Chapter 2
Quantum Phenomena and the Double-Slit Experiment

Abstract The aim of this chapter is to introduce, in concrete physical terms, quantum phenomena, by which I, again, mean those physical phenomena in considering which Planck's constant h cannot be neglected. I shall do so by way of the double-slit experiment, a paradigmatic or, it is sometimes argued, even *the* paradigmatic quantum experiment, in which the famously strange features of quantum phenomena manifest themselves. This experiment and the way it reflects such key features of quantum phenomena as the uncertainty relations and the probabilistic nature of our quantum predictions are considered in Sections 2.1 and 2.2. Sections 2.3 and 2.4 discuss two other experiments that are closely related to the double-slit experiment: the delayed-choice experiment, due to John A. Wheeler, and the quantum eraser experiment, due to Marlan Scully and his coworkers. Section 2.5 uses the quantum eraser experiment to establish the fundamental difference between classical and quantum physics by considering the repetition of the identically prepared experiments in each domain.

2.1 The Double-Slit Experiment: From an (Almost) Classical to a Nonclassical View

This section offers a general discussion of the double-slit experiment, initially by using the concepts and language of classical physics, as far as it is possible to do so, as the "almost" of my title indicates. Certain qualifications are necessary from the outset in view of the fact that these concepts and language appear to be ultimately inapplicable to quantum objects and processes, which are responsible for the phenomena appearing in the double-slit experiment. Part of the paradigmatic importance of the double-slit experiment consists in the fact that it reveals these difficulties, to which the nonclassical epistemology of quantum phenomena and quantum mechanics responds. Indeed, "an *almost* nonclassical to a *nonclassical* view" might be a more accurate description of my discussion of the double-slit experiment here.

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One does not need quantum mechanics to explain its key features, and in this regard this chapter is properly introductory, since it does not depend either on quantum mechanics itself or on the discussion of quantum mechanics offered in the subsequent chapters of this study. This experiment can be performed with all quantum objects (even, as was shown more recently, composite ones, such as carbon 60 fullerene molecules, which are rather large relative to elementary particles), rather than only with radiation. Not until the 1960s was it actually performed as a *quantum experiment* with anything other than light. Before then, it functioned as a thought experiment, without, however, much doubt that it could in principle be performed on any type of quantum objects. This confidence was further supported by a number of other key quantum experiments, which have been performed and which exhibit the key features of quantum phenomena exhibited in the double-slit experiment. As a classical experiment, Thomas Young's double-slit experiment with light has been around since 1801, when it was performed in order to resolve the question whether the light was composed of particles (according to Newton's corpuscular theory) or was formed by waves traveling through some form of ether. The interference patterns found in the experiment appeared to have answered the question in favor of the wave theory, which became a prevalent view before Planck's discovery of his black body radiation law and related developments of quantum theory. Other elementary constituents of matter, such as electrons, eventually revealed the same dual character, conjectured by Louis de Broglie and quickly demonstrated experimentally in the 1920s. Bohr's complementarity responded to and, to begin with, posed the question of the wave vs. particle nature of light in a very different form, whereby neither concept was any longer applicable to quantum objects and their behavior.

The double-slit experiment was first performed with electrons in the 1960s by Claus Jönsson and with "one electron at a time" by Pier Giorgio Merli in 1974. In the 2002 poll conducted in *Physics World* (September 1, 2002), Jönsson's experiment was voted "the most beautiful experiment" ever performed, just edging Galileo's experiment with falling bodies. Young's original experiment made the top 10 as well: It ranked fifth, following Newton's decomposition of sunlight with a prism. It is difficult to say whether one can, or needs to, claim as much for the double-slit experiment, whether as concerns its beauty (a more subjective matter to begin with, as the *Physics World* poll acknowledges) or even as concerns its archetypal significance in quantum physics. It has a few formidable rivals that are nearly as famous and can be, and have been, used equally well for illustrating the famously strange features of quantum phenomena. One can mention, for example, the Stern–Gerlach experiment, various experiments in quantum interferometry, the beam-splitter experiment and other experiments with half-silvered mirrors, or experiments of the EPR type, which I shall discuss in Chapters 8 and 9. However, the double-slit experiment appears to remain the most famous quantum experiment and the one most frequently deployed for these purposes, although it has been nearly supplanted by the experiments of the EPR type in more recent discussions, those following Bell's theorem and related developments.

Another advantage of the double-slit experiment is that, as I said, it can be especially easily (more so than the other quantum experiments mentioned above) explained *qualitatively* without any technical knowledge of quantum theory. Properly predicting the *quantitative* data associated with the outcomes of the corresponding actually performed (or simulated) experiments would, of course, require the mathematical formalism of some quantum theory, such as quantum mechanics, which predicts such outcomes with great accuracy. Finally, the double-slit experiment also manifests especially dramatically the key probabilistic and statistical aspects of our predictions concerning quantum phenomena—in particular, the relationships between randomness and probability and hence between randomness and certain (correlational) order, which the probabilistic predictions of quantum mechanics capture.

The experiment was crucial to Bohr's thinking about quantum phenomena and quantum mechanics, and to his exchanges with Einstein, including those concerning the EPR experiment. The double-slit experiment did not figure in Bohr's Como lecture of 1927, which introduced complementarity, or in the preceding work on quantum mechanics by Heisenberg, Schrödinger, and others, on which the Como argument was based. However, the experiment became central to Bohr's exchanges with Einstein immediately thereafter (Bohr 1949, *PWNB* 2, pp. 41–42). The main reason for the persistent appeal to the experiment on Bohr's part is that it can be effectively used to test our claims concerning quantum phenomena and quantum mechanics, which properly predicts the numerical data found in the double-slit experiment and thus responds to the peculiar character of the phenomena observed. In other words, once a given argument concerning either quantum phenomena or quantum mechanics leads to a conflict with these features, this argument may be set aside as something that is in conflict with the experimental evidence. As noted above, while the double-slit experiment was not actually performed as a quantum experiment until later, other quantum experiments that had been performed could be considered as equivalent to it with respect to the key features of quantum phenomena at stake, which enabled one to use the double-slit experiment as a thought experiment in theoretical arguments.[1] In particular, any attempt to circumvent Heisenberg's uncertainty relations, $\Delta q \Delta p \cong h$, leads to this type of inconsistency with the double-slit experiment. The physical meaning or interpretation of the uncertainty relations is subtle matter, which I shall

[1] Cf. Bohr's comments on the subject in (Bohr 1935b, 698, n.). This is not unusual in dealing with thought experiments. The EPR experiment, as originally proposed by EPR, cannot be performed in a laboratory, though this has never put in question its legitimacy for the theoretical arguments concerning or based on it. Related experiments, most famously those by Alain Aspect, based on Bohm's version of the EPR experiment for spin (Aspect et al. 1982), have subsequently been performed, as were experiments statistically approximating the EPR experiment.

address in the next section. Bohr saw the uncertainty relations as experimentally given, a law of nature, and the fact that they can be derived from quantum mechanics as further testimony that the latter adequately reflects the experimental data in question. Indeed, the uncertainty relations and the data observed in the double-slit experiment are equivalent to each other, a fact used by Bohr throughout his arguments for complementarity, especially, again, in his exchanges with Einstein (e.g., Bohr 1935b, pp. 697–700; Bohr 1949, *PWNB* 2, pp. 43–47, 52–61).

The experimental arrangement defining the double-slit experiment consists of a source, such as that of a monochromatic light (which makes it possible to emit photons one by one), and, at some distance from it, a diaphragm with a single slit (A); at a sufficient distance from it a diaphragm with two slits (B and C), widely separated; and finally, at a sufficient distance from the diaphragm, a screen, a silver bromide photographic plate (Fig. 2.1).[2] Two setups are considered, in each of which a sufficient number (say, a million) of quantum objects, such as electrons or photons, emitted from a source, are allowed to pass through the slits and collide with the screen, where the traces of these collisions become recorded. It is crucial that we can only observe such traces as *effects* of the processes involving a certain type of physical objects (ultimately seen as quantum objects), the existence of which we infer on the basis of such traces. In other words, in each event we can only observe a mark, which we infer to be a trace left by a "collision" between a quantum object and the screen. Each such collision is similar in appearance to a very small object, idealized as a particle in classical physics, and in their outward appearance, both cases are similar. In this sense, such individual quantum phenomena may be associated with the particle-*like* behavior of quantum objects, which need not and in the present view does not mean that quantum objects are particles (any more than they are waves) in the sense of classical physics.

In the first setup, both slits open and we do not—or more significantly, in principle cannot—know which slit each particle passes through. In the second, we can—either in practice or, again, in principle—have such knowledge by installing devices, such as counters, which allow us to do so without appreciably disturbing the course of each individual run of the experiment (defined by an individual emission from the source). Such devices are sometimes called the "which-path" or "which-way" devices. We can also close one of the slits for each such run, which allows each object to go through one slit only. A given quantum object could of course also be blocked by the diaphragm, but these runs of the experiment are discounted. There are more or less equivalent experiments that

[2] Technically, one does not need the first diaphragm and can merely use the source itself to define the initial stage of the experiment. The arrangement described here is sometimes convenient, however, especially if one wants to relate the experiment to the uncertainty relations. Bohr uses this arrangement in most of his arguments (Bohr 1935b, p. 697; Bohr 1949, *PWNB* 2, pp. 45–46, Fig. 3, pp. 47–48, Fig. 4).

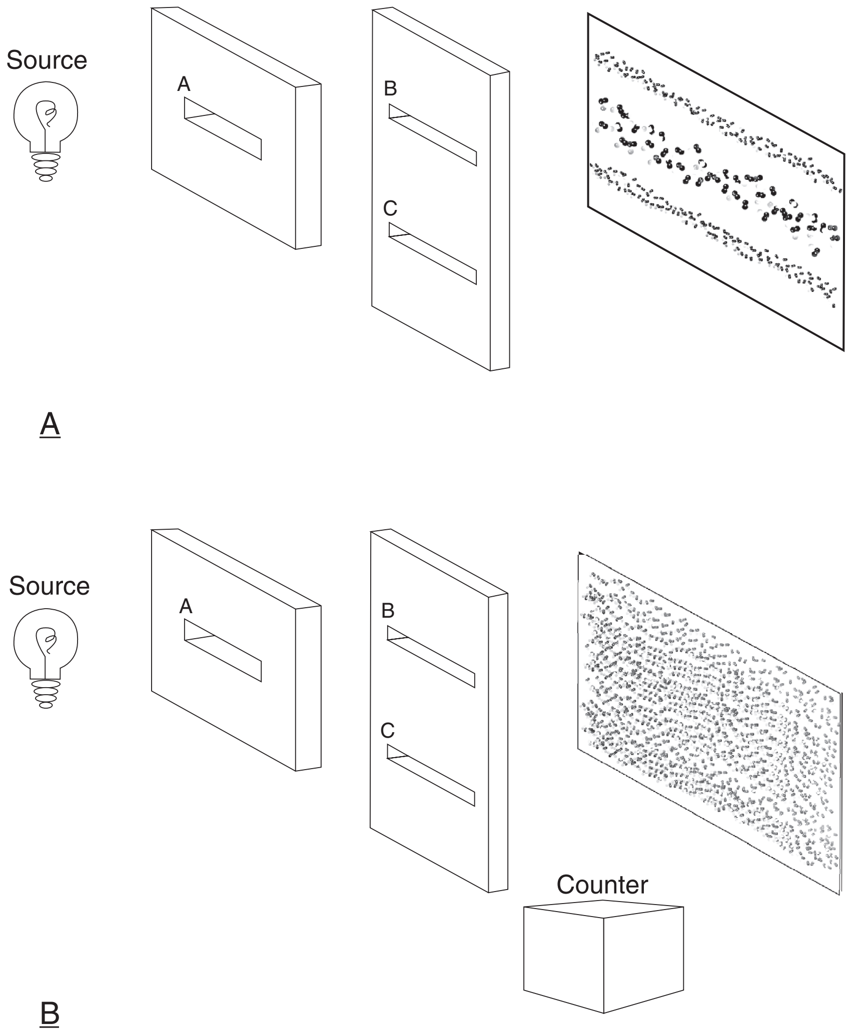

Fig. 2.1 The Double-Slit Experiment

allow us to “channel” each particle in a *more* controlled (it can never be fully controlled) way in each individual run of the experiment.

In the first setup, the traces of collisions between quantum objects and the screen will form a wave-*like* or, as it is usually called, “interference” pattern—a pattern similar (but, by virtue of its discrete individual constituents, not identical) to that produced by the traces of the wave processes in an appropriate medium (Fig. 2.1a). In principle (there could be practical limitations), the interference pattern will appear regardless of the distance between slits or the time interval between the emissions. This interval can be made sufficiently long for each emission to take place after the previously emitted object has reached the screen and been destroyed by its collision with the latter, which makes the appearance of the interference pattern especially remarkable and enigmatic. This interference pattern is the actual physical manifestation and, according to Bohr's and most interpretations, the *only* physical manifestation of quantum waves. Such wave-like effects are more pronounced and more suggestive of a physical wave propagation when we deal with very strong beams consisting of very large numbers of photons following one another in quick succession, which effects were at some point responsible for wave theories of light, culminating in Maxwell's electrodynamics. Indeed, the language of interference may not be rigorously suitable in this situation. Interference between what and what?[3] The "correlational pattern"—that is, something that refers to a correlated, ordered, rather than random, distribution of traces—appears to be a better term, and it is further justified by other correlational data characterizing quantum phenomena, such as that in the experiments of the EPR type.

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[3] Dirac contended that "each photon ... interferes only with itself. Interference between different photons never occurs" (Dirac 1958, p. 9). Dirac is correct on the second point, and he shows that making the assumption of interference between different photons "would contradict the conservation of energy" (p. 9). That interference between different photons does not occur is made clear by the fact that the interference pattern would emerge even if the interval between each emission were sufficiently large for the next photon to be emitted only after the previous photon has hit the screen and been destroyed by the collision. To assume interference between different photons under these circumstances would amount to rather radical assumptions concerning the collective behavior of photons. On the other hand, Dirac's statement that "each photon ... interferes only with itself" may not be sufficiently precise or sufficiently explained. It does, however, capture something essential about the situation. Part of the problem here is, again, the language of "interference," borrowed from classical wave physics. Dirac grounds his contention in the following point: "Some time before the discovery of quantum mechanics people realized that the connexion between light waves and photons must be of a statistical character. What they did not clearly realize, however, was that the wave function gives information about the probability of *one* photon being in a particular place and not the probable number of photons in that place" (p. 9). This is a profound statement which, apart from capturing the probabilistic nature of the wave function, suggests a Bayesian view of quantum probability adopted here, by linking the wave functions to the probabilities of *individual* events. The statement concerning each photon interfering only with itself could then be read as follows. (I am not sure whether Dirac says only this, rather than making further claims concerning the physical behavior of photons, but he appears to say at least this.) The probabilities encoded in the wave function enabling our predictions concerning where each photon will hit the screen correspond to the interference-pattern distribution of the traces left on the screen that will, inevitably, emerge in the corresponding setup. The probabilities are different in the alternative (no-interference-pattern) setup of the double-slit experiment and are differently predicted by quantum mechanics. Dirac also says that "[quantum mechanics] gets over the difficulty by making each photon go partly into each of the two components [of equal intensity]" into which a beam of light is split by a beam-splitter device (p. 9). As I shall argue below, that statement is difficult to sustain in this form, and Dirac does not appear to properly support it. While somewhat ambiguous, his overall analysis of the situation does not appear to necessarily imply that this statement is meant in a physical sense; rather, it concerns the linear superposition of quantum states defined by the wave function, which, again, deals with probabilities concerning the outcome of experiments (pp. 11–14). I shall explain these concepts below, and I shall revisit Dirac's argument in Chapter 6.

Now, in the second setup, when we install devices that allow us—either in practice or in principle—to know which slit each particle passes through (which can in principle be done without appreciably disturbing the course of each run of the experiment), the wave-like interference pattern never appears (Fig. 2.1b). Accordingly, in this setup quantum objects behave in a particle-like manner both individually *and* collectively, that is, the observed random pattern of collisions is similar to that which would appear if we conducted an analogous experiment with classical objects, idealized as particles. As I said, merely setting up the apparatus in a way that such knowledge could in principle be possible, even if not actually obtained, would suffice.

This strange behavior is sometimes referred to as the quantum measurement paradox, which is expressed by statements to the effect that, depending on how one staged the experiment, quantum objects change their "nature," or at least their behavior, from the particle-like to the wave-like one. It is worth reiterating that in each individual run of the experiment, the observed behavior or, better, phenomenon (a mark on the screen) is always particle-like; in the first setup just considered, the interference pattern only emerges out of multiple individual events (one needs about 70,000). This well-recognized fact does not prevent arguments to the effect that the unobserved, or even unobservable, behavior of individual quantum objects can be wave-like, specifically in the situation when the interference pattern or certain analogous phenomena appear. I shall address some among these arguments below, and shall only note at this point that there is no experiment that allows us to ever observe individual quantum objects as passing through both slits, and in this sense as behaving individually in the wave-like manner. The main point is that the totality of the phenomena observed in the double-slit experiment is incompatible with an explanation that classical physics (that of particle-like or wave-like classical objects) can provide. It might be added that classical physics also cannot properly predict the numerical data associated with these phenomena. Indeed, the situation appears to defy any possible explanation of how quantum objects behave in space and time, and possibly even the application of these latter concepts to this behavior. The behavior leading to the effects observed in the double-slit experiment cannot be exhibited by the same classical entities even in different circumstances; nor can we phenomenally conceive of entities that would be simultaneously particles and waves, or continuous and discontinuous, to begin with.[4] The classical objects exhibiting the different observed behaviors leading to the two incompatible kinds of observable effects are described by two rigorously different types of theories—by classical mechanics in the case of particle-like objects and by classical electrodynamics in the case of radiation. This is why

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[4] Even in Bohmian theories, where both concepts are used in describing the behavior of quantum objects, these concepts are not fused in a single entity: A wave accompanies or/and guides the particle in question, following de Broglie's idea, in turn inspired by Einstein's earlier suggestion, which was discarded by Einstein himself.

Planck's discovery that radiation can, under certain conditions, behave in the particle-like manner was such a shock.

The nonclassical epistemology of quantum phenomena and quantum mechanics responds to these difficulties, and, I argue, it does so in a logically and physically consistent way. Indeed, this epistemology owes most to Bohr's lifelong struggle, with a few defeats along the way, to develop, through complementarity, this kind of logically and physically consistent response to this "entirely new situation as regards the description of physical phenomena" (Bohr 1935b, p. 700). I would like now to use the key features of the double-slit experiment to illustrate how nonclassical thinking works in quantum physics, and reciprocally, to use this thinking to gain a better understanding of these features, and those of the delayed-choice experiment and the quantum eraser experiments, to be discussed below.

I shall begin by introducing two postulates that are motivated by these features and that are among my grounding assumptions in this study. While both of these postulates arise from and are motivated by experimental facts, they cannot in themselves be claimed to represent experimental facts. Nor, accordingly, can they be seen as physical laws, analogous, for example, to the uncertainty relations, although the experimental status of the latter is not straightforward either and requires careful consideration. However, these postulates are consistent both with the experimental data pertaining to quantum phenomena and with quantum mechanics as a physical theory accounting for these data in (probabilistically) predictive terms—and nature may not allow us to achieve more. These postulates can and here will be interpreted in nonclassical terms of suspending any possible description of quantum objects themselves and their behavior, and thus in accordance with Bohr's ultimate, nonclassical view of quantum phenomena, even though they were not expressly formulated by Bohr himself. The second postulate may be seen as related to the "quantum postulate," introduced by Bohr in the Como lecture as an interpretation of Planck's postulate concerning the discrete and, in Bohr's terms, individual character of radiation in certain circumstances. Both postulates could also be interpreted otherwise, including in ontological or realist terms, and in this sense they are more general. However, neither postulate, in whatever interpretation, would necessarily be acceptable to all physicists and philosophers working in quantum theory.

The first postulate may be called *the existence postulate* and is stated as follows:

> *Postulate 1.* There exist material physical systems, designated as "quantum objects," whose nature and behavior, as manifested in their impact upon our measuring instruments, cannot be described by means of classical physics. It is also assumed that the ultimate constituents of nature, "elementary particles," are quantum objects, although quantum objects can also be composite.

The postulate, thus, only asserts the existence of physical objects that cannot be treated by means of classical physics as concerns either the description or predictions of their nature and behavior. Accordingly, the postulate allows for a range of possible views concerning how far our theories can reach in approaching quantum objects and processes. If one adopts a nonclassical view, the postulate may be seen as *weakly* ontological, insofar as it postulates only *the existence* of quantum objects manifested in their capacity to have effects upon the world we observe, in particular in our measuring instruments. A nonclassical view does not imply or ultimately allow for any further claims concerning this existence; it deals only with what we can or cannot know concerning quantum *phenomena*, defined by the effects upon measuring instruments of the interactions between quantum objects and those instruments. In other words, there is no quantum-level *specifiable* ontology. On the other hand, the postulate allows one to ground a nonclassical interpretation of quantum phenomena and quantum mechanics in the specifiable classical and, hence, realist ontology of measuring instruments and the classical *epistemology* defined by this realist ontology—by what we *know* concerning the impact of quantum objects upon these instruments. It need not follow that classical objects are rigorously classical at the ultimate level of their constitution, since they may be—and generally (there are exceptions) are assumed to be—ultimately quantum.[5] A nonclassical view of the situation, too, would assume at the very least that measuring instruments have quantum strata, which enables their interaction with quantum objects. Only certain strata of measuring instruments may be described classically, and only in certain contexts; indeed, it appears they must be so described, since it does not appear possible for us to interact with quantum objects otherwise.

The second postulate, which may be called the *individuality* or *discreteness* postulate and which is close to Feynman's view (as well as to Bohr's), may also appear to be quantum-level ontological and is provisionally stated here in these terms for the sake of economy. However, it too need not be seen in this way, and it will be interpreted here in nonclassical terms.[6] The postulate is as follows:

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[5] Among the more intriguing alternatives is Anthony J. Leggett's argument for "macrorealism," an argument he advanced for over two decades (e.g., Leggett 1988). It can be summarized as follows: While quantum mechanics adequately describes the workings of nature at its ultimate micro-level, it may be incorrect at the macro-level. In other words, the question is whether quantum mechanics has a limited (micro)scale of application, rather than properly reflecting the constitution of all physical objects. Leggett designed clearly defined experiments for testing his proposal, although these experiments are difficult and as yet remain unperformed. This argument relates to a thorny and still unresolved problem of the transition from the quantum to the classical domain—a problem addressed with, in the present view, at most limited success by decoherence theories (e.g., Zurek 2003; Schlosshauer 2007), on which I shall comment in Chapter 10. More accurately, one should speak of the transition from the domain treated by quantum mechanics to that treated by classical physics, assuming, again, that the ultimate constitution of nature is quantum.

[6] It may be noted that, while Feynman states more unequivocally that "light behaves like particles," and not like waves, his actual interpretation is not that far from the one offered here, and his "*like* particles" already qualify his claim (Feynman 1985, p. 15).

Postulate 2. In certain specific respects, quantum objects individually behave physically *like* particles, while they never *individually* behave physically like waves or other continuously propagating (spreading) objects.

In particular, keeping in mind the qualifications indicated by my emphasis and speaking provisionally of quantum objects themselves and their behavior, in the double-slit experiment a quantum object—say, a photon—never goes through both slits, regardless of the setup. Each photon passes through one and only one slit, whether we do not or cannot know which slit it has passed through (which leads to the emergence of the interference pattern, once the experiment is repeated a sufficient number of times) or whether we have, or can in principle have, such knowledge (which precludes the emergence of the interference pattern). It is sometimes argued to the contrary that this—that is, passing through both slits and, hence, behaving in a wave-like spreading manner—is what quantum objects do in the first setup, and I shall discuss some arguments of this type and the reasons why I believe them to be problematic below.

Now, even though I state more unequivocally that photons *never* individually behave physically like waves and make only a qualified appeal to photons' particle-*like* individual behavior, both claims require further qualifications. For one thing, they amount to at least a partial assessment concerning how quantum objects behave or (as will be seen, this difference is important here) at least *do not behave* apart from measurements, which is hazardous in quantum theory. These qualifications will be presupposed whenever I use—again, for the sake of economy—ontological language, for example, stating that a quantum object passes through only one slit and never both slits. Qualifications concerning the appeal to quantum waves, as *physical* waves, are common, although the idea is not dead, even beyond the Bohmian theories, in which quantum waves are given a physical meaning, along with and alongside particles. As I have stressed, however, qualifications that must be made concerning the particle-*like* behavior of quantum objects, while less common, are no less significant. First of all, as I said, we do not appear to be able—nobody has ever accomplished this thus far—to observe, through any instrument, the independent behavior, say, motion (particle-like or wave-like), of quantum objects. We can only observe certain trace-like effects of this behavior manifested in these instruments, and we infer the existence of quantum objects from these effects. The drawings in Fig. 2.1 aim to symbolically capture this in the style of Bohr's famous drawings, mentioned in the Introduction (Bohr 1949, *PWNB* 2, pp. 48–49, 54). The instruments are schematically represented as large and heavy, while the pictures of the screen are semi-realistic in style, symbolizing what one would actually see.[7] Such traces, such as those registered in cloud chambers, can of course be seen as registering temporal classical processes and can also filmed accordingly. In any event, however, no motions of quantum objects are ever observed, only

[7] Cf. famous pictures found in Tonomura et al. (1989) and displaying, in the title of their important paper itself, a "demonstration of single-electron buildup of an interference pattern."

the irreducibly amplified traces of their interaction with a medium such as a silver bromide screen. Quantum objects themselves are usually destroyed in the process of this "irreversible amplification" of their quantum interaction with measuring instruments to the classical level (Bohr 1949, *PWNB* 2, p. 51; Bohr 1958, *PWNB* 3, p. 3). Some of these effects, such as a trace on a silver bromide screen or a click in a detector, define, in Bohr's terms, *individual* quantum events or phenomena. These phenomena are always particle-*like* in this sense of the character of the individual traces, that is, they form contained, point-*like*, individual entities, which are discrete relative to each other.[8] This is why I speak of this postulate as the *individuality* or *discreteness* postulate.

Accordingly, in the present interpretation, the statement "a photon passed through a slit" only means that a measuring device registered an event that is *analogous* to a certain classical physical event, say, that of the hitting of a screen by a small classical object that passed through an opening in some diaphragm on its way. The statement "a photon never passes through both slits" means that no event corresponding to such a statement can be observed or registered. We can never register an individual event simultaneously linked to both slits, say, by placing a detector near each slit. Only one of these detectors registers each individual event: The two detectors never click simultaneously. This fact already poses considerable difficulties for the assumption that a photon can pass through both slits, and, as will be seen, these difficulties are amplified by other factors. On the other hand, one could speak of a single photon as "passing through a slit" in the sense that the corresponding event could have been registered by a measuring device (a "which-path" measuring device), if this device were installed, but only in this sense. The very difficulty of conceiving of the independent behavior of individual quantum objects is in part due to the apparent change in their behavior depending on the measuring arrangements, such as their "propensity" to fit into collective patterns in some, but only some, arrangements, such as the interference pattern in the double-slit experiment or analogous patterns in other experiments.

In sum, either type of characterization—particle-*like* (which can be both individual and collective) and wave-*like* (which is only collective)—only relates to the behavior of quantum objects as concerns the effects of this behavior upon measuring instruments, or phenomena in Bohr's sense, since we observe nothing else. Neither concept—that of "wave" or that of "particle"—applies as a physical concept to quantum objects and their behavior themselves. The individual phenomenal *effects* in question, for example, in the double-slit experiment, may be seen as *particle-like* insofar as they are *similar* to the kind of traces classical particle-like objects colliding with the screen would leave as well. One cannot, however, automatically infer from this similarity that quantum objects are particle-like objects of the type we deal with in classical physics. Quantum

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[8] These traces are not really "points" either; they appear as discrete entities ("dots" on the screen in the double-slit experiment) only at a low resolution, and they actually comprise millions of atoms (Ulfbeck and Bohr 2001; Bohr et al. 2004).

objects certainly do not behave in the way particles do in classical physics (our primary model for the idea of particle), any more than in the way classical waves do. In particular, because of the uncertainty relations, a quantum object cannot be simultaneously assigned—as, at least ideally, in classical physics—both an exact position and an exact momentum, and hence a trajectory—the difficulty that became apparent early in the history of quantum theory.[9] In a nonclassical interpretation of the situation, we cannot ever assign even a single such property, any more than any other, to a quantum object, which view goes beyond the uncertainty relations but is obviously consistent with them. Nor can we apply to quantum objects classical physical concepts associated with these properties, such as those of motion, or even use words such as "happens" or "occurs." As both Bohr and Heisenberg argue, such words can apply only at the level of observation manifested in measuring instruments and not to what happens before an observation or between observations and hence not to quantum objects themselves (Heisenberg 1962, pp. 51–58).

Bohr, accordingly, sees the quantum mechanical situation as indicating "the ambiguity in ascribing customary physical attributes to atomic [quantum] objects" themselves or to their independent behavior, as against phenomena in his sense, something that is actually observed or registered (Bohr 1949, *PWNB* 2, p. 51). This perspective allows him to give a consistent view of the double-slit experiment and related experiments in terms of the complementary nature of the phenomena in question there ("complementarity in the narrow

[9] When elementary particles are considered in quantum theory, even when assigned a mass, they are idealized as zero-dimensional, point-like objects (or possibly one-dimensional strings). Such objects can be given a rigorous mathematical meaning but not a rigorous physical meaning. It is true that this type of point-like (mathematical) idealization of physical objects is also used in classical physics. There, however, this idealization allows one to approximate the actual behavior of the objects considered and, on the basis of this descriptive approximation, to make excellent predictions concerning this actual behavior. The physical objects themselves thus considered may be, and usually are, assumed to have extension, the property that has defined physical objects or, more generally, material bodies (*res extensa*) at least since Descartes. In the case of quantum objects, such an assumption is difficult to sustain. For example, in the case of electrons it leads to well-known contradictions with classical electrodynamics, since, if assumed to have extension, an electron would be torn apart by its negative charge. It is this circumstance that led to the idealization of the electron even before quantum mechanics. Accordingly, the nature of the point-like idealization of elementary quantum objects is different in classical and quantum physics. Quantum physics gives reasons for and logic to a still more radical idealization found in nonclassical interpretations of quantum objects, which keeps us from idealizing them or their behavior on any conceivable model—physical, mathematical, or other. Importantly, this view applies to composite quantum objects as well, including those that reach the level of macro-objects, such as the "squids," or even more interestingly, carbon 60 fullerenes, which can be observed either as classical or as quantum objects (Arndt et al. 1999). That is, we can also observe such objects, as concerns their macro-aspects and behavior, as classical macro-objects, which we cannot do with the elementary quantum objects, such as electrons and photons. On the other hand, just as in the case of these elementary constituents themselves, the constitution of such quantum macro-objects as quantum is beyond our capacity to observe and only manifest in their effects upon our measuring instruments.

sense"). He writes, "To my mind, there is no other alternative than to admit that, in this field of experience, we are dealing with individual phenomena and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena we want to study" (ibid.). The interference pattern itself only reflects the correlationally ordered distribution of the traces left by photons in the first setup, as opposed to a different distribution of such traces found in the second setup. The situation is correlative to the uncertainty relations, and both reflect the irreducible randomness of the outcome of quantum experiments. In other words, we are, again, dealing not with properties of quantum objects but with two different and mutually exclusive types of (individual) observable or registered effects upon measuring instruments of the interaction between quantum objects and those instruments under particular, rigorously specified physical conditions. By the same token, it is *not our knowledge of the behavior of quantum objects* but *our knowledge, actual or in principle possible, concerning classical physical events registered in measuring instruments* that defines the absence or the appearance of the interference pattern in the double-slit experiment. This view, I shall argue, is supported and amplified by other paradigmatic quantum experiments, such as the delayed-choice and the quantum eraser experiments, to be discussed in this chapter, or the EPR experiment, to be discussed in Chapters 8 and 9. First, however, I would like to consider the relationships among the double-slit experiment, the uncertainty relations, and the unavoidably probabilistic character of our predictions concerning the outcomes of quantum experiments.

2.2 The Double-Slit Experiment, the Uncertainty Relations, and Probability

As I said, the uncertainty relations, $\Delta q \Delta p \cong h$, reflect the insuperable limits on the simultaneous determination, either in measurement or in prediction, of both the position and the momentum (or certain other pairs of variables, such as time and energy) associated with a quantum object.[10] It is an experimental fact that both quantities can never be measured simultaneously beyond the limits of accuracy defined by h, regardless of the precision of our instruments. As I shall explain presently, the uncertainty relations would apply even in the case of ideal instruments, whose capacity far exceeds that of any instruments we could in principle have. Given that we do not have such instruments, this means the limitations expressed by the uncertainty relations are not a matter of the accuracy of our measuring instruments, which type of limitation we also encounter in classical

[10] As noted in the Introduction, technically, we measure the momentum in a given direction, and the uncertainty relations apply to this momentum and the corresponding coordinate. In the uncertainty relations for the position and the momentum associated with a quantum object in the three-dimensional space, each quantity will have three components defined by the chosen coordinate system.

physics. According to Bohr's interpretation of the uncertainty relations themselves, the two quantities not only can never be measured simultaneously they also cannot be assigned or even properly defined simultaneously. One can also put it as follows, given that, as I stressed from the outset, in physics we always deal with idealized mathematical models. Classical physics is grounded in mathematical models in which both the position and the momentum of a given object can simultaneously be assigned definite values, thus also assuring the causality of the behavior of classical objects (thus idealized). The uncertainty relations tell us that such models might no longer be possible in dealing with quantum objects, and they are strictly precluded in a nonclassical interpretation of quantum phenomena. Indeed, in the latter case, even a single such quantity (or any quantity) cannot be assigned to a quantum object, although it (but, again, never simultaneously both quantities together) can be assigned to a certain part of the measuring apparatus involved. By the same token, we can only obtain probabilistic predictions concerning *primitive* (indecomposable) individual quantum processes and events, as opposed to classical physics where, when probabilities are involved, they concern the outcomes of collective or otherwise non-simple processes and events.

The physical or experimental meaning of the formula itself is a subtle matter. Here and throughout the study, I adopt the following view, courtesy of Asher Peres, which is consistent with nonclassical epistemology:

> The only correct interpretation of [an uncertainty relation $\Delta x \Delta p \cong h$, where x is a coordinate and p the momentum in the same direction] is the following: If the *same* preparation procedure is repeated many times, and is followed either by a measurement of x, or by a measurement of p, the various results obtained for x and for p have standard deviations, Δx and Δp, whose product cannot be less than [h]. There never is any question here that a measurement of x "disturbs" the value of p and vice-versa, as sometimes claimed. These measurements are indeed incompatible, but they are performed on *different* [*quantum objects*] (all of which were identically prepared) and therefore these measurements cannot disturb each other in any way. An uncertainty relation [$\Delta x \Delta p \cong h$] [or the corresponding representation in the formalism of quantum mechanics] only reflects the intrinsic randomness of the outcomes of quantum tests. (Peres 1993, p. 93)

Not everyone would subscribe to Peres's claim that this is "the only correct interpretation" or to this interpretation itself. For my purposes in this study, it suffices that this interpretation is consistent with the experimental evidence in question. As Peres also observes, consistently with the view expressed above, "an uncertainty relation [. . .] is not a statement about the accuracy of our measuring instruments. On the contrary, its derivation assumes the existence of *perfect* instruments (the experimental errors due to common laboratory hardware are usually much larger than quantum uncertainty)" (Peres 1993, p. 93). Bohr corroborates this view in a striking sentence that also brings in the role of measuring instruments, which define *quantum phenomena*, as different from quantum *objects*. He says, "[I]n this context, we are of course not concerned with a restriction as to the accuracy of measurements, but with a limitation of the well-defined application of space–time concepts and dynamical conservation laws, entailed by the necessary distinction between measuring instruments and atomic objects" (Bohr 1958, *PWNB* 3, p. 5, also Bohr 1937, *PWNB* 4, p. 86; Bohr 1954, *PWNB* 2, pp. 72–73).

This situation (and accordingly the uncertainty relations themselves) is properly reflected in the mathematical formalism of quantum mechanics, and for Bohr is reciprocally a physical interpretation of both. As Heisenberg explains in his uncertainty relations paper

> One can . . . say that associated with every quantum-theoretical quantity or matrix is a number which gives its "value" within a certain definite statistical error. The statistical error depends on the coordinate system. For every quantum-theoretical quantity there exists a coordinate system in which the statistical error for this quantity is zero. Therefore a definite experiment can never give exact information on all quantum-theoretical quantities. Rather, it divides physical quantities into "known" and "unknown" (or more or less accurately known quantities) in a way characteristic of the experiment in question. The results of two experiments can be derived exactly one from the other only then when the two experiments divide the physical quantities in the same way into "known" and "unknown".... When two experiments use different divisions into "known" and "unknown," then their results can be related only statistically. (Heisenberg 1927, p. 70)

It may be noted, however, that—their physical, philosophical, and historical significance notwithstanding—the uncertainty relations are, to some degree, a remnant of classical physics. Feynman argues as follows: "I would like to put the uncertainty principle in its historical place: When the revolutionary ideas of quantum physics were first coming out, people still tried to understand them in terms of old-fashioned ideas (such as, light goes in straight lines). But at a certain point the old-fashioned ideas would begin to fail, so a warning was developed that said, in effect, 'Your old-fashioned ideas are no damn good when . . .' If you get rid of all the old-fashioned ideas and instead use the ideas that I'm expounding in these lectures—adding *arrows* for all the ways an event can happen—there is no need for an uncertainty principle!" (Feynman 1985, pp. 55, n. 3). This procedure amounts to estimating probabilities of the outcomes of certain experiments via the so-called "amplitudes," which I shall explain below. The situation may be more complex than Feynman makes apparent, but the statement conveys an important point, and perhaps nothing reflects it more strongly than the impossibility of ever assigning, as sharply defined, both quantities involved to the same quantum object.

As Feynman also notes on the same occasion and explains in detail elsewhere (Feynman et al. 1977, vol. 3, pp. 1–11), the situation is equivalent to the one that is obtained in the double-slit experiment. For the emergence of the interference pattern may be properly correlated with the possibility of the (ideally) precise *momentum* measurement for each quantum object involved in the corresponding setup, while the lack of the interference pattern is properly correlated with the possibility of the (ideally) precise *position* measurement for each quantum object in the alternative setup. However, the two outcomes are mutually exclusive or complementary, and both quantities cannot be measured at once—although one must be careful in applying Bohr's concepts to collective, rather than individual, phenomena. As I noted above, the same type of argumentation is used by Bohr throughout his exchanges with Einstein in order to counterargue Einstein's criticism of quantum mechanics (e.g., Bohr 1935b, pp. 697–700; Bohr 1949, *PWNB* 2, pp. 43–47, 52–61). By the same token, the situation is equivalent to the probabilistic and (statistically) correlational nature of our quantum predictions, with correlations manifested in the interference-pattern setup of the double-slit experiment—although that pattern and, hence, the corresponding correlational order, are, again, formed by an accumulation of *random* individual events. The "history" of any single event as such can never be certain, and no single run of the experiment is ever guaranteed to be repeatable. A single event registered by a counter cannot be used to establish unconditionally that an object passed through a slit, any more than can any given trace on the screen. As I said, these circumstances reflect one of the greatest mysteries of quantum phenomena, perhaps their greatest ultimate mystery: How events that are irreducibly random can, under certain circumstances, give rise to order, even if only a correlational order. Thus, the double-slit experiment and the uncertainty relations both, and correlatively, reflect the probabilistic and correlational order found in quantum phenomena, and hence the enigmatic relationships between chance and probability in quantum physics.

To further illustrate this aspect of the quantum situation, I would like to use, following Anthony J. Leggett, an experiment taken from the field of quantum interferometry, which, while different physically, is epistemologically equivalent to the double-slit experiment (Leggett 1988). Using this experiment also illustrates the pervasiveness of the features found in the double-slit experiment elsewhere in quantum experiments, in a certain sense in all quantum experiments. In this experiment, we consider the initial state A, two possible intermediate states B and C, and then a final state E, parallel, respectively, to a particle passing through the slit in the first diaphragm, one of the slits in the second, and, finally, hitting the screen in the double-slit experiment (Fig. 2.1). I, again, provisionally speak, as Leggett does, in terms of particles, while keeping in mind the qualifications indicated earlier, which apply here as well. In contrast to the double-slit experiment, however, where some quantum objects hit the diaphragm and do not pass through the slits, each quantum object involved in this experiment always passes through one of the two possible channels. This fact allows one to take into account each individual run of the experiment, since we need not discount those objects that collide with the diaphragm in the double-slit experiment and do not pass through the slit. First, we arrange to block the path via state C, but leave the path via state B open. (Unlike in the double-slit experiment, in this case we do not install any additional devices to check directly whether the object has in fact passed through state B.) In a large number of trials (say, again, a million), we record the number of objects or, in Leggett's language, micro-systems, reaching state E. Then we repeat the same number of runs of the experiment, this time blocking the path via B and leaving the path via C open. Finally, we repeat the experiment again with the same number of runs, now with both paths open. In Leggett's words, "the striking feature of the experimentally observed results is, of course, summarized in the statement [that] . . . the number reaching *E* via 'either *B* or *C*' appears to be unequal to the sum of the numbers reaching *E* 'via *B*' or 'via *C*' " (Leggett 1988, p. 940).

The situation is, thus, equivalent to the emergence of the interference pattern when both slits are open in the double-slit experiment. In the absence of any means of establishing through which slit each particle passes or, again, could even in principle have passed, or in any situation in which the interference pattern is found, one cannot assign probabilities to the two alternative "histories" of an object passing through either B or C on its way to the screen. If we do, the above probability sum rule would not be obeyed and the conflict with the interference pattern will inevitably emerge, as Bohr, again, stressed on many occasions (Bohr 1949, *PWNB* 2, pp. 46–47; Bohr 1935b, pp. 697–700). The fact, discovered already by Planck, that the counting of probabilities is different in classical and quantum physics is, again, due to the same type of behavior of quantum systems. One can also put it as follows. In calculating the probabilities of the outcomes of such experiments, we must, as it were, take into account the possibility of an object passing through both states B and C (or through both slits in the double-slit experiment) when both are open to it. As discussed above, however, it is difficult to assume that such an event physically occurs for any single quantum object, since there have been no experiments performed so far that would allow us to make such an assumption, while any attempt to establish which slit a given object passes through will inevitably disallow an emergence of an interference pattern. Leggett concludes his analysis as follows:

> In the light of this result, it is difficult to avoid the conclusion that each microsystem in some sense *samples both* intermediate states *B* and *C*. (The only obvious alternative would be to postulate that the ensemble as a whole possesses properties in this respect that are not possessed by its individual members—a postulate which would seem to require a radical revision of assumptions we are accustomed to regard as basic.) . . .
>
> On the other hand, it is perfectly possible to set up a "measurement apparatus" to detect which of the intermediate states (*B* or *C*) any particular microsystem passed through. If we do so, then as we know we will always find a definite result, i.e., each particular microsystem is found to have passed *either B or C*; we never find both possibilities simultaneously represented. (Needless to say, under these [different] physical conditions we no longer see any interference between the two processes.) . . . (Clearly, we can read off the result of the measurement only when it has been amplified to a macroscopic level, e.g., in the form of a pointer position.) (Leggett 1988, pp. 940–941; emphasis on "samples" added)

It is worth reiterating that we find a certain statistical distribution in either case, since we always register different outcomes, manifested in the distribution of traces on the screen in either setup of the double-slit experiment. The main point for the moment, however, is that correlational patterns are found only in one type of setup, those defined by the impossibility of knowing the "path" of the object, and not in the other, in which this knowledge is possible.

This "behavior" is indeed as remarkable as Leggett finds it to be, and it is difficult to conclude otherwise. It is all the more remarkable given the fact, noted earlier, that the interval between emissions could be made large enough for the preceding quantum object to be destroyed before the next one is emitted, without affecting the probability counting or the appearance or disappearance of the interference pattern in a given setup. Other standard locutions include strange, puzzling, mysterious (and sometimes mystical), and incomprehensible, for reasons that Leggett's statement makes apparent. The first possibility, here indicated, corresponds to a more familiar question asked in the case of the double-slit experiment, given that if one speaks in terms of quantum objects themselves, in the interference picture the behavior of each appears to be "influenced" by the location of the slits. How do particles "know," individually or (which may indeed be even more disconcerting) collectively, that both slits are open and no counters are installed or, conversely, that counters are installed to check which slits particles pass through and modify their behavior accordingly? Indeed, Einstein in his first paper on photo-effect and light quanta already spoke of optical wave observations of light as referring to [statistical] time averages and not "instantaneous values" (Einstein 1905, p. 132). He apparently also approved Johannes Stark's observation, made in 1909, that light quanta statistically add together, "conspire," as it were, to lead to the interference phenomena of light, and while overly anthropomorphic, the idea of the *conspiracy* of photons is not surprising.[11] The alternative proposed by Leggett would be as remarkable as any "explanation" of the mysterious behavior of quantum objects. Attempts to conceive of this behavior in terms of physical attributes of quantum objects themselves appear to lead to unacceptable or at least highly problematic consequences. Among such consequences are logical contradictions; incompatibility with one aspect of experimental evidence or the other; a bizarre behavior of quantum objects based on difficult assumptions, such as attributing volition or personification to nature in allowing these objects individual or collective "choices," like the one proposed by Leggett; or the nonlocality of the situation, in the sense of its incompatible with relativity.[12]

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[11] The comment is reported in Mehra and Rechenberg's *The Historical Development of Quantum Theory* (*MR* 6, p. 43).

[12] Yet another possibility to explain the situation would be a retroaction in time, which is hardly less problematic, although it is not inconceivable and is entertained by some (cf. Stapp (1997) and, for counterarguments, Mermin (1998b) and Shimony and Stein (2001)). As will be seen below, a retroaction in time also follows from the assumption that a quantum object can pass through both slits in the delayed-choice experiment. It is true that the possibility of retroaction in time is a mathematical consequence of general relativity, that is, a possible solution of its equations, as was demonstrated by Gödel (Gödel 1949). There are also arguments concerning the "wormholes" in general-relativistic physics that draw this implication. As things stand now, however, very few would accept retroaction at time as physically possible, given both the logical consequences involved, such as that of potentially changing the past, and the limits of the theories involved, such as the fact that general relativity is incompatible with quantum theory (there is, again, no quantum gravity as yet).

On the other hand, one can consistently account for the situation by means of a nonclassical argumentation, such as that of Bohr, or even by means of Bohr's proto-nonclassical argument, to be discussed in Chapter 7, according to which one could still attribute one of the two complementarity quantities to a given quantum object itself at the time of measurement. Bohr's logic is grounded in the fact that these two setups and the two types of phenomena occurring in the double-slit or related experiments are always mutually exclusive. Bohr was, arguably, the first to take advantage of this fact. It allowed him to contend that the features of quantum phenomena exhibited in the double-slit experiments or other key quantum experiments need not be seen as paradoxical. As he says, "[I]t is only the circumstance that we are presented with a choice of *either* tracing the path of a particle *or* observing interference effects, which allows us to escape from the paradoxical necessity of concluding that the behavior of an electron or a photon should depend on the presence of a slit in the diaphragm through which it could be proved not to pass" (Bohr 1949, *PWNB* 2, p. 46). Our tracing of the path of any quantum object could, again, only amount to (by classical standards) incomplete and indirect information, and indeed "tracing the path" (not the best expression here) only means that we can know which slits the particle has passed through, but this information is sufficient to avoid the paradoxes in question.[13]

Quantum mechanics predicts the probabilities in question in exact correspondence with experiment. It manages to do so in the following ingenious and hitherto unprecedented way, and we might indeed be lucky that nature allows us to do so. Added ad hoc, the procedure is not derived from the rest of the quantum mechanical formalism; it is justified only by the fact that it works, spectacularly well, in getting the right experimental predictions. In calculating the probabilities for the outcome of a certain event, such as that of a photon hitting the screen (in a given area), quantum mechanics first assigns to such an event—via the wave function, or the ψ-function, as it was called by Schrödinger—what is called "probability amplitude" or just "amplitude." (I shall explain the historical reasons for this terminology in Chapter 3.) However, this ψ-function is a complex-valued function, that is to say, the application of such a function generally yields a complex, rather than real, number quantity. A complex number is a number of the form $x + yi$, where x and y are real numbers and i is the imaginary unit equal to the square root of –1. Probabilities, on the other hand, are real numbers greater than 0 and less than or equal to 1. In quantum mechanics, the probability of an event is derived via the absolute square of the amplitude (technically, via the so-called square modulus $x^2 + y^2$ of a complex quantity), written as $|\psi|^2$, which is always a positive real number. The quantum mechanical formalism allows us to adjust the wave function so as to make the final outcome of the procedure a positive real number that is less

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[13] See Busch and Shilladay (2006) for an illuminating discussion of the relationships between uncertainty relations and complementarity.

than 1, just as probabilities are. The procedure involves further technical details and complexities (the wave function is a multi-dimensional entity and in most cases considered in this study indeed an infinite-dimensional one, and we need to integrate $|\psi|^2$ to get the probability), glossed over by my summary here and to be addressed later in this study. But these complexities do not affect the main point here. It is not the wave function itself (again, generally a complex-valued function) but its square modulus that yields a probability for the outcome of the experiment we want to predict. The procedure allows us to properly assess the probabilities involved in the experiments considered here, such as those in the interference-pattern setup in the double-slit experiments, when two paths are open to a photon (again, keeping in mind the qualifications given above), or in the corresponding setup of the experiment described by Leggett for neutrons. In these cases, we do not add (as we conventionally do in classical physics or elsewhere) the probabilities for the two alternatives—probabilities that can be established on the basis of the alternative setup of the experiment. If we did, our predictions would be incorrect, which is Leggett's main point. Instead, we add the corresponding amplitudes, ψ_1 and ψ_2, then derive the probability by squaring the modulus of the sum, $|\psi_1 + \psi_2|^2$, according to the rule just described. The two "states," usually designated $|\psi_1>$ and $|\psi_2>$, are considered to be in (linear) "superposition"—the concept of "state" requiring further qualifications, to be given later, since it has complex relations to the physical state of a quantum object.[14]

That quantum mechanics works so well in predicting the outcomes of quantum experiments does not, again, mean that alternative accounts of quantum phenomena (either mathematically equivalent but perhaps less artificial, or not) are not possible, although descriptive accounts appear difficult to achieve—difficult, but again not in principle impossible. Be that as it may, the nonclassical epistemology of quantum phenomena and of quantum mechanics responds both to the conceptual difficulties of the situation and to the fact that quantum mechanics properly predicts all of its numerical aspects. It does so by suspending or even forbidding, in principle, the possibility of knowing how such or any other effects of quantum objects upon our (classical) world are possible; or, correlatively, the possibility of knowing what actually happens to quantum objects between the experiments. More radically, it precludes any knowledge or even conceptualization of quantum objects and processes. In this respect, quantum mechanics may be even more incomplete than Einstein argues—although, as will be seen, eventually he comes close to making this point with a very different evaluation of it and, again, a hope that a better theory might eventually be possible. It is not only a matter of obtaining at most partial information concerning quantum objects and their behavior—for example, knowing only the position and not the momentum of a given quantum object

[14] See again Feynman's accounts of the situation in Feynman (1951) and Feynman et al. (1977, vol. 3, pp. 1–11).

at a given point, in accordance with the uncertainty relations (if one applies them to quantum objects, rather than to measuring instruments impacted by quantum objects). There is no knowledge of any kind available—and ultimately no conceptualization (beginning with conceiving of them as quantum objects or objects in any specific form) possible—concerning quantum objects and their behavior at all. There is only knowledge, essentially predictive and probabilistic in nature, concerning the effects of quantum objects upon measuring instruments or other macro-objects in the (classical) world we observe, conceptualize, and know. Thus, nonclassical epistemology does not resolve the great enigma and mysteries of quantum physics: What are quantum objects and how do they behave? How are the observable features of quantum phenomena possible? For example, how can the irreducibly random character of individual events coexist with the correlational patterns at the collective level found in certain experimental setups? The significance of nonclassical epistemology is that it tells us that this enigma may be irresolvable: Perhaps no explanation or spatio-temporal conceptualization of the behavior of quantum objects will ever be possible.

2.3 The Delayed-Choice Experiment

Following Wheeler's and most other discussions of the delayed-choice experiment, I shall, for the sake of convenience, use photons in considering it, and I shall do the same in my discussion of the quantum eraser experiment in the next section. As in the double-slit experiment, however, other quantum objects could be used just as well. Also, whenever I use (again, for the sake of convenience and economy) ontological language in referring to the behavior of quantum objects, such as photons, rather than to the events observed in measuring instruments, my earlier qualifications concerning such use should be kept in mind.

We may, in the double-slit experiment, set up our equipment beforehand in either way—to enable or to disable the appearance of the interference pattern—by switching off or on the counters, installed between the diaphragm with the slit and the screen, in the two corresponding runs of the experiment. We can, by means of suitable devices, also establish the possibility of knowing which slit each photon passes through even before each photon reaches the diaphragm and thus guarantee the absence of the interference pattern, as we do in quantum eraser experiments. If, however, we place the detectors between the diaphragm and the screen (as in Fig. 2.1b), we can decide to switch the detectors on in each run of the experiment after the photon has passed through the slit and is on its way to the screen. Making our decision at this later point does not change the outcomes of the two respective sets of runs of the experiment, corresponding to each setup, provided that the detectors are sufficiently far from the diaphragm for us to have time to do so before the photon hits the screen. This modified setup converts the double-slit experiment into Wheeler's delayed choice experiment, defined by this *delayed* decision on our part as concerns how we set up the detectors and, thereby, determine the outcome of the experiment. The experiment becomes especially dramatic when considered on the cosmological scale, at which we can, at least in principle, perform it by using photons emitted by a quasar and an intervening galaxy, both billions of light-years away from us (Wheeler 1983, pp. 190–192).[15] Split and focused by the galaxy, the light from the quasar will, in principle, display an interference pattern on a screen that we can set up. If, however, we install—billions of years after the photons in question have passed the galaxy!—a detector that allows us to determine the "path" taken by each photon, the interference pattern will no longer appear.

It is immediately evident that the assumption—apparently made by, among others, Wheeler in his analysis of the delayed-choice experiment and countered by Postulate 2 (again, keeping in mind the above qualifications concerning it)—that a single photon ever passes through both slits poses major difficulties. The *first* is, again, that no event confirming or even justifying this assumption has been registered in any experiment thus far; the assumption is only justified (by those who make it) as referring to an event that cannot be observed. The *second* difficulty, also noted above, is that the assumption appears to lead to spatial nonlocality in the sense of the conflict with relativity, if the diaphragms are sufficiently close to each other and the slits in the second diaphragm are sufficiently far apart. Since the interference pattern would still emerge under these conditions as well, under this assumption each photon would have to spread faster than c to pass through both slits, which relativity forbids.[16] In the case of the delayed-choice experiment on the cosmological scale, the assumption entails a highly implausible event of the (wave-like) spreading of a photon across a galaxy. Finally, the *third* difficulty is the following. By switching the counters on or off after a photon passes through the slits but before it reaches the screen, we can define the *past* event in two mutually exclusive ways—as that of the photon passing through one of the slits (as a particle would) or that of the photon passing through both slits (as a wave would). The assumption would, thus, entail a radical temporal nonlocality. This is a highly undesirable and even unacceptable feature, at least in the present view and in most views of quantum mechanics or physics in general, although it is, as I said, admitted by and even argued for by some. However, this difficulty (like the two others just mentioned) is avoided by the assumption, adopted here and expressed in Postulate 2, that a photon always passes through one slit and one slit only. The only physical manifestation (such as that by means of the interference pattern in the corresponding setup of the double-slit experiment) is created by many photons *sequentially* each passing through either one or the other slit and not by physical

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[15] Wheeler actually uses the beam-splitter experiment, but it does not affect the argument given here (Wheeler 1983, p. 183).

[16] Again, I leave aside Bohmian theories, to which my argument does not apply but which are manifestly nonlocal in any event.

waves conjectured on the basis of the assumption that a single photon can pass through both slits. As I have stressed, the appearance or lack of the interference pattern is, in this view, only due to our knowledge of what did or did not happen in the past, acquired (no matter at what point!) before the photons involved in the experiments hit the screen, without, accordingly, implying any retroactive determination of actual physical events.

At the same time, no claim concerning the actual behavior of photons is made. At least, *no positive claim* is made as to what actually happens apart from measurement, since we do not know which slit each photon passed through or, to begin with, in what way it "moves" (to the degree, again, that the latter concept applies to photons). This is an important qualification. Consider, for instance, Heisenberg's elaboration in his analysis of the double-slit experiment, which might appear to allow for the possibility that an individual photon can, in principle, go through both slits in the absence of measuring devices that would allow us to determine which slit it passes through (the interference-pattern setup). This view is sometimes attributed to Heisenberg (or to Bohr), in my view incorrectly. According to Heisenberg, "Therefore the statement that any light quantum must have gone *either* through the first *or* the second [slit] [in the interference-pattern set-up] is problematic and leads to contradictions. This example shows clearly that the concept of the probability function does not allow a description of what happens between two observations. Any attempt to find such a description would lead to contradictions; this must mean that the term 'happen' is restricted to the observation" (Heisenberg 1962, p. 52). Indeed, as noted earlier, it is the very nature of quantum phenomena that "does not allow a description of what happens between two observations; this must mean that the term 'happen' is restricted to the observation." As Bohr argued throughout his writing, in part in responding to Einstein's criticism of quantum mechanics, the difficulty or impossibility of carrying our analysis beyond a certain point, encoded in the uncertainty relations, appears to be defined by nature, at least as things stand now, and does not merely reflect the limitation of quantum mechanics, as Einstein appears to have thought. At least, in Bohr's view, Einstein did not demonstrate otherwise in his arguments, such as those to be discussed in Chapters 8, 9, and 10. Accordingly, quantum mechanics responds to these experimentally defined circumstances as well as possible, and nonclassical interpretations, such as that of Bohr, give a consistent physical and epistemological account of both quantum phenomena and quantum mechanics.

Heisenberg's second sentence is clearly in accord with this view. Would not, however, his first sentence—"Therefore the statement that any light quantum must have gone *either* through the first *or* the second [slit] [in the interference-pattern set-up] is problematic and leads to contradictions"—be in conflict with Postulate 2 and the present argument? Would not this statement contradict the claim that a photon always goes through only either one slit or the other, and never through both even in the interference-pattern set-up? Not necessarily, in my view. I would not deny that one might in principle read *this sentence* in this way. However, as Heisenberg's overall argument on this occasion and his discussions of quantum mechanics elsewhere suggest, the statement could also be read, consistently with the present analysis, as reflecting that it is in principle impossible, in the interference-pattern set, to ever ascertain which of the two slits (either the first or the second) a photon went through. If such a conclusion—pertaining to each photon involved—is possible, the interference pattern will not appear. In fact, as will be discussed below, in the delayed-choice version of the quantum eraser experiment, we could, in principle, separate the multiple photons involved and the corresponding traces on the screen into two groups, so as to be able to make such a conclusion (again, even in principle) or not to be able to do so. Then, the traces left on the screen by the photons from the second group will form an interference pattern, and those from the first will not. Thus, while it appears that we can never say what *actually happens* between experiments, we can say with reasonable certainty (as much as physics allows us) that certain things *cannot happen,* if the assumption that they do lead to consequences incompatible with the established experimental data. The assumption that a photon can pass through both slits would be in conflict with the locality requirements (spatial or temporal) imposed by relativity, thus far well confirmed by experiment.

However, the assumption that a single photon can go through both slits (no matter how wide apart they are) is not uncommon, and those who hold this view are in rather distinguished company. This company includes Einstein (at least at some point of his exchanges with Bohr), possibly Dirac, Wheeler (Wheeler 1993, p. 183), and, to give an example of a popular exposition, Brian Greene in his book *The Fabric of the Cosmos* (Greene 2004, pp. 176–204). In the case of Einstein, this view served his criticism of quantum theory, and this criticism would indeed be justified were this assumption necessary. By contrast, both Wheeler and Greene embrace quantum theory and the strangeness of quantum phenomena, which they appear to see as amplified by this assumption. The assumption leads Wheeler and, following him, Greene to speak of the participatory universe, in which even the past or, at least, the actualization of the past is defined by our subsequent participation in the observation and measurement process. In Wheeler's cosmological-scale version of the delayed-choice experiment, this actualization can take place literally millions of years and, in principle, arbitrarily long after the event. That Wheeler subscribes to the idea that a photon can pass through both slits (or both paths open to it in other quantum experiments) is especially intriguing because he is among the stronger advocates of Bohr's views, which appear to be in conflict with this idea, at least in the present reading of Bohr. In any event, I do not believe that statements to the contrary ever occur in Bohr's works, while statements at least suggesting the opposite are found throughout Bohr's writings (e.g., Bohr 1949, *PWNB* 2, pp. 46–47; Bohr 1935b, pp. 697–700).

In fairness, both Wheeler and Greene do assume that the past is physically fixed in the case of such quantum events as well and that the paradox arises only because our conventional ideas concerning temporality are not applicable at the quantum level. While they might be right on this last point (and the question of time in quantum mechanics is complicated on several grounds), it does not appear to me that their conception of the past as an array of future possibilities is workable or in any event is sufficiently developed by them. Neither Wheeler nor Greene—nor, to my knowledge, others who subscribe to the assumption that a single photon can pass through two slits or analogous assumptions related in other experiments—manage to find a satisfactory way of making such assumptions work. Could one assume that each photon is a wave-like object that always goes through both slits, if differently in different circumstances? Even apart from the difficulties of explaining the particle-like aspects of the behavior of quantum objects when they are registered by detectors or in other circumstances, this, again, does not solve the problem of affecting the past by the subsequent action. For the act of switching the detectors on or off would still change the way a single photon had propagated, as a wave, through the slits. Of course, if one believes that the past could be affected by the present, then the assumption that a photon can pass through both slits may be acceptable, even though such an event can never be observed.

We can make better sense of the situation by assuming that each photon passes through one and only one slit, while establishing that at any point before or after this passage, the *possibility* of knowing which slit it passes through destroys the possibility of the appearance of the interference pattern. It should be reiterated, however, that, in the present view, one could speak of the "fact" of a photon passing through a slit only in the sense that the corresponding phenomenal event, a "click," could, in principle, be registered by a measuring device, and that this fact would, again, destroy the possibility of observing the interference pattern. In this view, the two incompatible outcomes result from the fact that each of these two cases establishes a different measurement setup, which is mutually exclusive with or complementary to the alternative setup, and hence leads to the alternative predictions concerning the outcomes of the experiment and the correspondingly different statistical distributions of the traces on the screen. No concept of the independent behavior, individual or collective, of photons themselves needs to be assumed (Bohr 1949, *PWNB* 2, pp. 63, 50–51). The same considerations would also apply to analogous events recorded in other quantum experiments. Furthermore, as the quantum eraser experiment (discussed in the next section) tells us, the situation is defined not only by what we *actually* know or do not know but by what is *in principle* possible or impossible to know concerning our interactions with quantum objects. It is the possibility or impossibility of this knowledge that defines the kind of predictions we can or cannot make in each case—for example, whether the interference pattern will or will not appear on the screen in the double-slit experiment (or its delayed-choice and quantum eraser versions).

2.4 The Quantum Eraser

At least in the present view, then, it is our *interaction* with quantum objects by means of our experimental technology (whose role is irreducible in contrast to the situation that is obtained in classical physics) that defines our knowledge concerning them or, again, more accurately, concerning the effects of this interaction upon the world that we can describe. The quantum eraser experiments, designed by Marlan Scully and coworkers, further support this argument and amplify its significance (Scully and Drühl 1982).

In the (double-slit version of the) quantum eraser experiment, before photons pass the diaphragm with the slits, they are "marked" in such a way that by examining the traces of the collisions between each photon and the screen, we can use this marking to establish which slit each photon has passed through. How this marking and erasure is accomplished is not essential here, although the originality of the idea and the ingenuity of the experimental technique used command high respect. What is crucial is that we can mark photons in this way and that if we do so, the interference pattern will not emerge, *regardless* of whether we actually examine each trace and establish which slit each photon has passed through. This is further testimony to the fact that the mere possibility of such knowledge is sufficient to prevent the appearance of the interference pattern, and it reveals a deeper meaning of this fact.

In the alternative setup of the experiment, after photons pass the diaphragm but before they reach the screen, the Scully marking is erased (this marking of each photon is what the quantum eraser *erases*) so as to prevent us from knowing, even in principle, which slit each photon passes through. Once we do so, the interference pattern appears. It is crucial that the erasure forever disables the knowledge in question (concerning the passing of each photon through one slit or the other), as against the standard version of the double-slit experiment, where counters enable this knowledge, at the inevitable cost of making it impossible to observe an interference pattern. Thus, it is, again, the possibility or impossibility of this knowledge that defines the kind of predictions we can or cannot make in each case—for example, whether an interference pattern will or will not appear on the screen.

Accordingly, while the features of the quantum eraser experiment may appear to be, and in some respects are, remarkable, they should not be unexpected. Indeed, one might say that given what we know about quantum phenomena—for example, those observed in the double-slit experiment—it would be more remarkable if these features did not appear.[17] The (erased)

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[17] The delayed-choice version of the quantum eraser experiment uses half-silvered mirrors and EPR-type entangled photon pairs (Scully and Drühl 1982; Greene 2004, pp. 182–213). This setup allows us to gain or erase the knowledge in question (which way a given photon goes) without examining and hence in any way interfering with that given photon. We do this by interfering with and examining its EPR companion photons. This examination can, in principle, take place in a delayed-choice manner, indeed with arbitrary delay—for example,

"knowledge" in question is never available to us—assuming that one can speak of "knowledge" under these conditions, beyond knowing that photons *were* marked. Knowledge here only means that unless the second ("erasing") device is installed, in principle such knowledge would have been available because a corresponding experiment could be performed so as to yield an expected result—the lack of an interference pattern. As will be seen presently, the "erasure" of the *preceding* information as relevant to our future predictions, once a new measurement is made, is a defining feature of quantum phenomena, as against those of classical physics.

By the same token, it is our interaction with quantum objects that establishes the pattern of our knowledge concerning them—or, again, concerning the effects of this interaction upon the world that we can properly describe. Whatever version (i.e., standard or delayed choice) of the quantum eraser experiment one considers, it, I argue, demonstrates precisely this fact and its significance. The Scully marking of a photon is an interaction with a photon by means of our measuring devices, an act of measurement that allows for the possibility of knowledge that is incompatible with the appearance of the interference pattern, once a sufficient number of events are registered. Erasing a Scully marking is an alternative interaction with a photon, an interaction which restructures the measuring procedure involved and, by so doing, disables the possibility of such knowledge. Thus, once the experiment is repeated a sufficient number of times, this type of interaction reestablishes the possibility of the appearance of the interference pattern.

One should indeed say *establishes,* rather than reestablishes, since in each case we deal with two sets of disconnected and mutually exclusive—complementary—setups, and hence two sets of experiments that are completely disconnected from each other.[18] We cannot perform both experiments on any single photon at the same time, or combine them in the way we can combine the measurement of position and momentum in classical physics (which is what distinguishes classical from quantum physics, in view of the role of the uncertainty relations in quantum physics). The two corresponding experiments require two different photons. This fact becomes crucial in the EPR experiment, and while it was underappreciated in EPR's and Einstein's subsequent arguments concerning the subject, it largely shapes Bohr's reply to EPR and this

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years after the actual events of the experiment have physically taken place. The immediate examination of the medium (screen) with traces of photons will not reveal any interference pattern. However, the subsequent (delayed) examination of the traces left by their companions—whose Scully markings have been erased, thus disabling our knowledge concerning which way these particular photons went (again, possibly years ago)—will show the interference pattern of the corresponding subset of the traces left on the screen. I shall not discuss this version of the experiment further. While its features may appear even more striking than those of the standard version, they are consistent with the nature of quantum phenomena as manifest in the double-slit and other experiments, and as such, they are, again, more expected than unexpected.

[18] On further connections to Bohr's complementarity, see Herzog et al. (1995).

study's analysis of the situation in Chapters 8 and 9. In the case of the quantum eraser experiment, either a photon (each of the photons involved) is marked or it is no longer marked, and the knowledge concerning which slit it has passed through is no longer available, which must lead to the interference pattern, once the experiment is repeated a sufficient number of times. The quantum eraser erases *the (previously made) markings of the photon*s *involved* and *not the outcome of the same experiment*. The erasure of markings establishes a new set of measuring arrangements and individual experiments defined by them.[19]

Nor, given that the identically prepared quantum experiments do not in general produce the same outcomes, can we repeat the experiment so as to ever guarantee that a single photon would pass through the same slit, any more than we could guarantee the repetition of any other effect found in the run of the original experiment. There is no way to ever recover the behavior—or, again, more accurately, the effect—of any given single run of the experiment with a marked photon once this marking is erased, or for that matter if we repeat the experiment with another single photon, either marked or unmarked. In this regard, the situation is the same as in the standard double-slit experiment, where each individual run of the experiment in general gives a different outcome, even though each emission is identically prepared as concerns the state of the source. The delayed-choice nature of the "unmarking" of a photon after it passes through one slit or another is analogous to switching the detectors off before a photon reaches them in the standard double-slit experiment (thereby assuring the appearance of the interference pattern) and, hence, does not change anything in this respect. The quantum eraser experiment is as irreducibly *statistical* in this respect as all quantum experiments are, beginning, again, with the double-slit experiment. Both the double-slit experiment and the quantum eraser experiment are of course also statistical insofar as they deal with the collective effects (such as the interference/correlation pattern or the lack thereof) of multiple experiments. Similar considerations apply to the delayed-choice version of the quantum eraser experiment (which uses the beam-splitter experiment), in which one encounters the alternative sets of patterns, discernible only when we know for which photons such knowledge is not available.

The quantum eraser experiment further demonstrates the key aspects of quantum phenomena apparent in all paradigmatic quantum experiments. A striking feature of the quantum eraser experiment is the defining role of the *determinate possibilities of knowledge* defined by the experiments involved rather than the *actual knowledge* already obtained, which gives a new and more radical meaning to our interactions with quantum objects.

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[19] This point also applies to the delayed-choice version of quantum eraser. As explained in note 17, in this case those photons that are marked and those that are unmarked are sorted out later, thus enabling us to "carve out" the interference in the overall pictures related to those individual runs of the experiment in which the erasure of the Scully marking took place. However, each set is defined strictly in accordance with the marking or unmarking pertaining to particular photons from the two respective different sets, which thus disconnects them.

2.5 Repetition and Erasure, Classical and Quantum

The quantum eraser experiment is particularly revealing in exposing the significance of those features of quantum phenomena and quantum mechanics that have to do with repeated experiments. These features fundamentally distinguish the way the repetition of identically prepared experiments works in quantum and classical physics, as stressed by Bohr, Heisenberg, Schrödinger, Pauli, von Neumann, and others. In recent years, the question of the difference between quantum and classical physics has been primarily considered, via quantum correlations, in the context of the EPR experiment and Bell's and related theorems, and the key experiments confirming Bell's theorem, especially those by Aspect (Aspect et al. 1982). As will be seen in Chapters 7 and 8, the question of repeated measurements, including as correlative to the statistical nature of our predictions concerning quantum phenomena, is crucial in this context as well. For the moment, however, I would like to focus on the experiments discussed in this chapter, especially the quantum eraser experiment, and on the concept of "erasure," which is defined more generally than in relation to the quantum eraser experiment, in particular as essentially linked to the concept of "repetition." The particular conjunction of the two concepts as applicable to quantum phenomena manifests and even defines the essential difference between them and the phenomena of classical physics.

According to Bohr, "[In quantum experiments, as against the classical ones] a subsequent measurement to a certain degree deprives the information given by a previous measurement *of its significance for predicting the future course of the phenomena*. Obviously, these facts not only set a limit to the *extent* of the information obtainable by measurements, but they also set a limit to the *meaning* which we may attribute to such information" (*PWNB* 1, p. 18; emphasis added). Thus, whether one deals with the same or identically prepared different objects, one might speak of how the data obtained or even potentially obtainable in one measurement is "erased" by a second measurement and thus no longer useful for the purposes of our predictions concerning the subsequent outcome of the experiment. Bohr amplifies this point in the Como lecture: "It must not be forgotten . . . that in the classical theories any succeeding observation permits a prediction of future events with ever-increasing accuracy, because it improves our knowledge of the initial state of the system. According to the quantum theory, just the impossibility of neglecting the interaction with the agency of measurement means that every observation introduces a new uncontrollable element" (Bohr 1927, *PWNB* 1, p. 68). Accordingly, we can no longer use observation and measurement in the way we do in classical physics to help our quantum predictions. As Bohr notes, Heisenberg makes the same point in his uncertainty relations paper (Heisenberg 1927, pp. 66, 72–76; also Heisenberg 1930, p. 36). This point is equally crucial to Schrödinger in his cat-paradox paper (Schrödinger 1935a, *QTM*, pp. 152, 154, 157–158).

Pauli comments on this situation in his letter to Born (of March 31, 1954). The letter refers to Bohr and essentially follows Bohr's argumentation just cited, and, not coincidentally, it deals with Einstein's argumentation of the EPR type and Born's misunderstanding of this argumentation, acknowledged by Born. Pauli first considers "the determination of the path of a planet" as an example. He says, "if one is in possession of the simple *laws* for the motion of the body (for example, Newton's law of gravitation), one is able to *calculate* the *path* (also position *and* velocity at any given time) of the body with as *high* an accuracy *as one likes* (and also to test the assumed law again at different times). Repeated measurements of the position with limited accuracy can therefore successfully replace *one* measurement of the position with high accuracy. The assumption of the relatively simple law of force like that of Newton (and not some irregular zig-zag motion or other on a small scale) then appears as an idealization which is permissible in the sense of classical mechanics." By contrast, in quantum mechanics "the repetition of positional measurement in sequence with the same accuracy . . . is of *no use at all* in predicting subsequent positional measurements. For [given the uncertainty relations] every positional measurement to [the same] accuracy at [a given] time implies the inaccuracy [defined by the uncertainty relations] at a later time, and *destroys the possibility of using all previous positional measurements within these limits of error*! (If I am not mistaken, Bohr discussed this example with me many years ago.)" (Born 2005, p. 219). Indeed, Bohr's comments cited above clearly follow this logic. By the same token, our predictions are irreducibly probabilistic, even in the case of individual events.

This situation is also reflected in the impossibility (stressed throughout this study) of repeating identically prepared experiments with the same outcome, since one experiment does not tell us exactly what will happen in the next (again, identically prepared). Suppose we track an electron in a hydrogen atom. With Schrödinger's equation and Born's rule in hand, a given measurement allows us to form certain expectations concerning the future behavior of the electron. However, if we perform a subsequent measurement, the previous measurement becomes meaningless for any future prediction: Only the last measurement performed is meaningful for these purposes. Correlatively, if we prepare an atom in a certain state in order to make such predictions (and in fact "tracking" an electron usually amounts to such a preparation), any previous preparation—either in a different state or in the same prepared state (a repeated experiment)—offers no further help in predicting the measurement outcome.

I shall return to these considerations at several key junctures of this study, especially, again, in my discussion of the EPR-type experiment in Chapter 7. It may be briefly noted here that, in this case, we can prepare a pair of quantum objects in such a way that a subsequent measurement of, say, the momentum of the one allows us to predict the momentum of the other exactly. In the case of spin measurements, we can, as quantum information theorists would have it, even "teleport" the state of the first object in the sense that the second will be in the same state in terms of the outcome of the corresponding spin measurement. However, if we prepare two "identical" pairs of objects (identical, again, as concerns the state of the measuring instruments where the two preparations take place), the outcome of the measurement on the first object of the second pair will not be identical to that on the first object of the first pair. Nor, accordingly, will be our prediction concerning the second object of the second pair, although this prediction will be exact, just as was its counterpart in the first experiment. Any new measurement redefine our predictions. This irreducible coupling of "repetition" and "difference" gives a new meaning to the idea of "repeating" an experiment.

From this perspective, the difference between classical and quantum phenomena may be seen as follows. Suppose that one performs an experiment on a classical physical object—say, as Galileo did—by dropping a stone from a certain height. One can, at least ideally, repeat the same experiment on the same object or an identical object and obtain the same outcome. Indeed, such a repetition is always, in principle, possible insofar as one retains a proper record of the experiment. In classical physics—unlike in quantum theory—the distinction between the behavior of the objects under consideration and the observed phenomena, while present, can be disregarded. This possibility of repeating identically prepared experiments is essential to the disciplinary nature of modern physics, classical or quantum. There is, however, a crucial difference: In quantum experiments, we can only repeat the statistical data obtained in a given set of experiments, since the identically prepared experiments in general lead to different outcomes. In classical physics, this possibility of repeating a given experiment can be destroyed only by literally erasing the data in question, obliterating it without a trace. As long as the data are still available, the experiment could, in principle, be reconstituted exactly on a given—and for all theoretical and practical purposes identical—object, and in practice this of course happens all the time. In the case of quantum phenomena, one encounters the *effects* accompanying this type of erasure of the preceding history in any given experiment. While the data necessary to repeat the experiment on an object, such as a photon or electron, are identical to that used in the previous experiment (since all photons or all electrons are indistinguishable from each other), it is, again, in general impossible to repeat any given experiment with the same outcome. Once a measurement is made for the purposes of a prediction, the experiment is closed and the corresponding quantum object is no longer available for these purposes: It is as good as destroyed for the purposes of any future predictions compatible with this measurement. Conversely, any subsequent measurement establishes a new field of possible predictions. Accordingly, any given measurement "erases" the information previously obtained in the sense of making it meaningless for the purposes of predictions, which are defined only by the last measurement performed. While in classical physics an analogous erasure would require a complete obliteration of the previous relevant data, in quantum physics any measurement is an erasure of the previous data as relevant to our future predictions concerning the behavior of the object in question.