared in a state given by

$$\psi = C_1\psi_1 + C_2\psi_2 \quad (5)$$

where ψ_1 and ψ_2 are eigenstates of an observable O. Let the system be made to interact with an apparatus designed to measure O. After the measurement interaction, but before the apparatus is read, the system can, for all practical purposes, be described by a density matrix which is diagonal in the basis of ψ_1 and ψ_2 and has $| C_1 |^2$ and $| C_2 |^2$ as the diagonal elements. This density matrix would give the same results for all measurements made on the *system alone* as the true wave-function of the (system + apparatus) would give. It can be easily shown that the entropy of the system as determined by the diagonal density matrix is larger than the entropy of the system given by the pure state which is zero (Zeh 1971). This increase is a result of loss of information on the relative phase of C_1 and C_2 which cannot be determined after the measurement interaction as long as we are restricted to making macroscopic measurements on the apparatus.

The important point we wish to emphasize is that the wave-reduction and the consequent irreversibility associated with observation are results of the fact that the observer is restricted to observing a small subset of all the possible states in the Hilbert space, so that he must project all phenomena on this subset of states. Consequently, the observer must miss some detail in the phenomena. Our claim is that irreversibility belongs only to such a class of restricted observers, in other words, to the projected phenomena and not to the actual phenomena which are accessible to observation only by a completely unrestricted observer. It should be pointed out that the Hilbert space consisting of states with a definite number of particles is itself a restricted one and our ideal observer must transcend this restriction also.

4. Discussion

The general picture that emerges from the discussion in the preceding sections can be summarized as follows:

(*a*) Physical science deals with the universe as observed by an observer.

(*b*) A finite observer who is limited to observing only a restricted class of states of the universe because of the fact that he is able to ask only a restricted class of questions about the universe determined by his concepts, language, etc., is never able to 'see' the universe as it is. He must inevitably introduce features in the observed universe that are not present in the unobserved universe.

(*c*) An important feature that is introduced by the observer in the observed universe is irreversibility, which is absent in the unobserved universe; the latter is accessible only to a completely unrestricted observer.

There are several questions that are raised by this general picture. The most important one is, *why* are we restricted observers? It is the opinion of the author that this question cannot be answered by a restricted observer. The next question is whether there is any hope that we can be anything but a class of restricted observers? On this question, the author's stand is that since there is nothing in principle that excludes this possibility, it must exist. In fact if we take into account the fact of evolution, it seems even plausible. Let us observe the simple and well-known fact that the existence and evolution of the observer, biological as well as intellectual, is a consequence of the fact that the universe is not in thermal equilibrium, but is ' running down '. If we then make the somewhat far-fetched extrapolation that all entropy increase in the observed universe contributes to the evolution of the observer, we can have a very interesting self-consistent picture. We could say the purpose of ' phenomena '* that an observer sees in any given projection is to enable him to evolve into a more and more refined observer until he is able to see everything as it is, at which point he does not see any phenomena at all! It is as if the purpose of the whole display is to make one realize that it is not there.

It might be possible to cast the idea in a quantitative form. For example, it would be very interesting if it could be shown that the rate of entropy increase in the observed universe decreases as one describes it in more and more enlarged projections.

Acknowledgements

The author is grateful to Rajaram Nityananda for several illuminating discussions on the subject.

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* The word ' phenomena ' is used here in place of irreversibility because the author feels that only irreversible processes constitute what we intuitively regard as phenomena.