Chapter 27

Quantum Theory and Reality

27.1 Introduction

The connection between human knowledge and the real world to which it is (hopefully) related is a difficult problem in philosophy. The purpose of this chapter is not to discuss the general problem, but only some aspects of it to which quantum theory might make a significant contribution. In particular, we want to discuss the question as to how quantum mechanics requires us to revise pre-quantum ideas about the nature of physical reality. This is still a very large topic, and space will permit no more than a brief discussion of some of the significant issues.

Physical theories should not be confused with physical reality. The former are, at best, some sort of abstract or symbolic representation of the latter, and this is as true of classical physics as of quantum physics. The phase space used to represent a classical system and the Hilbert space used for a quantum system are both mathematical constructs, not physical objects. Neither planets nor electrons integrate differential equations in order to decide where to go next. Wave functions exist in the theorist's notebook and not, unless in some metaphorical sense, in the experimentalist's laboratory. One might think of a physical theory as analogous to a photograph, in that it contains a representation of some object, but is not the object itself. Or one can liken it to a map of a city, which symbolizes the locations of streets and buildings, even though it is only made of paper and ink.

We can comprehend (to some extent) with our minds the mathematical and logical structure of a physical theory. If the theory is well developed, there will be clear relationships among the mathematical and logical elements, and one can discuss whether the theory is coherent, logical, beautiful, etc. The question of whether a theory is true, its relationship to the real world "out there", is more subtle. Even if a theory has been well confirmed by experimental tests, as in the case of quantum mechanics, believing that it is (in some sense) a true description of the real world requires a certain amount of faith. A decision to accept a theory as an adequate, or even as an approximate representation of the world is a matter of judgment which must inevitably move beyond issues of mathematical proof, logical rigor, and agreement with experiment.

If a theory makes a certain amount of sense and gives predictions which agree reasonably well with experimental or observational results, scientists are inclined to believe that its logical and mathematical structure reflects the structure of the real world in some way, even if philosophers will remain permanently sceptical. Granted that all theories are eventually shown to have limitations, we nonetheless think that Newton's mechanics is a great improvement over that of Aristotle, because it is a much better reflection of what the real world is like, and that relativity theory improves upon the science of Newton because space-time actually does have a structure in which light moves at the same speed in any inertial coordinate system. Theories such as classical mechanics and classical electromagnetism do a remarkably good job within their domains of applicability. How can this be understood if not by supposing that they reflect something of the real world in which we live?

The same remarks apply to quantum mechanics. Since it has a consistent mathematical and logical structure, and is in good agreement with a vast amount of observational and experimental data, it is plausible that quantum theory is a better reflection of what the real world is like than the classical theories which preceded it, and which could not explain many of the microscopic phenomena that are now understood using quantum methods. The faith of the physicist is that the real world is something like our best theories, and at the present time it is universally agreed that quantum mechanics is a very good theory of the physical world, better than any other currently available to us.

27.2 Quantum vs. Classical Reality

What are the main respects in which quantum mechanics differs from classical mechanics? To begin with, quantum theory employs wave functions belonging to a Hilbert space, rather than points in a classical phase space, in order to describe a physical system. Thus a quantum particle, in contrast to a classical particle, Secs. 2.3 and 2.4, does not possess a precise position or a precise momentum. In addition, the precision with which either of these quantities can be defined is limited by the Heisenberg uncertainty principle, (2.22). This does not mean that quantum entities are "fuzzy" and ill-defined, for a ray in the Hilbert space is as precise a specification as a point in phase space. What it does mean is that the classical concepts of position and momentum can only be used in an approximate way when applied to the quantum domain. As pointed out in Sec. 2.4, the uncertainty principle refers primarily to the fact that quantum entities are described by a very different mathematical structure than are classical particles, and only secondarily to issues associated with measurements. The limitations on measurements come about because of the nature of quantum reality, and the fact that what does not exist cannot be measured.

A second respect in which quantum mechanics is fundamentally different from classical mechanics is that the basic classical dynamical laws are deterministic, whereas quantum dynamical laws are, in general, stochastic or probabilistic, so that the future behavior of a quantum system cannot be predicted with certainty, even when given a precise initial state. It is important to note that in quantum theory this unpredictability in a system's time development is an intrinsic feature of the world, in contrast to examples of stochastic time development in classical physics, such as the diffusion of a Brownian particle (Sec. 8.1). Classical unpredictability arises because one is using a coarse-grained description where some information about the underlying deterministic system has been thrown away, and there is always the possibility, in principle, of a more precise description in which the probabilistic element is absent, or at least the uncertainties reduced to any extent one desires. By contrast, the Born rule or its extension to more complicated situations, Chs. 9 and 10, enters quantum theory as an axiom, and does not result from coarse graining a more precise description. To be sure, there have been efforts to replace the stochastic structure of quantum theory with something more akin to the determinism of classical physics, by supplementing the Hilbert space with hidden variables. But these have not turned out to be very fruitful, and, as discussed in Ch. 24, the Bell inequalities indicate that such theories can only restore determinism at the price of introducing nonlocal influences violating the principles of special relativity.

Of course, there is no reason to suppose that quantum mechanics as understood at the present time is the ultimate theory of how the world works. It could be that at some future date its probabilistic laws will be derived from a superior theory which returns to some form of determinism, but it is equally possible that future theories will continue to incorporate probabilistic time development as a fundamental feature. The fact that it was only with great reluctance that physicists abandoned classical determinism in the course of developing a theory capable of explaining experimental results in atomic physics strongly suggests, though it does not prove, that stochastic time development is part of physical reality.

27.3 Multiple Incompatible Descriptions

The feature of quantum theory which differs most from classical physics is that it allows one to describe a physical system in many different ways which are *incompatible* with one another. Under appropriate circumstances two (or more) incompatible descriptions can be said to be true in the sense that they can be derived in different incompatible frameworks starting from the same information about the system (the same initial data), but they cannot be combined in a single description, see Sec. 16.4. There is no really good classical analog of this sort of incompatibility, which is very different from what we find in the world of everyday experience, and it suggests that reality is in this respect very different from anything dreamed of prior to the advent of quantum mechanics.

As a specific example, consider the situation discussed in Sec. 18.4 using Fig. 18.4, where a nondestructive measurement of S_z is carried out on a spin-half particle by one measuring device, and this is followed by a later measurement of S_x using a second device. There is a framework $\mathcal{F}$, (18.31), in which it is possible to infer that at the time t_1 when the particle was between the two measuring devices it had the property $S_z = +1/2$, and another, incompatible framework $\mathcal{G}$, (18.33), in which one can infer the property $S_x = +1/2$ at t_1. But there is no way in which these inferences, even though each is valid in its own framework, can be combined, for in the Hilbert space of a spin-half particle there is no subspace which corresponds to $S_z = +1/2$ AND $S_x = +1/2$, see Sec. 4.6. Thus we have two descriptions of the same quantum system which because of the mathematical structure of quantum theory cannot be combined into a single description.

It is not the multiplicity of descriptions which distinguishes quantum from classical mechanics, for multiple descriptions of the same object occur all the time in classical physics and in everyday life. A teacup has a different appearance when viewed from the top or from the side, and the side view depends on where the handle is located, but there is never any problem in supposing that these different descriptions refer to the same object. Or consider a macroscopic body which is spinning. One description might specify the z component L_z of its angular momentum, and another the x component L_x. In classical physics, two correct descriptions of a single object can always be combined to produce a single, more precise description, and if this process is continued using all possible descriptions, the result will be a *unique exhaustive description* which contains each and every detail of every true description. In the case of a mechanical system at a single time, the unique exhaustive description corresponds to a single point in the classical phase space. Any true description can be obtained from the unique exhaustive description by coarsening it, that is, by omitting some of the details. Thus specifying a region in the phase space rather than a single point produces a coarser description of a mechanical system.

For the purposes of the following discussion it is convenient to refer to the idea that there exists a unique exhaustive description as the *principle of unicity*, or simply *unicity*. This principle implies that every conceivable property of a particular physical system will be either true or false, since it either is or is not contained in, or implied by the unique exhaustive description. Thus unicity implies the existence of a universal truth functional as defined in Sec. 22.4. But as was pointed out in that section, there cannot be a universal truth functional for a quantum Hilbert space of dimension greater than two. This is one of several ways of seeing that quantum theory is inconsistent with the principle of unicity, so that unicity is not part of quantum reality. It is the incompatibility of quantum descriptions which prevents them from being combined into a more precise description, and thus makes it impossible to create a unique exhaustive description.

The difference between classical and quantum mechanics in this respect can be seen by considering a non-destructive measurement of L_z for a macroscopic spinning body, followed by a later measurement of L_x. Combining a description based upon the first measurement with one based on the second takes one two thirds of the way towards a unique exhaustive description of the angular momentum vector. But trying to combine S_z and S_x values for a spin-half particle is, as already noted, an impossibility, and this means that these two descriptions cannot be obtained by coarsening a unique exhaustive quantum description, and therefore no such description exists.

In order to describe a quantum system, a physicist must, of necessity, adopt some framework and this means choosing among many incompatible frameworks, no one of which is, from a fundamental point of view, more appropriate or more "real" than any other. This freedom of choice on the part of the physicist has occasionally been misunderstood, so it is worth pointing out some things which it does *not* mean.

First, the freedom to use different incompatible frameworks in order to construct different incompatible descriptions does not make quantum mechanics a subjective science. Two physicists who employ the same framework will reach identical conclusions when starting from the same initial data. More generally, they will reach the same answers to the same physical questions, even when some question can be addressed using more than one framework; see the consistency argument in Sec. 16.3. To use an analogy, if one physicist discusses L_z for a macroscopic spinning object and another physicist L_x, their descriptions cannot be compared with each other, but if both of them describe the same component of angular momentum and infer its value from the same initial data, they will agree. The same is true of S_z and S_x for a spin-half particle.

Second, what a physicist happens to be thinking about when choosing a framework in order to construct a quantum description does not somehow influence reality in a manner akin to psychokinesis. No one would suppose that a physicist's choosing to describe L_z rather than L_x for a macroscopic spinning body was somehow influencing the body, and the same holds for quantum descriptions of microscopic objects. Choosing an S_z, rather than, say, an S_x framework makes it possible to discuss S_z, but does not determine its value. Once the framework has been adopted it may be possible by logical reasoning, given suitable data, to infer that $S_z = +1/2$ rather than

$-1/2$, but this is no more a case of mind influencing matter than would be a similar inference of a value of L_z for a macroscopic body.

Third, choosing a framework $\mathcal{F}$ for constructing a description does not mean that some other description constructed using an incompatible framework $\mathcal{G}$ is false. Quantum incompatibility is very different from the notion of mutually exclusive descriptions, where the truth of one implies the falsity of the other. Once again the analogy of classical angular momentum is helpful: a description which assigns a value to L_z does not in any way render false a description which assigns a value to L_x, even though it does exclude a description that assigns a *different* value to L_z. The same comments apply to S_z and S_x in the quantum case.

In order to avoid the mistake of supposing that incompatible descriptions are mutually exclusive, it is helpful to think of them as referring to *different aspects* of a quantum system. Thus using the S_z framework allows the physicist to describe the "S_z aspect" of a spin-half particle, which is quite distinct from the "S_x aspect". To be sure, one still has to remember that, unlike the situation in classical physics, two incompatible aspects cannot both enter a single description of a quantum system. While using an appropriate terminology and employing classical analogies are helpful for understanding the concept of quantum incompatibility, it remains true that this is one feature of quantum reality which is far easier to represent in mathematical terms than by means of a physical picture.

27.4 The Macroscopic World

Our most immediate contact with physical reality comes from our sensory experience of the macroscopic world: what we see, hear, touch, etc. A fundamental physical theory should, at least in principle, be able to explain the macroscopic phenomena we encounter in everyday life. But there is no reason why it must be built up entirely out of concepts from everyday experience, or restricted to everyday language. Modern physical theories posit all sorts of strange things, from quarks to black holes, that are totally alien to everyday experience, and whose description often requires some rather abstract mathematics. There is no reason to deny that such objects are part of physical reality, as long as they form part of a coherent theoretical structure which can relate them, even somewhat indirectly, to things which are accessible to our senses.

Two considerations suggest that quantum mechanics can (in principle) explain the world of our everyday experience in a satisfactory way. First, the macroscopic world can be described very well using classical physics. Second, as discussed in Sec. 26.6, classical mechanics is a good approximation to a fully quantum mechanical description of the world in precisely those circumstances in which classical physics is known to work very well. This quantum description employs a quasi-classical framework in which appropriate macro projectors represent properties of macroscopic objects, and the relevant histories, which are well-approximated by solutions of classical equations of motion, are rendered consistent by a process of decoherence, that is, by interaction with the (internal or external) environment of the system whose motion is being discussed.

It is important to note that all of the phenomena of macroscopic classical physics can be described using a *single* quasi-classical quantum framework. Within a single framework the usual rules of classical reasoning and probability theory apply, and quantum incompatibility, which has to do with the relationship between *different* frameworks, never arises. In this way one can understand why quantum incompatibility is completely foreign to classical physics and invisible in the everyday world. (As pointed out in Sec. 26.6, there are actually many different quasi-classical frameworks, each of which gives approximately the same results for the macroscopic variables of classical physics. This multiplicity does not alter the validity of the preceding remarks, since a description can employ any one of these frameworks and still lead to the same classical physics.)

Stochastic quantum dynamics can be reconciled with deterministic classical dynamics by noting that the latter is in many circumstances a rather good approximation to a quasi-classical history that the quantum system follows with high probability. Classical chaotic motion is an exception, but in this case classical dynamics, while in principle deterministic, is as a practical matter stochastic, since small errors in initial conditions are rapidly amplified into large and observable differences in the motion of the system. Thus even in this instance the situation is not much different from quantum dynamics, which is intrinsically stochastic.

The relationship of quantum theory to pre-quantum physics is in some ways analogous to the relationship between special relativity and Newtonian mechanics. Space and time in relativity theory are related to each other in a very different way than in nonrelativistic mechanics, in which time is absolute. Nonetheless, as long as velocities are much less than the speed of light, nonrelativistic mechanics is an excellent approximation to a fully relativistic mechanics. One never even bothers to think about relativistic corrections when designing the moving parts of an automobile engine. The same theory of relativity that shows that the older ideas of physical reality are very wrong when applied to bodies moving at close to the speed of light also shows that they work extremely well when applied to objects which move slowly. In the same way, quantum theory shows us that our notions of pre-quantum reality are entirely inappropriate when applied to electrons moving inside atoms, but work extremely well when applied to pistons moving inside cylinders.

However, quantum mechanics also allows the use of non-quasi-classical frameworks for describing macroscopic systems. For example, the macroscopic detectors which determine the channel in which a spin-half particle emerges from a Stern-Gerlach magnet, as discussed in Secs. 17.3 and 17.4, can be described by a quasi-classical framework $\mathcal{F}$, such as (17.25), in which one or the other detector detects the particle, or by a non-quasi-classical framework $\mathcal{G}$ in which the initial state develops unitarily into a macroscopic quantum superposition (MQS) state of the detector system. Is it a defect of quantum mechanics as a fundamental theory that it allows the physicist to use either of the incompatible frameworks $\mathcal{F}$ and $\mathcal{G}$ to construct a description of this situation, given that MQS states of this sort are never observed in the laboratory?

One must keep in mind the fact mentioned in the previous section, that two incompatible quantum frameworks $\mathcal{F}$ and $\mathcal{G}$ do not represent mutually-exclusive possibilities in the sense that if the world is correctly described by $\mathcal{F}$ it cannot be correctly described by $\mathcal{G}$, and vice versa. Instead it is best to think of $\mathcal{F}$ and $\mathcal{G}$ as means by which one can describe different aspects of the quantum system, as suggested at the end of Sec. 27.3. To discuss which detector has detected the particle one must employ $\mathcal{F}$, since the concept makes no sense in $\mathcal{G}$, whereas the "MQS aspect" or "unitary time development aspect" for which $\mathcal{G}$ is appropriate makes no sense in $\mathcal{F}$. Either framework can be employed to answer those questions for which it is appropriate, but the answers given by the two frameworks cannot be combined or compared. (Also see the discussion of Schrödinger's cat in Sec. 9.6.)

If one were trying to set up an experiment to detect the MQS state, then one would want to employ the framework $\mathcal{G}$, or, rather, its extension to a framework which included the additional measuring apparatus which would be needed to determine whether the detector system was in the MQS state or in some state orthogonal to it. In fact, by using the principles of quantum theory one can argue that actual observations of MQS states are extremely difficult, even if "macroscopic" is employed somewhat loosely to include even an invisible grain of material containing a few million atoms. The process of decoherence in such situations is extremely fast, and in any case constructing some apparatus sensitive to the relative phases in a macroscopic superposition is a practical impossibility. It may be helpful to draw an analogy with the second law of thermodynamics. Whereas there is nothing in the laws of classical (or quantum) mechanics which prevents the entropy of a system from decreasing as a function of time, in practice this is never observed, and the principles of statistical mechanics provide a plausible explanation through assigning an extremely small probability to violations of the second law. In a similar way, quantum mechanics can explain why MQS states are never observed in the laboratory, even though they are very much a part of the fundamental theory, and hence also part of physical reality to the extent that quantum theory reflects that reality.

The difficulty of observing MQS states also explains why violations of the principle of unicity (see the previous section) are not seen in macroscopic systems, even though readily apparent in atoms. The breakdown of unicity is only apparent when one constructs descriptions using different incompatible frameworks, so it is never apparent if one restricts attention to a single framework. As noted earlier, classical physics works very well for a macroscopic system precisely because it is a good approximation to a quantum description based on a single quasi-classical framework. Hence even though quantum mechanics violates the principle of unicity, quantum mechanics itself provides a good explanation as to why that principle is always obeyed in classical physics, and its violation was neither observed nor even suspected before the advent of the scientific developments which led to quantum theory.

27.5 Conclusion

Quantum mechanics is clearly superior to classical mechanics for the description of microscopic phenomena, and in principle works equally well for macroscopic phenomena. Hence it is at least plausible that the mathematical and logical structure of quantum mechanics better reflect physical reality than do their classical counterparts. If this reasoning is accepted, quantum theory requires various changes in our view of physical reality relative to what was widely accepted before the quantum era, among them the following:

1. Physical objects never possess a completely precise position or momentum.

2. The fundamental dynamical laws of physics are stochastic and not deterministic, so from the present state of the world one cannot infer a unique future (or past) course of events.

3. The principle of unicity does not hold: there is not a unique exhaustive description of a physical system or a physical process. Instead, reality is such that it can be described in various alternative, incompatible ways, using descriptions which cannot be combined or compared.

All of these, and especially the third, represent radical revisions of the pre-quantum view of physical reality based upon, or at least closely allied to classical mechanics. At the same time it is worth emphasizing that there are other respects in which the development of quantum theory leaves previous ideas about physical reality unchanged, or at least very little altered. The following is not an exhaustive list, but indicates a few of the ways in which the classical and quantum viewpoints are quite similar:

1. Measurements play no fundamental role in quantum mechanics, just as they play no fundamental role in classical mechanics. In both cases, measurement apparatus and the process of measurement are described using the same basic mechanical principles which apply to all other physical objects and physical processes. Quantum measurements, when interpreted using a suitable framework, can be understood as revealing properties of a measured system before the measurement took place, in a manner which was taken for granted in classical physics. See the discussion in Chs. 17 and 18. (It may be worth adding that there is no special role for human consciousness in the quantum measurement process, again in agreement with classical physics.)

2. Quantum mechanics, like classical mechanics, is a local theory in the sense that the world can be understood without supposing that there are mysterious influences which propagate over long distances more rapidly than the speed of light. See the discussion in Chs. 23 to 25 of the EPR paradox, Bell's inequalities, and Hardy's paradox. The idea that the quantum world is permeated by superluminal influences has come about because of an inadequate understanding of quantum measurements—in particular, the assumption that wave function collapse is a physical process—or through assuming the existence of hidden variables instead of (or in addition to) the quantum Hilbert space, or by employing counterfactual arguments which do not satisfy the single-framework rule. By contrast, a consistent application of quantum principles provides a positive demonstration of the *absence* of nonlocal influences, as in the example discussed in Sec. 23.4.

3. Both quantum mechanics and classical mechanics are consistent with the notion of an *independent reality*, a real world whose properties and fundamental laws do not depend upon what human beings happen to believe, desire, or think. While this real world contains human beings, among other things, it existed long before the human race appeared on the surface of the earth, and our presence is not essential for it to continue.

The idea of an independent reality had been challenged by philosophers long before the advent of quantum mechanics. However, the difficulty of interpreting quantum theory has sometimes been interpreted as providing additional reasons for doubting that such a reality exists. In particular, the idea that measurements collapse wave functions can suggest the notion that they thereby bring reality into existence, and if a conscious observer is needed to collapse the wave function (MQS state) of a measuring apparatus, this could mean that consciousness somehow plays a fundamental role in reality. However, once measurements are understood as no more than particular examples of physical processes, and wave function collapse as nothing more than a computational tool, there is no reason to suppose that quantum theory is incompatible with an independent reality, and one is back to the situation which preceded the quantum era. To be sure, neither quantum nor classical mechanics provides watertight arguments in favor of an independent reality. In the final analysis, believing that there is a real world "out there", independent of ourselves, is a matter of faith. The point is that quantum mechanics is just as consistent with this faith as was classical mechanics. On the other hand, quantum theory indicates that the *nature* of this independent reality is in some respects quite different from what was earlier thought to be the case.