# 1

# Introduction: quantum peculiarities

## 1.1 Introduction

This book is an overview and further development of the transactional interpretation of quantum mechanics (TI), first proposed by John G. Cramer (1980, 1983, 1986, 1988). First, let's consider the question: why does quantum theory need an "interpretation"? The quick answer is that quantum theory is an abstract mathematical construct that happens to yield very accurate predictions of the behavior of large collections of identically prepared microscopic systems (such as atoms). But it is just that: a piece of mathematics (together with rules for its application). The interpretational task is to understand what the mathematics signifies physically; in other words, to be able to say *what* the theory's mathematical quantities represent in physical terms, and to understand why the theory works as well as it does. Yet quantum theory has been notoriously resistant to interpretation: most "common-sense" approaches to interpreting the theory result in paradoxes and riddles. This situation has resulted in a plethora of competing interpretations, some of which actually change the theory in either small or major ways. In contrast, TI (and its new version, "possibilist TI", or PTI) does not change the basic mathematical formalism; in that sense it can be considered a "pure" interpretation.

One rather popular approach is to suggest that quantum theory is not "complete" – that is, it lacks some component(s) which, if known, would resolve the paradoxes – and that is why it presents apparently insurmountable interpretational difficulties. Some current proposed interpretations, such as Bohm's theory, are essentially proposals for "completing" quantum theory by adding elements to it which (at least at first glance) seem to resolve some of the difficulties. (That particular approach will be discussed below, along with other "mainstream" interpretations.) In contrast to that view, this book explores the possibility that quantum mechanics *is* complete and that the challenge is to develop a new way of interpreting its message, even if that approach leads to a strange and completely unfamiliar metaphysical picture. Of course, strange metaphysical pictures in connection with quantum theory are nothing new: Bryce DeWitt's full-blown "many worlds interpretation" (MWI) is a prominent example that has entered the popular culture. However, I believe that TI does a better job by accounting for more of the quantum formalism, and that it resolves other issues facing MWI.

### *1.1.1 Quantum theory is about possibility*

This work will explore the view that quantum theory is describing an unseen world of possibility which lies beneath, or beyond, our ordinary, experienced world of actuality. Such a step may, at first glance, seem far-fetched; perhaps even an act of extravagant metaphysical speculation. Yet there is a well-established body of philosophical literature supporting the view that it is meaningful and useful to talk about possible events, and even to regard them as real. For example, the pioneering work of David Lewis made a strong case for considering possible entities as real.[1] In Lewis' approach, those entities were "possible worlds": essentially different versions of our actual world of experience, varying over many (even infinite) alternative ways that "things might have been." My approach here is somewhat less extravagant:[2] I wish to view as physically real the possible quantum *events* that might be, or might have been, experienced. So, in this approach, *those possible events are real, but not actual; they exist, but not in spacetime*. The *actual* event is the one that is experienced and that can be said to exist as a component of spacetime. I thus dissent from the usual identification of "physical" with "actual": an entity can be physical without being actual. In more metaphorical language, we can think of the observable portion of reality (the actualized, spacetime-located portion) as the "tip of an iceberg," with the unobservable, unactualized, but still real, portion as the submerged part (see Figure 1.1).

Another way to understand the view presented here is in terms of Plato's original dichotomy between "appearance" and "reality." His famous allegory of the Cave proposed that we humans are like prisoners chained in a dark cave, watching and studying shadows flickering on a wall and thinking that those shadows are real objects. However, in reality (according to the allegory) the real objects are behind us, illuminated by a fire which casts their shadows on the wall upon which we gaze. The objects themselves are quite different from the appearances of their shadows (they are richer and more complex). While Plato thought of the "unseen" level of reality in terms of perfect forms, I propose that the reality giving rise to the "shadow"-objects that we see in our spacetime "cave" consists of the quantum

[1] Lewis' view is known as "modal realism" or "possibilist realism."
[2] So, for example, I will not need to defend the alleged existence of "that possible fat man in the doorway," from the "slum of possibles," a criticism of the modal realist approach by Quine ("On what there is," p. 15 in *From A Logical Point of View*, 1953).

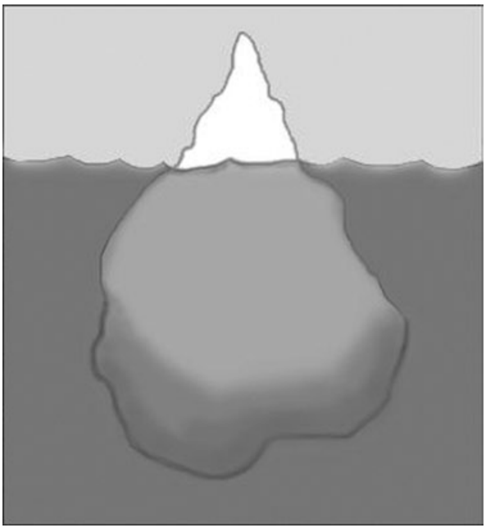

Figure 1.1 Possibilist TI: the observable world of spacetime events is the "tip of the iceberg" rooted in an unobservable manifold of possibilities transcending spacetime. These physical possibilities are what are described by quantum theory. (Drawing by Wendy Hagelgans.)

objects described by the mathematical forms of quantum theory. Because they are "too big," in a mathematical sense, to fit into spacetime (just as the objects casting the shadows are too big to fit on a wall in the cave, or the submerged portion of the iceberg cannot be seen above the water) – and thus cannot be fully "actualized" in the spacetime theater – we call them "possibilities." But they are *physically real* possibilities, in contrast to the way in which the term "possible" is usually used. Quantum possibilities are physically efficacious in that they *can* be actualized and thus can be experienced in the world of appearance (the empirical world).

This basic view will be further developed throughout the book. As a starting point, however, we need to take a broad overview of where we stand in the endeavor of interpreting the physical meaning of quantum theory. I begin with some notorious peculiarities of the theory.

## 1.2 Quantum peculiarities

### *1.2.1 Indeterminacy*

The first peculiarity I will consider, *indeterminacy*, requires that I first discuss a key term used in quantum mechanics (QM), namely "*observable*." In ordinary classical physics, which describes macroscopic objects like baseballs and planets, it is easy to discuss the standard physical properties of objects (such as their position and momentum) as if those objects always possess determinate (i.e., well-defined, unambiguous) values. For example, in classical physics one can specify a baseball's position $x$ and momentum $p$ at any given time $t$. However, for reasons that will become clearer later on, in QM we cannot assume that the objects described by the theory – such as subatomic particles – always have such properties independently of interactions with, for example, a measuring device.[3] So, rather than talk about "properties," in QM we talk about "observables" – the things we can observe about a system based on measurements of it.

Now, applying the term "observable" to quantum objects under study seems to suggest that their nature is dependent on observation, where the latter is usually understood in an anthropocentric sense, as in observation by a conscious observer. The technical philosophical term for the idea that the nature of objects depends on how (or whether) they are perceived is "antirealism." The term "realism" denotes the opposite view: that objects have whatever properties they have independent of how (or whether) they are perceived: i.e., that the real status or nature of objects does not depend on their perception.

The antirealist flavor of the term "observable" in quantum theory has led researchers of a realist persuasion – a prominent example being John S. Bell – to be highly critical of the term. Indeed, Bell rejected the term "observable," and proposed instead a realist alternative, "beable." Bell intended "beable" to denote real properties of quantum objects that are independent of whether or not they are measured (one example being Bohmian particle positions; see Section 1.3.3). The interpretation presented in this book does not make use of "beables," although it shares Bell's realist motivation: quantum theory – by virtue of its impeccable ability to make accurate predictions about the phenomena we can observe – is telling us something about reality, and it is our job to discover what that might be, no matter how strange it may seem.[4]

I will address in more detail the issue of how to understand what an "observable" is in the context of the transactional interpretation in later chapters. For now, I simply deal with the perplexing issue of indeterminacy concerning the values of observables, as in the usual account of QM.

Heisenberg's famous "uncertainty principle" (also called the "indeterminacy principle") states that, for a given quantum system, one cannot simultaneously

[3] The apparent "cut" between macroscopic (e.g., a measuring device) and microscopic (e.g., a subatomic particle) realms has been one of the central puzzles of quantum theory. We will see (in Chapter 3) that under the transactional interpretation, this problem is solved; the demarcation between quantum and classical realms need not be arbitrary (or based on a subjectivist appeal to an observing "consciousness").

[4] The realist accounts for the success of a theory in a simply way: it describes something about reality. Antirealist and pragmatic approaches such as "instrumentalism" – that theories are just instruments to predict phenomena – can provide no explanation for why the successful theory works better than a competing theory. A typical account in support of such approaches would say that the demand for an explanation for why the theory works simply need not be met. I view this as an evasion of a perfectly legitimate, indeed crucial, question.

determine physical values for pairs of incompatible observables. "Incompatible" means that the observables cannot be simultaneously measured, and that the results one obtains depend on the order in which they are measured. Elementary particle theorist Joseph Sucher has a colorful way of describing this property. He observes that there is a big difference between the following two processes: (1) opening a window and sticking your head out, and (2) sticking your head out and then opening the window.[5]

Mathematically, the *operators* (i.e., the formal objects representing observables) corresponding to incompatible observables do not commute:[6] i.e., the results of multiplying such operators together depend on their order. Concrete examples are position, whose mathematical operator is denoted X (technically, the operator is really multiplication by position *x*), and momentum, whose operator is denoted P.[7] The fact that X and P do not commute can be symbolized by the statement

$$XP \neq PX$$

Thus, quantum mechanical observables are not ordinary numbers that can be multiplied in any order with the same result; instead, you must be careful about the order in which they are multiplied.

It is important to understand that the uncertainty principle is something much stronger (and *stranger*) than the statement that we just can't physically measure, say, both position and momentum because measuring one property disturbs the other one and changes it. Rather, in a fundamental sense, the quantum object *does not have* a determinate (well-defined) value of momentum when its position is detected, and vice versa. This aspect of quantum theory is built into the very mathematical structure of the theory, which says in precise logical terms that there simply is no yes/no answer to a question about the value of a quantum object's position when you are measuring its momentum. That is, the question "Is the particle at position *x*?" generally has no yes or no answer in quantum theory in the context of a momentum measurement. This is the puzzle of quantum indeterminacy: quantum objects seem not to have precise properties independent of specific measurements which measure those specific properties.[8]

A particularly striking example of indeterminacy on the part of quantum objects is exhibited in the famous two-slit experiment (Figure 1.2). This experiment is often discussed in conjunction with the idea of "wave/particle duality," which is a

[5] Comment by Professor Joseph Sucher in a 1993 UMCP quantum mechanics course.
[6] "Commute" literally means "go back and forth"; so that the standard commuting property is expressed by noting that for two ordinary numbers $a$ and $b$, $ab = ba$.
[7] The mathematical form of P (in one spatial dimension) is given by $P = \frac{\hbar}{i}\frac{d}{dx}$.
[8] Or properties belonging to a compatible observable (whose operator commutes with the one being measured). Bohmians dissent from this characterization of the theory; this will be discussed below.

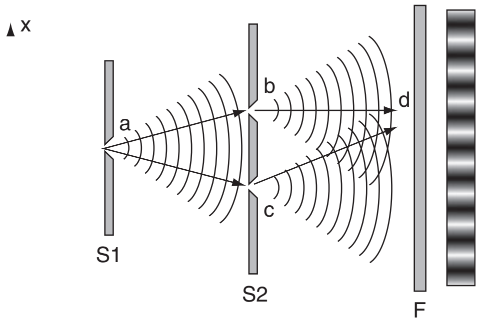


Figure 1.2 The double-slit experiment.
*Source*: http://en.wikipedia.org/wiki/File:Doubleslit.svg

manifestation of indeterminacy. (The experiment and its implications for quantum objects are discussed in the Feynman Lectures, Vol. 3, chapter 1 (Feynman *et al*., 1964); I revisit this example in more detail in Chapter 3.)

If we shine a beam of ordinary light through two narrow slits, we will see an interference pattern (see Figure 1.2). This is because light behaves (under some circumstances) like a wave, and waves exhibit interference effects. A key revelation of quantum theory is that material objects (that is, objects with non-zero rest mass, in contrast to light) also exhibit wave aspects. So one can do the two-slit experiment with quantum particles as well, such as electrons, and obtain interference. Such an experiment was first performed by Davisson and Germer in 1928, and was an important confirmation of Louis de Broglie's hypothesis that matter also possesses wavelike properties.[9]

The puzzling thing about the two-slit experiment performed with material particles is that it is hard to understand what is "interfering": our classical common sense tells us that electrons and other material particles are like tiny billiard balls that follow a clear trajectory through such an apparatus. In that picture, the electron must go through one slit or the other. But if one assumes that this is the case and calculates the expected pattern, the result will *not* be an interference pattern. Moreover, if one tries to "catch it in the act" by observing which slit the electron went through, this procedure will ruin the interference pattern. It turns out that interference is seen only when the electron is left undisturbed, so that in some sense it "goes through both slits." Note that the interference pattern can be slowly built up dot by dot, with only one particle in the apparatus at a time (see Figure 1.3). Each of those dots represents an entity that is somehow "interfering with itself" and represents a particle whose

[9] Davisson, C. J. (1928) "Are electrons waves?," *Franklin Institute Journal* **205**, 597.

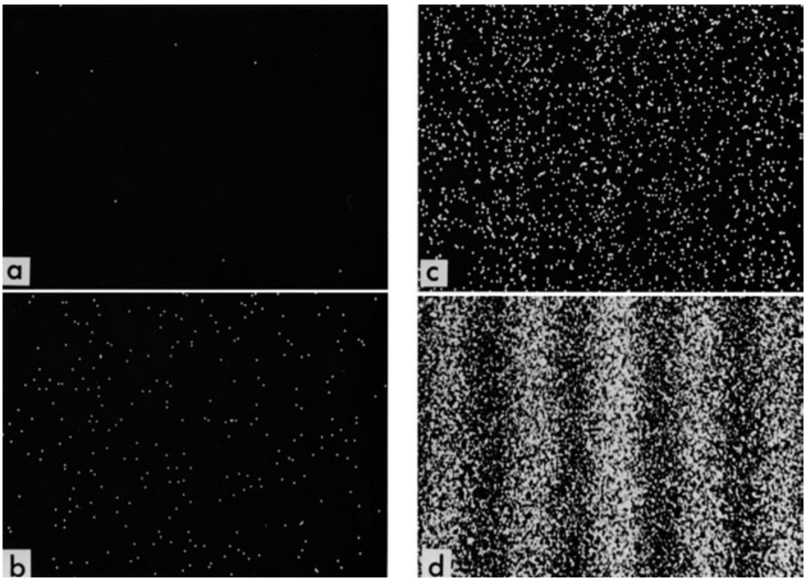


Figure 1.3 Results of a double-slit experiment performed by Dr Tonomura showing the build-up of an interference pattern of single electrons. Numbers of electrons are 11 (a), 200 (b), 6000 (c), 40 000 (d), 140 000 (e).
*Source*: Reprinted courtesy of Dr Akira Tonomura, Hitachi Ltd, Japan

position is indeterminate – it does not have a well-defined trajectory, in contrast to our classical expectations.[10]

### *1.2.2 Non-locality*

The puzzle of non-locality arises in the context of composite quantum systems: that is, systems that are composed of two or more quantum objects. The prototypical example of non-locality is the famous Einstein–Podolsky–Rosen (EPR) paradox, first presented in a 1935 paper written by these three authors (Einstein *et al.*, 1935). The paper, entitled "Can quantum-mechanical description of reality be considered complete?," attempted to demonstrate that QM could not be a complete description of reality because it failed to provide values for physical quantities that the authors assumed must exist.

Here is the EPR thought-experiment in a simplified form due to David Bohm, in terms of spin-1/2 particles such as electrons. Spin-1/2 particles have the property

[10] One of the interpretations I will discuss, the Bohmian theory, does offer an account in which particles follow determinate trajectories. The price for this is a kind of non-locality that may be difficult to reconcile with relativity, in contrast to TI.

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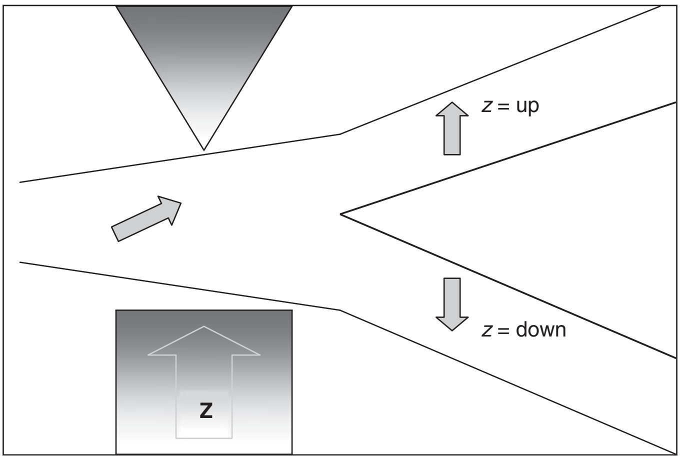


Figure 1.4 Spin "up" or "down" along the $z$ direction in a SG measurement.

that, when subject to a non-uniform magnetic field along a certain spatial direction $z$, they can either align with the field (which is termed "up" for short) or against the field (termed "down") (see Figure 1.4).

I designate the corresponding quantum states as "$|z\ \mathrm{up}\rangle$" and "$|z\ \mathrm{down}\rangle$," respectively. The notation used here is the bracket notation invented by Dirac, and the part pointing to the right is the "$|\mathrm{ket}\rangle$." We can also have a part pointing to the left, "$\langle\mathrm{brac}|$." (Since one is often working with the inner product form $\langle\mathrm{brac}|\mathrm{ket}\rangle$, the name is an apt one.) We could measure the spin and find a corresponding result of either "up" or "down" along any direction we wish, by orienting the field along a different spatial direction, say $x$. The states we could then measure would be called "$|x\ \mathrm{up}\rangle$" or "$|x\ \mathrm{down}\rangle$," and similarly for any other chosen direction.

We also need to start with a composite system of two electrons in a special type of state, called an "entangled state." This is a state of the composite system that cannot be expressed as a simple, factorizable combination (technically a "product state") of the two electrons in determinate spin states, such as "$|x\ \mathrm{up}\rangle|x\ \mathrm{down}\rangle$."

If we denote the special state by $|\mathrm{S}\rangle$, it looks like

$$|\mathrm{S}\rangle=\frac{1}{\sqrt{2}}[|\mathrm{up}\rangle|\mathrm{down}\rangle-|\mathrm{down}\rangle|\mathrm{up}\rangle] \qquad (1.1)$$

where no directions have been specified, since this state is not committed to any specific direction. That is, you could put in any direction you wish (provided you use the same "up/down – down/up" form); the state is mathematically equivalent for all directions.

Now, suppose you create this composite system at the 50-yard line of a football field and direct each of the component particles in opposite directions, say to two observers "Alice" and "Bob" in the touchdown zones at opposite ends of the field. Alice and Bob are each equipped with a measuring apparatus that can generate a local non-uniform magnetic field along any direction of their choice (as illustrated in Figure 1.4). Suppose Alice chooses to measure her electron's spin in the $z$ direction. Then quantum mechanics dictates that the spin of Bob's particle, if measured along $z$ as well, must always be found in the opposite orientation from Alice's: if Alice's electron turns out to be $|z\ \text{up}\rangle$, then Bob's electron must be $|z\ \text{down}\rangle$, and vice versa. The same holds for any direction chosen by Alice. Thus it seems as though Bob's particle must somehow "know" about the measurement performed by Alice and her result, even though it may be too far away for a light signal to reach in time to communicate the required outcome seen by Bob. This apparent transfer of information at a speed greater than the speed of light ($c = 3\times10^8$ m/s) is termed a "non-local influence," and this apparent conflict of quantum theory with the prohibition of signals faster than light is termed "non-locality."[11]

Einstein termed this phenomenon "spooky action at a distance" and used it to argue that there had to be something "incomplete" about quantum theory, since in his words, "no reasonable theory of reality should be expected to permit this."[12] However, it turns out that we are indeed stuck with quantum mechanics as our best theory of (micro)-reality despite the fact that it does, and must, permit this, as Bell's Theorem (1964) demonstrated. Bell famously showed that no theory that attributes local "elements of reality" of the kind presumed by Einstein to exist can reproduce the well-corroborated predictions of quantum theory; specifically, the strong correlations inherent in the EPR experiment. *Quantum mechanics is decisively non-local*: the components of composite systems described by certain kinds of quantum states (such as the state (1.1)) seem to be in direct, instantaneous communication with one another, regardless of how far they may be spatially separated.[13] The interpretational challenge presented by the EPR thought-experiment combined with Bell's Theorem is that a well-corroborated theory seems to show that reality *is* indeed

[11] I say "apparent conflict" here because it is a very subtle question as to what constitutes a genuine violation of, or conflict with, relativity. It is suggested in Section 6.4.2 that PTI can provide "peaceful coexistence" of QM with relativity, as envisioned by Shimony (2009).

[12] I am glossing over some subtleties here concerning Einstein's objection. A more detailed account of the EPR paper would note that Einstein's objection was in terms of "elements of reality" concerning the presumably determinate physical spin attributes of either electron and the fact that their quantum states seemed not to be able to specify these. As noted in the subsequent discussion, Bell's Theorem of 1964 showed that there can be no such "elements of reality."

[13] I should note that a small minority of researchers dissent from this characterization. A way out of the conclusion that quantum theory is necessarily non-local is to dispute the way "elements of reality" are defined. See, for example, Willem M. de Muynck's discussion at http://www.phys.tue.nl/ktn/Wim/qm4.htm!thermo_analogy. I am skeptical of this approach because it must introduce what appears to be an ad hoc further level of statistical randomness, beyond that of the standard theory, whose sole purpose is to enforce locality.

"unreasonable," in that it allows influences at apparently infinite (or at least much faster than light) speeds, despite the fact that relativity seems to say that such things are forbidden.

### *1.2.3 The measurement problem*

If indeterminacy and non-locality seem to violate common sense, one should prepare for further violations of common sense in what follows. The measurement problem is probably the most perplexing feature of quantum theory. There is a vast literature on this topic, testifying to the numerous and sustained attempts to solve this problem. Erwin Schrödinger's famous "cat" example, which I will describe below, was intended by him to be a dramatic illustration of the measurement problem (Schrödinger, 1935).

The measurement problem is related to quantum indeterminacy in the following way. Our everyday experiences of always-determinate (clearly defined, non-fuzzy) properties of objects seems inconsistent with the mathematical structure of the theory, which dictates that sometimes such properties are *not* determinate. The latter cases are expressed as superpositions of two or more clearly defined states. For example, a state of indeterminate position, let's call it "$|?\rangle$," could be represented in terms of two possible positions $x$ and $y$ by

$$|?\rangle = a|x\rangle + b|y\rangle \tag{1.2}$$

where $a$ and $b$ are two complex numbers called "amplitudes." A quantum system could undergo some preparation leaving it in this state. If we wanted to find out where the system was, we could measure its position and, according to the orthodox way of thinking about quantum theory, its state would "collapse" into either position $x$ or position $y$.[14] The idea that a system's state must "collapse" in this way upon measurement is called the "collapse postulate" (see Section 1.3.4) and is a matter of some controversy. Schrödinger's cat makes the controversy evident. I now turn to this famous thought-experiment.

Here is a brief description of the idea (with apologies to cat lovers). A cat is placed in a box containing an unstable radioactive atom which has a 50% chance of decaying (emitting a subatomic particle) within an hour. A Geiger counter, which detects such particles, is placed next to the atom. If a click is registered indicating

[14] The probability of ending up in $x$ would be $a^*a$ and in $y$ would be $b^*b$. This prescription for taking the absolute square of the amplitude of the term to get the probability of the corresponding result is called the "Born Rule" after Max Born who first proposed it. Amplitudes are therefore also referred to as "probability amplitudes." There is no way to predict which outcome will result in any individual case. TI provides a concrete, physical (as opposed to statistical or decision-theoretic) basis for the Born Rule.