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ARTICLE

A Quantum Mechanics without Subjective Element – An interpretation from an experimental point of view

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ABSTRACT: It is not easy for practicing physicists to keep track of the ongoing philosophical debate concerning the “reality” of the entities they manipulate or the “objective validity” of the results of their work. In addition, the role of the observer and the theory of the measuring process seem to be themselves controversial. Therefore it may be appropriate to present an interpretation of quantum mechanics which corresponds to the perspective of most practicing physicists, although the author makes no claim to possessing any particular knowledge of the literature in this domain. The final four sections present some more specific descriptions of the concepts used, so that they may also serve for more philosophical discussions.

KEYWORDS: Interpretation of Quantum Mechanics, Practice of Physics

1 Introduction

We take the term "Quantum mechanics" here to mean the totality of all the concepts and laws that describe the behaviour of the smallest parts of matter – molecules, atoms, electrons, nuclei, photons etc. These we refer to as its "reference objects". It exists in a mathematical form, is entirely consistent and agrees with all the experiments ever done to test it. We are thus confronted in what follows by the twin tasks of expressing this mathematical form in terms of our everyday language and of visualizing its physical content in the light of our prior experience in observing the behaviour of material bodies. This prior experience is that of classical physics.

The difficulty of this task is evident in the fact that the smallest parts of matter behave in strange ways that go beyond our experience with ordinary material bodies in classical physics. This novel behaviour is nevertheless precisely described in the equations of quantum mechanics. Once we are able to translate the mathematical symbols into every day language we may indeed claim to have "interpreted quantum mechanics", but as long as the language is not itself adapted for describing the novel behaviour, our familiar notions and images will turn out to contain inconsistencies and contradictions.

When Planck and Einstein established the corpuscular properties of light waves, light acquired a twofold nature, appearing both as a wave and as a particle. Soon afterwards De Broglie realized that electrons too have this dual nature. Matter had become particle and wave at the same time. The wave length λ was given by the momentum p as $\lambda = h/p$ (h = Planck's constant). Whereas in classical mechanics position x and momentum p were independent variables that together completely determined the state of motion of a pointlike mass, now there was a link between them because the wave length carries a space property. A length is a difference in position after all. The concepts of position and momentum would from now on be in conflict with each other on a scale given by Planck's constant. This conflict was fundamental, and it had become impossible to assign exact values to both position and momentum (i.e. wavelength) simultaneously.

Heisenberg responded to this conflict by assigning "operators", as they were later called, to these observables instead of numbers, and these became essential elements in the mathematical formalism of quantum mechanics. Not only did they make it possible to take the interdependence of position and momentum into account, they also led to statements about probability distributions of positions and momenta instead of exact values for them. Whereas in classical physics exact ("sharp") values were assigned to the properties of objects, in quantum mechanics they were replaced by probability distributions, here called "unsharp values"; it is they that are assigned to the incommensurate observables of the reference objects of quantum mechanics.

The dual nature of light and matter means that they have the potential to be wave or particle depending on the circumstances. In the case of light this means that we will observe photons (light quanta) in certain experiments like the photoelectric and Compton effects, but waves in others, such as interference experiments. In the limit the photon is pointlike, but the wave fills the entire space – the contradiction could not be more pronounced. Two particular aspects result from this situation:

(a) If we describe the phenomenon as a wave we must refrain from trying to understand it as pointlike; if we describe the behaviour of the pointlike photon we must refrain from trying to understand it as a wave. There is an unavoidable renunciation implicit in this, as if having looked at one side of a coin , we must not look at the other. Bohr has described this situation with his complementarity principle, which he saw as general principle which does justice in our every day language to the contradictions we encounter in atomic phenomena.

(b) It seems as if the observer can choose whether the object he is contemplating is a wave or a particle. A subjective element thus appears in the understanding of atomic phenomena, *implying that an objective description of nature is itself at stake.*

What exactly do we have to renounce in order to be able to express the atomic phenomena and their mathematical quantum mechanics in ordinary language, that is in terms of a language that was formed by previous experience including classical physics? In this essay we will investigate where this line must be drawn, in particular, whether we must indeed give up objectivity in describing atomic phenomena. In what follows we will develop the view that an objective description, i.e. one which is binding upon all observers, is very well possible. Accepting the concept of probability as being part of our every day language, as something rooted in our experience, it will turn out that we need not in fact renounce objectivity, provided that we refrain from trying to understand atomic phenomena as being governed by causality in space and time. Objectivity, we will point out, is to be based upon repeated rather than single measurements of observable attributes.

2 Classical objects, attributes and their quantification with numbers

The attributes of the objects of classical physics are usually given numerical values that have dimensions attached to them. Examples are the mass of a body, its position und its velocity at a given time, its magnitude of angular momentum, and the direction of angular momentum, or the body's volume. Other phenomena of classical physics have quantifiable attributes as well: the electric current in a conductor, the magnetic field in a space or a swarm of birds in the sky. We shall refer to such carriers of quantifiable attributes as the objects of classical physics.

This classical characterization of attributes using numbers is the starting point of modern science and its description of nature. There are laws of physics according to which such quantities change with time, either under the influence of forces or as a continuation of a motion begun earlier. An empirical determination of the numerical value of such quantities is a measurement, and in classical physics we take it for granted that this measurement is objective (i.e. the same for all observers, without room for contention). The measurement may be repeated and will always yield the same result, even for different observers.

There are obviously phenomena that change so fast that a second measurement is difficult or impossible to perform. We can nevertheless imagine an idealized measurement which can be repeated before the disturbing influence has changed the phenomenon. The concept of ideal measuring instruments is part of the idealization implied in every law of physics. We understand the law of falling bodies in such a way that we may neglect the disturbing influences when performing a measurement intended to empirically test the law. The air must as far as possible be removed from the tube that protects the falling body, and the effect of any that remains must be shown to be negligible (perhaps by a series of measurements approaching the vacuum state stepwise, without ever reaching it). Also such light beams as we may use to signal instants at which the body intercepts them must not disturb the free fall. The remaining disturbances that cannot be taken in to account are united in the experimental margin of error, or “measurement error”.

In classical physics the attributes of its reference objects are objectively measurable in an idealized sense. Even if some observable was not at a given time exactly measurable in the historical development of the art of measurement, we may suppose that we can take it for granted that in *principle* it could have been measured and empirically verified. Classical physics unites the quantified attributes of its reference objects with their memorability in principle, and it is for the sake of this unity that we imagine idealized measurements where, by abstraction, we neglect measurement errors.

The objects of classical physics always carry several attributes at the same time. For example, the size of a building is characterized by several dimensions, the properties of a cannonball in flight comprise the position and the velocity at a given moment, and perhaps the angular momentum vector of the ball. These values can be measured independently of one another: A length measured at the front of the building does not change when another length is measured at the back. The velocity of the cannonball remains the same when its position is being measured, because this measurement can be made so accurately that its impact on the velocity of the cannonball may be neglected. The act of measurement of such attributes does not influence them, they can all be determined simultaneously.

In other words, a classical object possesses all of its quantified attributes at once. We can then say that each such attribute is quantified by a “sharp number”.

3 Quantum mechanical attributes

All this changes when we turn our attention to the small objects dealt with in quantum mechanics (the reference objects of quantum mechanics). Determining the position of an atom or an electron always involves the collision with a photon (or some other particle) of unknown direction so that the velocity of the atom or electron is changed in an unpredictable way (Heisenberg, 1930). So once a value of the coordinate has been determined, any previous determination of the velocity is destroyed, and vice versa, any velocity measurement destroys the result of a previous coordinate determination. This means that among the attributes of a quantum object there are some that are incommensurable, that so to speak “do not fit together”, in the sense that one cannot determine simultaneously valid values for both of them. Such attributes are related to each other by Heisenberg’s uncertainty relations.

The picture of unavoidable perturbations in measurements made on small objects is a good illustration for the uncertainty relations. Their basic justification, however, is in the theory of quantum mechanics, the mathematical apparatus of which tells us that those properties which do not fit together are just the ones whose operators do not commute in their Hilbert space. It should be remarked that even though some such properties of (say) an electron do not fit together pairwise, some others *can* be determined simultaneously. So while neither the position along a direction and the momentum (therefore the velocity) along the same direction, nor the angular momentum components along two different directions, fit together in this sense, the values for position and velocity along *different* directions, as well as the total spin, mass and electric charge, can all be determined simultaneously. This implies that quantities without an incommensurable partner have a sharp value, whereas the others must be characterized by a range of values within which a given measurement may yield any random value. Within this range, however, not all values are realized with equal probability; they appear according to a probability distribution that is calculable in quantum mechanics for every given situation. The probability distribution over the range of an observable quantity then defines how frequently a particular value appears when that quantity is measured. We can then say that the quantities with incommensurable partners have “unsharp values”. In this way quantum mechanics, being a calculus of *possibilities*, is connected to the classical world of *facts*. This is done by producing a weighting of these possibilities in the form of probabilities with which the possible is converted into the factual in a measurement.

It is worth stressing that unsharp values associated with attributes of atomic objects are not of the same kind as the classical measurements with their measurement errors that we have above considered to be in principle negligible. (As long as they are not neglected they contain a subjective element because the measurement of a competing group of scientists will not yield the same result.) It is only in the abstraction of negligible measuring errors that a classical quantity carries a sharp value.

The unsharpness attached to attributes of atomic objects, the ability to be unsharp, appears as part of the very concept that describes the attribute in quantum mechanics: Once the momentum is represented by an operator in Hilbert space the position operator has a non-zero commutator associated with it. This produces automatically a Heisenberg uncertainty relation between the two quantities, i.e. a lower limit for the product of the widths of the two probability distributions. Assigning values to quantities with unsharp values is part of their mathematical representation in the theory. This does not mean that a particular property is always unsharp, it may have a small unsharpness or none at all, provided that its incommensurable partner has a large or even an infinite width of the probability distribution, the product of the widths being of necessity always larger than the Planck constant times a numerical factor.

It is clearly not possible to talk about the “properties of the electron” without considering its past history. An electron emanating from a pointlike source cannot have an exact value of velocity; coming out of a slit of a Stern-Gerlach experiment (in which one component of angular momentum has been measured), it cannot have an exact value of the other two components. The equations of quantum mechanics thus result in a precise description of the state of the electron as a function of its past history, which we refer to as its “preparation”. The quantum mechanical description of the measurable properties of the electron with a well defined preparation consists of a series of values of classical quantities, with attached probabilities for each value.

The requirement of a well defined preparation is not peculiar to the world of atomic phenomena, since classical objects also have different properties depending on the way they have been prepared: the cannonball in flight, for example, does not have the same properties as one at rest.

4 Frequency measurements using separated samples

The mathematical description of the properties of an electron with a given preparation can be experimentally verified. The sharp values can be directly measured, and the unsharp values (probability distributions) can be measured by determining the frequency of occurrence of all the values in the respective range. To do this, a sample of identically prepared electrons is required. While such frequency measurements can determine a probability distribution with only limited accuracy, this can always be improved by increasing the sample size. We thus conclude that the quantum mechanical description of the properties of an electron with a well defined past history can indeed be measured, provided a large number of identically prepared electrons is used.

The quantum mechanical situation is characteristically different from the classical one. *There* the object is immune against the measurement of its properties, *here* the individual electron becomes unusable once a measurement (of an incommensurable property) has been performed in order to count the frequency of occurrence of a particular value. The electron must subsequently be thrown away, and the next measurement takes place with a new electron from the sample. One may say that the entire sample, the "ensemble" has taken the place of the classical object.

Let us take the measurement of the spin orientation of the electron as an example of the quantum mechanical measurement of the properties of a prepared sample. On the mathematical side the pure state is given by a spinor consisting of two complex (4 real) numbers. Discarding the over-all phase and normalisation we are left with two real numbers that define the pure normalised state. Experimentally we set up a Stern Gerlach experiment in the x-direction, and with the first half of the sample we determine the relative frequency of electrons that come through the two slits. This is our first measured number. Now we turn the apparatus into the y-direction and use the second half of the sample to measure the second number. These two frequencies are our probabilities, within, of course, the limits of accuracy set by the size of the sample. From these probabilities we can then calculate the spinor that defines the state of the electron (the sample). Provided one takes the sample of identically prepared electrons as the object, there is a one-to-one correspondence between the quantum mechanical properties of the object and the classical quantities measured.

As another example we irradiate an atom with a light beam and observe the atom's fluorescence. If we represent it in Hilbert space by a development in energy eigenstates, the coefficients are complex valued numbers whose magnitudes are the occupation densities, and whose phases determine the phase differences between incoming light and outgoing fluorescence light. Heisenberg discusses in (Heisenberg, 1930) how the phases are destroyed when the occupation densities are measured, whereas a measurement of the phases does not allow any empirical statements about the occupation densities. So as with our previous example, a complete determination of the quantum mechanical parameters of this atom is possible using a sample of identically prepared atoms, the first half of which measures the magnitudes, and the second half the phases.

Dividing the samples into different parts as described above thus makes it possible to measure all quantities in sequence, thereby avoiding the conclusion that, for example, measuring the frequency distributions of the momenta makes it impossible to measure those of the positions What was calculated "behind the curtain" with the concepts and equations of quantum mechanics then has an equivalent counterpart in the sum of all possibilities of what can happen "this side of the curtain" (i.e. in the real world using classical concepts). The sum of all possibilities according to the calculated probability laws can then be measured. In the example of the third paragraph, the quantum mechanical wave function for spin 1/2 could be uniquely determined up to an overall phase using the frequency measurements described. The same is true for higher spins. For the moment it is, however, an open question whether for every possible situation a set of experiments can be specified to uniquely determine the quantum mechanical parameters.

5 Probability distributions

The probability distribution of a quantity, like position or momentum, is a real function over this quantity. It tells us how probable it is that a measurement comes out with just this numerical value, (or with a numerical value in a small interval around it). The integral (or the sum over all values in the range) must be equal to 1. For even if it cannot be predicted which numerical value will be selected in the next event, it is certain that it will be *some* value within the given range. We will call such a normalised probability distribution a "probability law" so that it is distinguished from less well defined probabilities like the one with which a falling star appears in the sky.

Multidimensional probability distributions can also be defined as real functions of several variables. If there are correlations between some of the variables, those that can be measured simultaneously do not vary independently of one another. An important principle of quantum mechanics states that pure chance governs the appearance of measured values, limited only by the probability law that is valid in the particular situation. Not only do we not *know* any other influence – there are in fact no others.

The probability distribution should not be confused with the quantum mechanical amplitude or wave function which is a complex valued function whose absolute square is proportional to probability. The somewhat misleading term "interference of probabilities" is used to refer to a situation in which several *amplitudes* may reinforce or subtract each other according to the principle of superposition of amplitudes. The probability of a variable may become zero for some values due to this interference. By contrast, the concept of probability used here is a real number and never negative, it is measured or verified in the real world of facts. There can be no probability that cancels out another one.

In order to avoid misunderstanding connected to the idea of the "collapse of the wave function" we would like to stress that the concept of probability used here is the one that describes the frequency of occurrence of random events. The alternate Bayesian concept of probability describes a subjective expectation as to what degree a hypothesis appears to be true. This probability jumps to 1 when the hypothesis turns out to be true, while probability distributions used here do not change when they are measured.

There are also discrete probability distributions in quantum mechanics relating to properties that are capable of assuming only discrete values. Examples of such properties are the electric charge, the magnitude of spin, and the spin component along a given direction, of which only the latter is subject to an appropriate uncertainty relation. These probability distributions are given over the discrete values of the variable, and here too we use the previously defined expression “unsharp value” to refer to a quantity that takes on more than one value of its spectrum.

6 The role of an individual event

What should be the role of an individual event now, when a probability distribution is being measured? Referring to the example in the third paragraph of Section 4, let the first electron of the sample go through the upper slit (belonging, say, to larger x). It should behave as if it is in a pure polarized spin state because in this case all electrons will take this path. Am I now to speculate whether *it is my own choice* whether I test first the x-direction or first the y-direction? This does not seem very plausible. The individual event has no meaning.

Another simple example is an atomic state with zero angular momentum which radiates a particle. The spherically symmetric form requires all directions to be equally distributed. In a direction-sensitive instrument the first event will be observed in some arbitrary direction. Any speculation about which direction this is would be futile. In the next event another arbitrary direction is found. After thousands of events we will notice that the number of events is approximately the same in every interval of the solid angle. With a sample a hundred times as large the deviations from uniformity will be reduced by a factor ten (they always go with the square root). Again, the individual event has no meaning.

There are implicit idealizations involved when measuring a quantum mechanical object, an ensemble. Just as in the case of classical measurements, we first remove from consideration all instrumental measurement errors. However in quantum mechanics we must consider two additional points. First, the sample is taken to be “sufficiently large” in the sense that with an increase of the sample the statistical error can be brought below any given limit. Second, there is an idealization in the understanding of the measuring process as it was described in detail by B. Falkenburg (Falkenburg, 1995).

When measuring a probability distribution of some quantity this quantity must be determined repeatedly (using always the next copy in the sample). Each time we deal with an individual event. Further reservations may be expressed as to whether the phenomena inside the detector are sufficiently understood using the ensemble-method. Could it not be that rare events involving quantum mechanical scattering and long range quantum mechanical correlations get lost in the physicist's usual pattern of explanation which is, after all, classical ?

7 Measuring errors again

It must be conceded that when analysing a track in a tracking detector the individual measuring points along the track do not constitute an ensemble because they do not result from the same preparation. According to B. Falkenburg, an ensemble interpretation is to be excluded when quantum theory is applied to individual tracks in the theory of measurement (Falkenburg, 1995, p. 197).

All the same, in the art of measurement a method has developed in which conceptual discrepancies are included in the numerical error estimates that are part of the final result. The measurements in question are obviously always classical. In the determination of the momentum of a track as discussed in (Falkenburg, 1995) the important thing is that the momentum be measured sufficiently well in order to determine (or verify) the frequency distribution over the range concerned. The effects in the individual measuring points originating in quantum mechanics that are not known in detail can be (conservatively) estimated in order to limit their influence on the actual value of the momentum. This is done using an understanding based on the ensemble behaviour. Moreover, there is additional support for making sure that the (classical) value of the measured momentum lies within the estimated error limits, for example by varying the magnetic field or making comparisons with other tracks from a particle decay.

The situation is the same as that encountered when we measure quantities of classical physics. The probability information of quantum mechanics always refers to classical quantities – it is these that must be caught in the art of measurement. It is not important that these probabilities are calculated using quantum mechanics, they could have some other source. When it comes to the calculation of the measuring errors the atomic phenomena must now be taken into account so that the behaviour of the classical apparatus can be evaluated. The implicit idealization of measurement presupposes that the measuring errors are under control, this being so for classical as well as quantum mechanical predictions.

8 Quantum mechanics as a calculus of possibilities

The classical quantities like energy, momentum, position, angular momentum etc. were characterized by numerical values (with dimensions attached to them). The quantum mechanical matrices that replace them contain not only one but all the possible numerical values the quantity is capable of assuming. A calculation with these aggregates of possible values results in not one predicted measurement value but in all the possible values one can find when setting up a measuring instrument. The instrument can obviously measure only one value per event. Also the solutions of the Schrödinger equation or a Feynman path integral solution result in predictions about all the possible measurement values that may occur, properly weighted with their probabilities of occurrence.

Quantum mechanics is a calculus of all the possibilities that may be the actual result of measurements. In the world of possibilities (behind the curtain which separates the domain of the possible from reality) particles and waves coexist. In the real world it is *either* the wave *or* the particle which appears, depending on the apparatus in which it appears as a real phenomenon, enters into reality. Recall that we assumed above that all possibilities can in principle be measured. For this, each instrument to be used for measuring the various quantities must be set up in sequence, and the various probability distributions measured. So this side of the curtain we can experience *sequentially* what coexists behind the curtain in *parallel*.

A familiar picture may serve to show the peculiar relation between the mathematical form of quantum mechanics and the observable facts. The shadow of a short round cylinder, projected along the axis onto a screen oriented at right angles to the axis, will appear as an area of a circle. Projected in a different direction, orthogonal to the axis, the cylinder appears as a rectangle. What we can observe is on the screens. We can detect *either* the circle *or* the rectangle, depending on the projection that the observer has chosen. Circle and rectangle seem to exclude each other. The cylinder itself cannot be observed because it just stands for the different possibilities of observation. In the comparison the cylinder is the quantum mechanical state in its mathematical form. When all the various projections have been measured, the quantum mechanical state is empirically determined.

9 The observer

The role of the observer depends on whether he looks at an individual event or employs the method of the separated sample of identically prepared atoms. Confronted by an individual event he has the choice of which real quantity he lets the object appear to be in, i.e. in which apparatus he wants to observe the transition from a possibility into a fact. But using the method of the separated sample his choice is limited to the sequence in which he wants to scan all the possible properties of the atom. The sequence, however, has no meaning. Only the "impatient observer" who begins to reason already about the first event, without measuring all the probabilities, has a choice.

The individual event then decides the role of the observer. If the individual event is no longer needed the observer drops out of the picture and quantum mechanics may then be understood as an objective description of nature.

If quantum mechanics is a correct description of atomic phenomena in agreement with all measurements, it must be true that for all situations investigated, the probability distributions that were predicted by the equations have been empirically verified. The measurement of probability distributions implies that the role of the observer is eliminated. The other predictions of quantum mechanics that are not probability distributions are anyway independent of any special observer.

10 Laws of motion

Quantum mechanics contains precise laws of motion by which an initial state, under the influence of forces or simply by the passage of time, is transformed into a final state. The catalogue of possibilities inherent in the initial state is thus transformed into a final one. Both catalogues can in principle be measured (scanned) and the relevant law of motion verified. What is not possible, however, is to calculate the result of the second measurement from the first one *using classical concepts*. A catalogue of possibilities does not define an initial set of conditions for a classical law of motion. nor can it be interpreted as a description of a classical statistical ensemble. Classical physics cannot in fact handle the incommensurability between quantities describing atomic phenomena. We must go back behind the curtain to calculate the catalogue of the second state from the first state. For this, we need the complex-valued matrices (or generally speaking the operators) of quantum mechanics, for the real-valued functions of classical physics only work for sharp numbers.

The statements of the previous paragraph require some qualifications. There are limiting cases (such as the eigenstates of time invariant operarators) which do allow the time development of the probability distributions to be calculated classicaly, as long as there are no additional forces involved. One such limiting case is the plane wave propagating in some direction with a given wavelength; another is the angular momentum eigenstate of an atom, angular momentum being a conserved quantity. In these examples, the situation is simplified because no incommensurable quantities are simultaneously involved. The classical concepts can deal with the situation in such exceptional cases, and allow us to calculate directly the results of the second measurement from the results of the first. See also Sect. 17.

In general this impossibility of classical concepts to deduce the second catalogue of possibilities from the first does not arise because these lack definiteness. The second catalogue is exactly determined on the basis of the “law of causality of quantum mechanics”. What is meant by this is that the quantum mechanical state has a unique time development. There is, in contrast, no application for the “law of causality of the real world”. The realizations of the probability distributions are governed by chance, there is no unbroken sequence of real situations, although there is an unbroken sequence of possibilities.

11 A question of language

It was stated above that the properties of an electron can be measured using a sample of identically prepared electrons. Insofar the ensemble stands in place of the object of classical physics. The electron to be investigated carries sharp and unsharp properties (probability distributions). Now it is a matter of language whether we associate the object's properties only with the sample of identically prepared electrons (effectively saying that the electron is not an object), or whether we call the electron an object whose properties, as far as the unsharp numbers are concerned, can only be verified using a sample of identically prepared individuals. We prefer the second figure of speech, for the following reasons:

(a) The electron does have some sharp properties, e.g. mass, electric charge. These could in principle be verified on one single electron because they are not subject to uncertainty relations. To say that an electron is an "object with respect only to some of its properties" sounds like a very confusing use of language.

(b) If we accept the electron as an "object" we have provided ourselves with the advantage of a unified description of the things we are interested in in physics. Otherwise, the following would happen: Starting from an unquestionable object of classical physics, say a heavy piece of matter which we imagine to be repeatedly cut in half, the uncertainty relation would come into play after a certain number of cuts. We would then slowly have to deny the status of being an object to this piece of matter as it becomes smaller and smaller. In other words, the status of "object" would have to be granted as a function of some quantitative circumstances. We would perhaps have to say "There is an object when the uncertainty relations do not play a role". A more practical statement however would seem to be: "When the uncertainty relations play a role, the verification of the properties of the object requires the use of a sample of identically prepared objects."

(c) Even in cases where no incommensurable quantities are involved, it is common practice when determining or verifying probability distributions to work with samples of identically prepared individuals that are as large as possible. In such cases it makes no difference whether the sample is subdivided for the study of incommensurable properties or whether the properties are studied sequentially using identically prepared individuals.

In the spirit of the above we call electrons "objects" (dropping the first term of the name "reference objects of quantum mechanics" used in the Introduction). They carry some attributes to which sharp numerical values can be assigned and some others for which this is not possible, and probability distributions must be used instead, the properties of the electron being partly fact and partly possibilities. The possibilities of an electron prepared in a well-defined way are given by the laws of quantum mechanics as the relevant probabilities for their conversion into facts.

The unsharp properties they carry are conversion possibilities from the fluid state of the still-undecided into the solid state of the final circumstance. This means: *After* the measurement they are facts and can be counted, before the measurement they are possibility, not fact. As long as an electron can still disappear at a given position (interference of the amplitudes), it is *not real* there, “has no position”. The transition of possibilities into a fact may also happen spontaneously; a radioactive (unstable) atomic nucleus can decay into several decay products with a certain probability per minute. As long as the decay has not happened, it is a possibility, endowed with an unsharp value (probability distribution) of the decay time. Once the decay has happened the decay time is an irrevocable fact that may be assigned a numerical value. (A decay qualifies as a fact as long as it is irreversible. Situations can be constructed in which a mirror reflects an emitted photon and sends it back to the nucleus which reabsorbs it. More analysis is needed for such situations.)

12 And when the sample is too small?

There could be circumstances where not enough electrons from an identical preparation are at hand, so the probabilities cannot be measured or verified “with arbitrary precision”. When measuring elementary particle reactions at an accelerator one may imagine that it is at the discretion of the experimenter to be satisfied with a given size of the sample or whether the sample should be increased in order to reduce the statistical error. But if there are only a few particles (perhaps arriving from outer space) the probabilities in question can only be measured in a very coarse way, and when there is only one particle, not at all.

Even in classical physics there may be circumstances that make it impossible to measure a quantity with arbitrary precision, for example when a celestial body hides behind another one. In such cases we acknowledge the idealization that the hidden object *has* certain quantified properties although they cannot be verified under the given circumstances. In a general context of knowledge we are allowed to imagine the circumstances changed or the difficulty removed because they are acknowledged to be unimportant. When neglecting the unavoidable measuring errors of classical quantities this idealization is already at work.

We may understand the quantum mechanical situation in the same way. Although under certain circumstances the probability distribution over a microphysical quantity may not be measurable, we can at least imagine hypothetically changed circumstances under which it can. So we say that *probability distributions can conceptually be measured.*

13 The factual and the possible

The abrupt change of quantities to be measured from possibility to fact is expressed in the idea of an “event”, which is so familiar in the laboratory practice. It is characteristic of the abrupt change that it only happens in one direction. There is no change from a fact to a possibility, the change cannot be reversed. The fact remains, and continues to be a fact. Notice that in some peculiar way we find the *time*, whose direction cannot be reversed, entering into the picture. (This property of time is given irrespective of some special equations of motion in physics that are invariant against time reversal, i.e. reversal of the direction of motion.)

The distinction between the possible and the factual is part of the general human experience and was understood long before quantum mechanics, indeed even before physics. We do not have to discuss the question of which physical circumstances distinguish one from the other. The question addressed in this essay is whether we are obliged to give up an objective description of atomic phenomena, and for this, a theory of the irreversibility is not expected to be so important and will here be omitted.

14 Reality of the electron

“Is the electron real?” This question must mean: Can it already be part of the real world into which it will soon enter when, say its position is to change from a possibility into a fact? For an answer to this question we must take into account that the electron carries sharp as well as unsharp properties. By having at least some sharp attributes it is already part of the real world. Enclosed in a box, its weight could in principle be determined in the gravitational field of the earth, independently of its position in the box which is only given by probability. A single electron can be locked up in a an electron trap and its magnetic moment (Dehmelt, 1984) measured precisely, while of course its position and momentum are subject to the uncertainty relation. An electron is, from the moment of its creation onwards, part of the real world on account of its sharp properties. By annihilation with a positron, for example, it can cease to exist in the real world – like a drop of water falling into the ocean.

The above statements hold for a single individual electron. In quantum mechanics another characteristic feature comes into play : If two or more electrons interact with each other they usually cannot be individualized, i.e. considered separately. Together they then form a whole whose properties are described by one quantum mechanical amplitude and the associated correlated probability distributions. The optical properties of an atom can only be understood when its electrons are conceived as a totality and not as individuals. Such a totality is the object, and can also consist of a double electron that is measured at two places remote from each other in such a way that one half of the double electron enters with one of its properties into reality *here*, the other half *there*; two different facts are created. The experiments of the EPR-type (Einstein, 1935) deal with such “entangled” events. If several facts per event are being counted the measured frequency distributions are in general correlated and must be compared with correlated probability distributions of the theory.

15 Probability as a concept of common language

The concept of probability has a long history and has been discussed in many ramifications (von Weizsäcker, 1985). The Bayesian idea of a *subjective* probability, this being a measure of belief in the truth of a hypothesis, has already been introduced above. We limit ourselves here to the laboratory practice of physicists, where the probability for the fulfillment of a certain condition is verified by a large number of independent trials, and the relative frequency of events that meet this condition approaches the probability more and more closely as the number of trials is increased. In this context C.F. v. Weizsäcker has proposed the following introduction of the concept of probability: *For this we interpret the concept of probability in a strictly empirical sense. We consider probability to be a measurable quantity whose value can be just as well empirically verified as e.g. the value of an energy or a temperature.* (von Weizsäcker, 1985, p. 101)

In everyday language this is what we mean when we say that “The chance that this throw of a die will be a ’3’ is one sixth”. That the Bayesian form is present in everyday language is also evident in statements like “the doctor has said the patient has gallstones with 50% probability”.

We may consider the probability law for the appearance of the values of a quantum mechanical quantity as a concrete, measurable quantity in terms of our ordinary language. If we accept the concept of probability law as part of this everyday language, a (partial) translation of the mathematics of quantum mechanics into common language will have been achieved. We then have an interpretation of quantum mechanics in which the observer no longer plays any role.

16 Relation to the Copenhagen interpretation

This essay remains essentially inside the frame of the Copenhagen interpretation of quantum theory (Heisenberg, 1958) (Heisenberg, 1955) (Bohr, 1928). In particular it feels committed to the rule that *any experiment in physics, whether it* *refers to the phenomena of daily life or to atomic events, is to be described in the terms of classical physics* (Heisenberg, 1958, p. 44). Bohr's complementarity principle (Bohr, 1928) seems to be an appropriate tool to play with mutually exclusive pictures of classical physics in order to do justice to the different aspects of quantum theory that are contradictory in the common language. *This possibility of playing with different complementary pictures has its analogy in the different transformations of the mathematical scheme* (Heisenberg, 1958, p. 50).

In the question of objectivity, subject of this essay, there is a shift of emphasis of the arguments when compared to the Copenhagen interpretation; in addition, the whole array of questions concerning the transition from the possible to the factual and how to understand it in physics has here been omitted.

The shift of emphasis takes place from the individual event to the statistical ensemble or, in other words, from the discussion of the real results of every measurement to a discussion of the probabilities and their experimental mapping. Here it is of special interest to understand in which way the subjective elements of the Copenhagen interpretation come into the picture. The result of a quantummechanical computation is a probability function. *The probability function combines objective and subjective elements. It contains statements about possibilities or better tendencies ("potentia" in Aristotelian philosophy), and these statements are completely objective, they do not depend on any observer; and it contains statements about our knowledge of the system, which of course are subjective in so far as they may be different for different observers* (Heisenberg, 1958, p. 53). So in the Copenhagen version the Subject comes into play when interpreting an individual event – which would have looked different with a different choice of measuring apparatus; maybe it would have come out in a form that would be classically in contradiction to the event observed. In our approach, the Subject disappears in this role (as a "chooser of the apparatus") because all the measuring apparatuses are employed in sequence and all probabilities are being measured using the method of the separated sample (Section 4).

In the Copenhagen interpretation the psychical act of observation and the consciousness of the observer are not claimed to play any role. *We may say that the transition from the "possible" to the "actual" takes place as soon as the interaction of the object with the measuring device, and thereby with the rest of the world, has come into play; it is not connected with the act of registration of the result by the mind of the observer* (Heisenberg, 1958, p. 54-55). So also in this respect we do not have to deal with the Subject in the understanding of the quantum theory.

One may get the impression that there is a certain tendency visible in the Copenhagen interpretation that excludes a straightforward "objective" character of the observations. For example, Heisenberg when talking in a different context about closed systems of concepts in physics, says: *In the fourth set, that of quantum theory, man as the subject of science is brought in through the questions which are* *put to nature in the a priori terms of human science. Quantum theory does not allow a completely objective description of nature* (Heisenberg, 1958, p. 106-107). To the extent that the role of the observer as a "chooser of the apparatus" is meant, he is no longer relevant for us.

Perhaps the presence of the subjective in the Copenhagen interpretation comes from still some other source as one might infer from the following statements of Heisenberg: *Objectivity has become the first criterion for the value of any scientific result. Does the Copenhagen interpretation of quantum theory still comply with this ideal? One may perhaps say that quantum theory corresponds to this ideal as far as possible. Certainly quantum theory does not contain genuine subjective features, it does not introduce the mind of the physicist as a part of the atomic event. But it starts from the division of the world into the "object" and the rest of the world, and from the fact that at least for the rest of the world we use classical concepts in our description. This division is arbitrary and historically a direct consequence of our scietific method; the use of the classical concepts is finally a consequence of the general human way of thinking. But this is already a reference to ourselves, and insofar our description is not completely objective* (Heisenberg, 1958, p. 106-107).

The concept of "objective" as used by Heisenberg in this last sentence is not the (more narrow) concept of "objective (binding upon all observers)" that is the guideline of our essay. Heisenberg's term seems to refer to a reality existing independently of man (of mankind) which Heisenberg rejects on the ground that Man cannot understand Nature without reflecting the conditions of his own science, thereby involving himself. Classical physics is more naïve in this respect, it is only in quantum theory that this consideration imposes itself, especially when there is the apparently unavoidable observer that is needed to state the facticity of each individual event. When we get away from the observer of the individual event we have reached the objectivity that is binding upon all observers, and the subjective element has disappeared.

The resulting interpretation of quantum mechanics may be called a "Copenhagen interpretation without subjective element".

17 Reality and possibility

As pointed out in Section 8 the mathematics of QM is a calculus of possibilities. It allows attributes of quantum mechanical objects to be represented in coexistence that cannot coexist in reality. We must understand more clearly what this means in precise terms. Therefore we want to reconsider some of the physics arguments of the previous sections in a more philosophical perspective.

In addition to the mode of being (Seinsmodus) of *Reality* of classical physics we consider a mode of being of *Closed Possibility*, characteristic for quantum mechanics. The word “closed” is to indicate a qualification by a probability law which restricts the possibility.

The two modes of being have in common that they can be empirically verified: a proposition about the existence of a classical attribute can be empirically decided in the same way as a claim about the existence of a closed possibility of a quantum mechanical attribute.

The concept of possibility has a meaning with respect to something real that may appear or begin to exist in reality as time goes on. The dividing line between the accomplished fact in reality and the possibility that it may arrive, shall be agreed to be such that the fact cannot change back into a possibility.

The possibility is called “closed” if it comes with a probability law for the arrival of the fact the possibility stands for. The arrival of the fact is the transition between the two modes of being: the possibility turns into a real fact. The probability law makes the closed possibility empirically verifiable; the verification is in comparing the observed frequency of arrival with the probability law.

Examples of propositions mentioned in paragraph 3 could be: (a) The planet is located in this designated segment of the sky. (b) The electron is located with probability p (a fixed number $0 \leq p \leq 1$) in this designated segment of the apparatus.

The empirical verification can only be achieved under circumstances that there is a transition between the two modes. As the case arises this may be made to happen by applying a measuring instrument. An empirical verification is not required in each individual instance, but we should in principle be able to perform one if we want to be sure of a claim that a certain closed possibility exists. This is the same for real attributes, they only have to be verifiable in principle.

A possibility that is more general than closed is not in general accompanied by a probability law and cannot always be empirically verified. For the verification consists of measuring the probability law.

18 Relation between the two modes of being

There are special situations in quantum mechanics where a measurement of a physical quantity always yields the same value, although in other situations it yields a range of values. In this special case the probability distribution is 1 (it it is discrete) or represented by a Dirac delta function (if it is continuous). We have a quantum mechanical eigenstate of the attribute at hand. The probability is concentrated on this one value, the measurement of it is a certainty. This is a limiting case to the general one where there are many possibilities for the outcome of the measurement. We may say that the quantum mechanical description of an attribute "turns into" the realistic description. Also conceptually there is no essential difference.

The quantum mechanical attribute exists only as a possibility before the measurement, the classical one exists continuously, can be measured at any time and will yield the same result each time it is measured. In the limiting case we discuss, also the quantum mechanical property will yield the same result each time it is measured, even when measured repeatedly at the same individual. In contrast to the method of the separated sample (Sect. 4) where each measured individual had to be discarded and was no longer investigated, we may now in this limiting case measure and remeasure the same individual with identical results. This is true for quantum mechanical attributes that are conserved quantities like momentum, energy or spin component. We say that under these circumstances a *sharp possibility is a reality.*

A comparison with number theory shows a useful analogy with the relation between reality and the quantitatively defined possibility (closed possibility) we are discussing. In the same way as the real numbers become limiting cases of the complex ones by letting the imaginary part go to zero, the reality of an attribute emerges from the closed possibility when the width of its probability distribution goes to zero. The complex number $(R + i\ 0)$ is being identified with the real number R, and the sharp possibility is being identified with the real attribute. *The closed possibility reveals itself to be an extension of reality* in the same sense as the complex numbers are an extension of the real ones.

The idea of an extension of reality brings about that an attribute may be called "almost real" (a closed possibility with a very narrow probability distribution) or "little real" (a closed possibility with a broad probability distribution). There is a continuous, not discrete transition from "real" to "not real" attributes. The real world is in the neighbourhood of the world of closed possibilities. – Quantum mechanics has taught us metaphysics.

The understanding of quantum mechanics began with its mathematical formalism. When Heisenberg replaced the numbers appropriate for the classical kinematic variables by the matrices of quantum mechanics, and when he admitted that the various possibilities influence each other, the limits of reality were broken. It may be allowed to visualize the metaphysical situation by saying: In the concept of reality there was not enough room for the large diversity of the newly discovered behaviour of the atoms. The attributes of the quantum mechanical objects did not find enough space in the real world, which therefore had to be enlarged by the world of closed possibilities in order to "accommodate" all the verifiable attributes of the new objects.

The ontological proposition that the reality of classical physics must be extended by a world of possibilities if one wants to understand quantum mechanics, cannot please the philosophical realist if he expects an answer to the "measuring problem" – why it is that the quantum mechanical state, originally a superposition of all the possible eigenstates of the measuring device, has been transformed into just the one eigenstate that the instrument has registered. This expectation is owed to his interest in the individual event. We, on the other side, do not concede that the individual event has any meaning where the quantum mechanical predictions for the outcome of measurements are probability statements.

That which is dealt with in quantum mechanics contains the real world as well as the world of closed possibilities.

19 Emergence of a track, observer and semiclassical language

Heisenberg wrote: *The trajectory is created due to the fact that we observe it* (Heisenberg, 1927). As we are concerned about the necessity of "the observer" we have to examine whether the terminology developed up to here can be justified vis à vis Heisenberg's ideas about the creation of a trajectory. We want to describe the creation of a track in our terminology using as an example an experimental sut-up that contains all the essential parts.

Imagine a source of radioactive nuclei at a given position inside a field-free cloud chamber, emitting charged particles in a state of angular momentum zero. The momentum direction of each emitted particle is consequently isotropically distributed. A first ion is created by chance somewhere in the chamber, a location near the nucleus being more probable than one further away. If it forms a droplet (and does not recombine before), a fact is created because the droplet cannot disappear again, according to the design idea of the cloud chamber, it remains a droplet. The ionisation with the subsequent formation of the droplet is the transition between the two modes of being, which is characteristic of the measuring process; the closed possibility becomes a real irrevocable fact according to its probability law. The closed possibility is verifiable by comparing the probability law with the measured frequency of occurrence when repeating the measurement.

Once a first ionisation has taken place the direction of the particle is a new closed possibility according to the probability law that depends on the scattering parameters of the first ionisation, its position and the one of the radioactive nucleus. The two positions of the nucleus and the first ionisation determine a direction. The scattering law of the first ionisation is such that the probability of the new flight direction is largest along this direction, but also other, nearby directions are possible. (The deviation is the smaller the smaller the electric charge and the larger the momentum of the particle.) As a result, a second ionisation takes place at a position usually not exactly on and most often not too far away from the straight line joining the nucleus and the first ion. Again there is a transition from the possible into a fact, and a new droplet is created. In this way the track continues until it ends either through energy loss or a particle interaction or by leaving the cloud chamber.

There is no observer in this description, but we believe that this description of the creation of a track is entirely compatible with Heisenberg's view. It was important for him that the "trajectory" (put by him in quotation marks) does not exist in reality before it is materialized so that it can be observed. In our terminology the sentence quoted in the first paragraph would read: *The trajectory is created due to the fact that it enters into reality.*

The physicist who looks at this track talks about it in the language of his experience: *The track is a record of the trajectory of the particle that flew there. It has undergone multiple scattering on the atoms of the gas, visible in the scattered positions of the droplets along the trajectory.* This language does not consider that, according to quantum mechanics, the trajectory between the droplets did not exist in reality but only as a (closed) possibility; the particle with its other attributes did indeed exist as a reality due to its sharp properties. Nevertheless, this language is completely adequate for the purposes of the physicist on account of the scattering law containing only very fine deviations from the classical trajectory, and because the stochastic behaviour is imputed to the classical particle. This manner of speaking is also known as "a semiclassical language". It uses the idea of a *continuous reality* of the particle and its attributes, whereas in quantum mechanics there is only a continuous possibility of its position and momentum between the individual ionisations. The effective practical equivalence of both ideas has its counterpart in the close vicinity of the real world and the world of closed possibilities (Sect. 18).

20 Historical view

The physical and technical development since the discovery of quantum mechanics has enlarged the world of our imagination, which always has been a source of our language. In the nineteen-twenties the observation of atomic phenomena was quite different from what it is today. The Geiger counter had just been invented, and the coincidence method was first applied in the experiment of Bothe and Geiger to demonstrate the existence of the Compton effect. Being able to register individual events in such experiments was in fact the starting point of the investigation of atomic-scale phenomena. Today, at particle accelerators, this capability has been developed to such an extent that we can register millions of events automatically. It has consequently become technically very easy to test theoretical statements about probabilities by measuring with high statistical accuracy the frequencies with which events occur. This is now a general laboratory practice.

We can now see that early efforts to comprehend quantum mechanics started with the individual event. The pioneers interpreted the observed *facts* in the real world. That quantum mechanics is a theory of *possibilities* was of course known to them, in fact we have learnt it from them. Possibility, central concept of quantum mechanics, is connected with the real world of facts through the concept of the probability law. What the pioneers did not consider was that the probability laws could one day be directly measured. Testing statements about probability is the empirical basis of quantum mechanics, which also reveals that it is an objective science. At the same time this point of view opens the way to a better understanding of quantum mechanics in terms of our everyday language. (There are other measurements in the empirical basis that are not, technically speaking, verifications of probability distributions but ordinary measurements like of wave lengths of spectral lines, they have even more reason to be objective.)

The laws of classical physics are valid for the real world, for the factual, real attributes of its objects. It was the great discovery of quantum mechanics to establish laws for the development in space and time of *possibilities*; they arise as attributes of aomic objects.

The concept of *substance*, central element of classical physics, is brought to bear once more in quantum mechanics when we attach unsharp properties to its objects. “Once more” is meant in view of the development of classical physics of the bodies towards a theory of elementary particles whose reference objects are interpreted as representations of the relevant symmetry groups. This interpretation makes them even further removed from the classical concept of substance than the objects of quantum mechanics.

21 Summary

The properties of an object of the classical world have sharp values and are measurable in principle. The properties of an object of the atomic world have both sharp and unsharp values, the unsharp values being probability densities. The properties of an object of the atomic world are also measurable in principle. Such measurements are described in the language of classical physics and yield the same result for all observers. For this, the real world has to be extended by the one of possibilities which is continuously connected to reality. Only together do they form the world of quantum mechanics and the basis for an objective description of atomic phenomena.

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