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THE Quantum Divide

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CHRISTOPHER C. GERRY & KIMBERLEY M. BRUNO

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Dedication

CCG: To the memory of my parents, Clayton and Phyllis Gerry

KMB: To my parents, Paul and Mary Ann Bruno, for your unending love and support

Preface

This book is about the essential ideas of quantum physics as elucidated by a selection of key experiments, mostly, but not entirely, taken from the field of quantum optics, the study of the interaction of light and matter. The intended audience for this book is anyone with a keen interest in learning about nature of the quantum world as revealed by intriguing experiments performed over the past few years. This includes layman as well as students of physics.

In this book, we discuss a number of experiments chosen to illustrate the sharp discontinuity in the way one thinks about physical phenomena in the everyday world of the large scale and the way nature forces us to think about phenomena that occur on the scale of the very small, the scale of atoms. It isn't just that atomic-scale phenomena are very different than large scale phenomena, but that the former seem to not conform to the logic of the large-scale phenomena of everyday experience. The planet Mars is right now in a particular location on its orbit around the sun. We don't know what it is at this moment of writing, but we know can find out easily enough. Even if we don't know the position of Mars, we can nevertheless be assured that it does have a definite location in space at any given moment. On the other hand, think of the simplest of atoms: the hydrogen atom which consists of a single proton and a single electron held together by the electrical force of attraction between them. In the simplest quantum-like model of the hydrogen atom, the so-called Bohr model of 1913 that you probably encountered in your high school chemistry course, the electron orbits the more massive proton very much like the planets orbit about the sun. However, in the modern version of quantum mechanics, developed in 1925-26, an electron doesn't have such easily visualized electron orbits. In fact, it doesn't have *any* orbits at all in the ordinary sense of that word: it has only a probability distribution in the space around the proton. Furthermore, the quantum theory allows for situations where the electron could be in a special kind of state where it *superficially* seems to be on *both* sides of the atom at the same time. We hasten to emphasize that quantum mechanics *does not* actually say that an electron can be two places at once, hence the use of the proviso that quantum mechanics only superficially appears to allow the electron to be in two places at once. Such a question would never even occur in the connection with the motions of large scale objects be they planets, baseballs, or grains of pollen. Of course, we have no direct experience with the atomic world. But strange states of matter and of light can and are produced routinely in laboratories around the world. As we indicated above, it is not quite accurate to say that even a quantum particle can be in two places at once. Things are much more subtle than that. We shall also ponder the prospect that some of these very weird atomic scale quantum phenomena can actually make an appearance in the everyday world. In fact, the main title of this book, *The Quantum Divide*, references that exact problem: *where one can draw the line between the classical and quantum worlds*? One possibility is that no such divide may actually exist.

We do *not* present quantum mechanics through a historical account of the development of the subject as there are numerous books already available for that purpose. However, certain historical references are unavoidable. As an aid to the reader, we provide, as an appendix, an historical outline (timeline) that highlights the primary developments of the subject, including relevant experiments, and several books that follow the historical development can be found in the bibliography. For the most part, we do not deal with the personalities of those involved with that development and interpretation of quantum mechanics, or those who continue to elucidate the strange nature of the quantum world in the laboratory and in theoretical studies. Again, numerous books have already appeared where history and personalities have been discussed to some degree or another, though sometimes at a superficial level. Indeed, sometimes quantum physics itself is described rather superficially in these books. Our intention is to stick to the physics of the quantum world, with the expectation that the world at that level has more than enough quirky and counter-intuitive phenomena to keep the reader intellectual challenged and at the same time even entertained.

In our presentation, we do not shy away from using some aspects of the mathematical formalism of quantum mechanics, particularly for the representation of quantum states and their superpositions, and for entangled quantum states. This is done to help the reader better understand (we hope!) what quantum theory is trying to tell us about the world. No actual calculations are performed in any of our discussions.

Acknowledgments

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Contents

1

Physics Fundamentalism

A man said to the universe:
Sir, I exist!
However, replied the universe,
The fact does not create within me
a sense of obligation.

STEPHEN CRANE

1.1 Dividing Up the World

It has famously been said that there are two kinds of people in the world: those who divide the world into two kinds of people, and those who do not. But human beings have always had a preoccupation with classification. Despite our valiant efforts, divisions that we propose and categories that we form are often fluid. In science, we differentiate between the three basic natural sciences—physics, chemistry, and biology—in the sense that each must be studied in its own terms. However, we also fully realize that there is much overlap among them. Within physics, the proper category for this book, we find another kind of division, a divide which seems rather natural. First, there is the physics of the *macroscopic* world, that is, the world of everyday phenomena and of the universe on a large scale. This includes the motion of golf balls, planets, galaxies, clusters of galaxies, and so on. In this world, the laws of classical physics—the laws of Newton, Faraday, Maxwell, Einstein (his gravitational theory, we mean here), and so on—hold true. But then there is the physics of the *microscopic* world—the world of atoms, molecules, photons, quarks, and so on—which appears to be operating by a rather different set of laws. Although there are vestiges of the classical laws in quantum physics, the way we must think about the quantum world is very different than how we think about and describe mathematically the classical world.

Quantum mechanics is supposed to be a more fundamental theory than classical mechanics. Moreover, classical physics presumably emerges from quantum physics as a limiting case when certain parameters, (energy, momentum, and so on) become large. Nevertheless, there is a divide between the way the world works on the microscopic and macroscopic scales. An important question concerns the "location" of the quantum/classical divide: At what scale does quantum mechanics go over to classical mechanics in the sense that one can dispense with the strange outlook provided by the quantum theory and go on using the familiar outlook of everyday life? In addressing this question we must examine the *mesoscopic* world—the world between the two extremes where somehow the laws of both regimes should merge. At the same time, we must be sufficiently open-minded to consider the possibility that in a large context there really is no quantum/classical divide at all, that the perceived divide is an illusion. After all, it is quantum mechanics, not classical mechanics, that is generally thought to be the most fundamental theory. So perhaps the real question is not so much about the location of the quantum/classical divide rather than about whether there even is a divide.

As the reader will learn, the major difference between the classical and quantum domains is not just in the mathematical forms of the laws. In fact, we will not even explicitly write down these laws. Rather, it is the way we are forced to think about the quantum world and of what can objectively be known about it. To highlight the differences in the ways we need to think about the quantum world versus the classical world, let us consider the following example: Suppose you have a cat and you know with complete certainty that it is inside your house, but that you are outdoors so that you do not know *exactly* which room it is in. Nevertheless, being a rational person you would probably conclude that the cat is definitely *in one* of the rooms. We could call this *objective ignorance*: The cat is definitely somewhere, but we do not know where. This makes sense in the everyday, classical, world. The cat's location is *objectively definite* even if unknown. In very sharp contrast, if the cat were an object that obeyed the laws of quantum physics (which it does not, because it is macroscopic in scale) it could be the case that the cat is in the house but not in a definite location within the house. It would not be just a matter of your not knowing in which room the cat is located; rather, its location would be *objectively indefinite*. That is, it has no definite location at all. Such a shocking notion is never encountered in ordinary life. However, in the quantum world, electrons, photons, and other "microscopic" particles can, under certain conditions, have attributes that are objectively indefinite. Certainly, the idea that *anything*, cat or electron, may not have well-defined attributes is shocking when one first learns about it, and, we must admit, remains shocking even after many years of thinking about it. It is just "common sense" to posit that a cat, or any object, will be in either one place or another, and a rational person would not even think twice about it. But in the atomic world it is commonplace for objects to have objectively indefinite attributes. In such cases there is a kind of "smearing-out" of the attribute in question. For our example, the *location* of the cat could be smeared-out over the house, though we do not hesitate to say that the cat itself is *not* smeared over the house. Quantum theory does *not* predict that an object can be in two or more places at once. The false notion to the contrary often appears in the popular press,* but is due to a naïve interpretation of quantum mechanics. Nevertheless, the idea that objects can have attributes that are objectively indefinite certainly clashes with our everyday "common-sense" view of the world. And objective indefiniteness, however, is perhaps the least shocking thing about the quantum, as the reader will soon discover, but much of the rest of quantum weirdness follows from it. One thing that is worth keeping in mind as you read the following pages is that while quantum *theory* is weird, its weirdness is no more than a reflection of the weirdness of nature *itself* on the level of the atomic world. That is, experiments reveal counter-intuitive phenomena in nature that give rise to the modern quantum theory, which provides consistent explanations in the form of mathematical expressions of the laws of nature in the atomic world.

Before we enter into our subject proper, it would be useful to better understand the relationship of physics to the fundamental sciences.

* For example, the cover of the June 2005 issue of *Discover* magazine asks: "If an electron can be in two places at once, why can't you?" Well, quantum theory does not say that even an electron can be in two places at once.

1.2 Physics as Fundamental

We begin with the following pronouncement: Physics is the most fundamental of all the natural sciences. To anyone not a physicist (which means approximately everybody) such a proclamation needs justification.

According to the dictionary, physics is the science that deals with matter and energy and their interactions in the fields of mechanics, acoustics, optics, heat, electricity, magnetism, radiation, atomic structure, and nuclear and elementary particle phenomena. So, why do we think of physics as being somehow more fundamental than any of the other sciences?

Consider biology, the science of life. Fundamental to biology is deoxyribonucleic acid, commonly known as DNA, the molecule of life. DNA stores and transmits genetic information from one generation to the next. In other words, it provides all instructions for the creation and maintenance of life. Each trait of an organism is encoded in a segment of DNA called a *gene*. Each gene is constructed out of groups of other kinds of molecules called nucleotides, and nucleotides are constructed out of atoms of the elements carbon, hydrogen, oxygen, nitrogen, and phosphorous. The atoms of the various elements are more elementary than molecules. Biology may be ultimately *reduced* to chemistry—complicated chemistry, but chemistry nevertheless.

Chemistry, as we all know, is the study of how different chemical substances can combine to form new chemicals. Chemists spend a good deal of their professional lives thinking about atoms and how atoms bond together to build molecules. Therefore, underlying chemistry must be the science that describes the atoms themselves, and, as may be deduced from the dictionary definition above, this science to which we are referring is *physics*.

Although the atomic hypothesis had been proposed by John Dalton in the early 1800s, the rules governing the structure of atoms and the mechanisms of how they are able to bond together to form molecules were not worked out until the early part of the twentieth century. These rules were devised mainly by physicists applying the newly developed theory known as *quantum mechanics*. Not until there existed an understanding of the chemical bond could it be said that chemistry had a firm theoretical basis. Chemistry, in this sense, has been *reduced* to quantum physics. Of course, chemistry must be studied in its own terms, not merely as a branch of physics. Nevertheless, it must always be kept in mind that quantum physics underlies the entire discipline.

Physics, however, is not just about atoms, which are a relatively recent scientific discovery. It is fair to say that throughout most of the history of physics, atoms were hardly the center of attention. Once called natural philosophy, physics originated in the study of the motion of inanimate objects. From those studies emerged a body of knowledge, including various natural laws, that today we call "classical" physics. Newton's laws of motion, the basis of the science of mechanics, come to mind, as does his law of universal gravitation. These laws are obeyed by objects that in some sense are "large" and, in fact, the laws were discovered after careful observation of the behavior of such objects. But what do we mean by *large*? It is difficult to be precise. Perhaps the best way to delineate *large* objects from *small* objects is to operationally posit that objects obeying Newton's laws are large-scale objects. Since this seems like circular reasoning, let us explain further. Planets, obeying Newton's laws of motion and his law of universal gravitation, that are orbiting about the Sun, are clearly "large" in this sense. In fact, on a human scale they are quite large. However, a golf ball also obeys Newton's laws, as do much smaller particles such as specks of dust and grains of pollen. These objects are also thought of as "large" in this sense. Therefore, Newton's laws have a vast range of validity.

After the time of Newton, electricity and magnetism (*electromagnetism*) due to the work of Franklin, Faraday, Maxwell, and others, and *thermodynamics*, the study of heat and its transformation, which was stimulated by the development of steam engines during the industrial revolution, was systematically developed by Joule, Carnot, Clausius, and many others, and incorporated into what we now call *classical physics*. Again, this was done on the basis of observations of phenomena on a fairly large scale. For example, as demonstrated by Ben Franklin, lightning is a large-scale electrical phenomenon. So is the magnetic field that affects the needle of a compass. Thermodynamics is a theory of heat and its transfer that considers matter only in bulk and completely disregards underlying structure. It is therefore a *phenomenological* theory. A phenomenological theory is one that mathematically models phenomena without constructing a detailed microscopic picture underlying the phenomena in question. Thermodynamics does not concern itself with the details of the bulk systems that it describes. It is a powerful theory that allows us to construct useful devices such as refrigerators and internal combustion engines. The laws of electromagnetism and of thermodynamics were established during the eighteenth and nineteenth centuries.

In the late nineteenth century and into the early twentieth century, it was recognized that something working on a much smaller scale seemed to underlie electromagnetism and thermodynamics. As we now understand, electricity and magnetism depend on the fact that there exist tiny particles that carry electric charge and act as if they also carry tiny circular electric currents that generate tiny magnetic fields. Most everyday electromagnetic phenomena can be explained in terms of the motion of the charged particles that we call *electrons*. An electric current is nothing but the flow of charged particles—usually electrons—and electrical currents generate magnetic fields that surround the currents. If a conducting wire is placed in a *changing* magnetic field, or moved within a magnetic field, a current will flow within the wire. This is the basis of modern large-scale generation of electricity. But think now of a so-called "permanent magnet". There are no large-scale electrical currents flowing in the slab of iron or nickel that constitutes a permanent magnet. The origin of this magnetism is *atomic*. Specifically, electrons act as though they are spinning and carrying tiny electric currents inside them—quite a feat for particles that have no physical size whatsoever, as far as any experiment has been able to show. Nevertheless, it is ultimately the *combined* effects of many such atoms that are responsible, when they are all properly aligned, for the magnetic field of the entire permanent magnet.

Thermodynamics, it turns out, can be reduced to *statistical mechanics*—a theory developed by Maxwell, Boltzmann, Gibbs, and many others—which relates averages taken over the motions of small particles to bulk properties such as pressure, heat capacity, and so on. Heat is now fundamentally understood in terms of the average energy of motion of these small particles. The higher the temperature, the more energy the particles have.

Atoms have been found to be made up of even smaller particles—namely electrons (mentioned already), protons, and neutrons. Electrons carry the negative charge and protons the positive, while, as the name indicates, the neutron is electrically neutral. But the trend of finding structure on a smaller scale has continued. It now seems that protons and neutrons are made up of other particles—the quarks and the "gluons"—that mediate the strong nuclear force binding the quarks together. (Quarks have never been seen as "free" particles; they are thought to be permanently trapped inside protons and neutrons and other particles that interact through the strong nuclear force, although this has yet to be proved from the theory of the strong nuclear force.) At this point we have reached the level of our present understanding of the structure of matter. There has been speculation that quarks might be composed of something even more elementary, but as yet there is no compelling experimental evidence that this is so. Note that reductionism takes place at every stage: the properties of matter on one scale depend on the properties of matter on a smaller scale (and on fields through which the particles of matter interact), and so on, to the next smallest scale. It is this modern, and secular, version of the "Great Chain of Being" that informs us of the functional relationships between the small world of atoms and of the macroscopic world of everyday life.

This book mostly is about the "small" world of the atom, by which we mean not only atoms, but also electrons, photons, atomic nuclei, molecules, and even some aspects of solids. In that world, as we have said, the laws of physics turn out to be different from the laws of classical physics that we use to explain phenomena in the macroscopic world of everyday life. Although vestiges of classical physics persist, those laws just do not work in the atomic domain. Perhaps it is more accurate to say, given that quantum mechanics is the more fundamental theory, vestiges of the *quantum* disappear as we go into the classical world. Early attempts at providing a quantum theory, from 1900 to 1925, did, in fact, attempt to modify classical laws with various *ad hoc* rules. But these rules, already *ad hoc*, seemed to need *ad hoc* modification for almost every new application, and in some cases, no rules whatsoever could be found to explain observations. The quantum theory of this period, now known as the *old quantum theory*, pretty much ran out of steam by the early 1920s, and was in any case unsatisfactory due to the fact that the rules for quantization could not be determined systematically from any general principle. In 1925, new laws of the physics of the atomic world were discovered independently by Werner Heisenberg and Erwin Schrödinger. This new set of laws is collectively known as *quantum mechanics*. So, we now have two sets of laws: one set operating in the world of the *large*, the world of *classical physics*, and another operating in the world of the *small*, the world of *quantum physics*. In fact, there is a great divide between these two worlds, not only with respect to phenomena and the laws operating on the two levels, but also with respect to the way one must think about them. Classical intuition and the "common sense" of everyday life do not apply in the quantum world. Perhaps the most startling difference between these two worlds is with respect to the issue of causality—the principle that events are always preceded by their causes. In the classical world, when something happens it happens for a reason. But in the quantum world events can occur without any reason. The theory gives us only statistical predictions, i.e. the probabilities for events to occur, but gives us no deeper picture with regard to causes. The statistical predictions of quantum mechanics are inherent. There is nothing quite like this in classical physics.

Our goal in this book is to demonstrate and elaborate upon the failure of classical intuition through a discussion of a number of mostly recent experiments on quantum mechanical foundations, most of them involving light at the level of a few photons—sometimes only one. The relevant area of research is known as *quantum optics*—the study of the nature of light and its interaction with matter. This is an important area of contemporary physics research, not only for its intrinsic interest in elucidating the nature of light and its interactions with matter, but because of its potential applications to the emerging field known as *quantum information processing*. This field includes quantum computing and quantum cryptography (otherwise known as quantum key distribution)—issues that we touch upon in the later chapters. Among many things, we shall address the question as to whether or not there is any possibility that quantum phenomena can, on occasion, cross over the divide into the world of the large, even if only briefly.

The quantum world differs in several ways from the picture we have of the classical world. One significant difference has to do with the role of measurement. In the latter case, if we measure, say, the position of a planet or of a baseball, the measurement itself is not suspected of having any effect on the future motions of such objects. We assume further that when we measure the position of a baseball, one that is just sitting on the field, to make it simple, that the measurement merely reveals the position it had just before the measurement. However, as we shall see, in the quantum world measurements generally do not reveal pre-existing information about quantum systems, and because of this they can be used to steer quantum systems into useful states for practical applications.

We cannot experience the quantum world directly through the senses. However, carefully controlled experiments have shown that the quantum world holds more surprises than the famous rabbit-hole of Alice in Wonderland. It turns out that in the quantum domain, the experimenter *can*, in very subtle and very limited ways, influence the *kinds* of results that can be obtained from a complete experiment. By making certain kinds of choices in experimental design, nature can be forced to behave in certain mutually exclusive ways. Other choices force a different kind of behavior, a complementary behavior, with qualitatively different *kinds* of results. In general, the results of any given run of an experiment cannot be predicted, as the quantum world is not deterministic and many of the predictions of the theory are statistical, as we shall explain in the pages that follow. Unfortunately, this aspect of quantum mechanics has led to all kinds of distortion and hyperbole in the popular press, some of which we address in the final chapter. In the balance of the book we intend our presentation to be as sober as possible and to let the facts stand for themselves. Quantum phenomena are strange enough on account of their contradictions with common sense without any need for hyperbole. You, the reader, will find in the course of this book that "common sense" (highly overrated in science anyway) may be almost entirely (but not totally!) tossed to the wind when it comes to quantum phenomena. That is what makes the quantum world so fascinating.

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2

The Duality of Particles and Waves: The Split Personality of Electrons

2.1 The Macroworld versus the Microworld

How often have I said to you that when you
have eliminated the impossible, whatever remains,
however improbable, must be the truth?

ARTHUR CONAN DOYLE, *Sherlock Holmes: The Sign of Four*

We hope you have been convinced by the discussion of the previous chapter that physics is *the* fundamental science. If so, you might expect that the foundations of physics are rock solid. Well, they are and they are not. Large-scale phenomena are well described by the classical laws of physics, mostly established by the beginning of the twentieth century, as we discussed in Chapter 1. But by the early 1900s it was realized that these laws *do not* seem to work very well when applied on the atomic scale. In 1911 Ernest Rutherford discovered the atomic nucleus, wherein resides most of the mass of an atom and all of its positive charge. He found that the nucleus contains the all protons (the positive charge in an atom) and the neutrons (chargeless particles), but takes up only a very small volume of the atom. He did this by bombarding a gold foil with alpha particles (now known to be the helium nucleus—two protons and two neutrons), and noticed that occasionally the alpha particles scattered straight backwards—a feat not possible if the positive and negative charge of the atom were distributed uniformly throughout, as was thought to be the case at the time. But if the positive charge of the atom were concentrated in a massive nucleus, the occasional backscattering of the alpha particles could be explained as being the result of near head-on collisions of alpha particles with a nucleus. Furthermore, knowledge of the energies of the alpha particles allowed for the determination of the closest approach of the particles to the nucleus, which in turn gave an