CHAPTER 1

From Classical Physics to Quantum Physics: A Still Aborning Paradigm Shift

Classical physics is the physics that Isaac Newton built some 350 years ago. It gave us the idea that objects of the world follow a mathematical prescription independent of us, the subjects; indeed, the entire reality is independent of us and is objective. Classical physics has also given us a view of the world that is mechanistic, deterministic, and materialistic.

The idea of a ***mechanistic*** world is that the world is machine-like, its changes and movements are continuous, describable by algorithms, step-by-step mathematical procedures. The philosophy of ***determinism*** holds that every movement of every object in the world can be determined from the laws of physics, once we know some of their initial conditions. Finally, materialism is the idea that the world consists of matter and its correlates, energy and force fields, and is reducible to basic building blocks, the elementary particles, and their interactions. In materialist philosophy, formally called ***material realism***, all causality in the world comes from elementary particles and their interactions, which are the ground of all being. Elementary particles make atoms, atoms make molecules, molecules make cells (including neurons), neurons make the brain. The brain makes us, but underneath we are the play of the elementary particles, the product of the ***upward causation*** due to their interactions.

This view of ourselves is conceptually very bleak because if we lack causal efficacy it is hard to ascribe any meaning to our endeavors that include science. Some scientists unabashedly resign themselves to this meaninglessness of the universe. "The more the universe seems comprehensible, the more it seems pointless," says the Nobel laureate physicist Steven Weinberg. Others look for a way out of this conceptual dark alley.

Quantum physics, sometimes called the new physics (in contrast to the "old" classical physics), began with the idea of the quantum–a discontinuously discrete quantity. As such, quantum physics insists that movements of the world are not only continuous but also discontinuous. What this means is that not all movement has causal continuity, causal explanation in terms of upward causation. Quantum physics is revolutionizing our worldview by opening a window–the window of discontinuous movement–through which the light of consciousness is entering physics and illuminating all of its conceptual darkness. This book is about this quantum revolution.

Anomalous Data

Classical physics deals with the movement of macroscopic bodies, bodies of large mass and bulk around us. Toward the end of the 19th century, physicists began investigations into the world of the submicroscopic constituents of macrobodies. And almost immediately, anomalous data were revealed that violate one or more of the fundamental principles of classical physics. At the turn of the 19th century, the physicist Lord Kelvin was supposedly asked about the future of physics, to which Kelvin gave the famous reply that physics is a finished product except for a couple of little things that would soon find explanation. One of these little things was the anomalous data regarding how radiation is emitted from incandescent bodies, the eventual explanation of which led to the idea of the quantum, to the overthrow of the classical principle of continuity, and to the development of quantum physics (see Chapter 3).

Another anomaly that showed up is radioactivity: certain chemicals spontaneously emit radiation. The law of this emission is probabilistic, not deterministic. We cannot predict when a particular emission will take place, but only the probability of that emission. Thus the classical physics idea of strict determinism is violated.

In the 20th century, physicists gained the technology for investigating the heart of matter, atoms, and even their constituents, the elementary particles. Investigations revealed further anomaly; in truth, classical physics was found to be unable to explain even the simple fact of atomic stability–why the atoms around us that make up the bodies of our macroworld are stable. You know the basic picture of the atom: light elementary particles called electrons orbit the relatively heavy central core called the nucleus of the atom. But according to classical physics, orbiting electrons must lose energy via the emission of electromagnetic radiation. Thus, their orbits must shrink and eventually the electrons must fall into the nucleus. In this way the atom of classical physics is unstable, contradicting our experience.

Classical physics cannot explain an important order established in chemistry. There is an orderly arrangement of the chemical elements, called the periodic table, which was discovered by the chemist Dimitry Mendeleev. But no explanation of this kind of regularity can be given using Newton's laws of motion. It is not at all clear why such regularity should exist.

The list here is not complete. What became clear at the tail end of the 19th and in the beginning of the 20th century is that the complacency and certainty of classical physicists regarding the success of their physics (as voiced by the legendary statement by Lord Kelvin) came from incomplete knowledge. So long as we keep to the study of macrobodies, classical physics seems to work well. But this old physics does not work at all in the submicroscopic world, the investigation of which would become one of the specialties of the 20th century.

What Is Quantum Physics?

What, again, is quantum physics? We will develop a fuller answer later, but for now, suffice it to say a few things to reveal the revolutionary nature of quantum physics. Etymology will not be of much help here. The word ***quantum*** originates from a Latin word meaning quantity. The word was first used to signify a discrete quantity of energy, angular momentum, and other such physical quantities. So, in finer examination of the law of emission of radiation from radiant bodies, energy is found to be exchanged in discrete lumps, the energy quanta; energy is not indefinitely continuous, it cannot be broken down to arbitrarily small amounts. So at the base level of things, in the submicroscopic world, matter clearly exist as discrete bundles of energy, charge, angular momentum, and so forth; these are the elementary particles. From this beginning came the huge ideas of atomic, nuclear, solid state, and elementary particle physics that gave us lasers, atomic bombs, transistors, giant atom-smashing accelerating machines, and more. It gave us a new way of looking at reality.

One thing before you delve into the submicroscopic world. Recently, several books have come out with titles like *Alice in Quantumland* with the idea that the land of quantum physics is like the wonderland that Alice explored. Remember Alice's tree? Classical physics explores things above ground, where the tree is, where we can see the results of our measurement. Even the measurement of the submicroscopic roots of the macroworld requires the amplification of macro apparatuses, seemingly bound by the rules of classical physics. We never see the submicroscopic world directly, you know. How should we explore the roots, then, since empirical investigation is limited? We have to trust our theories and the philosophies we use to interpret our theories. Most of all, we, and you, too, dear reader, have to go down the "rabbit's hole" of imagination to where the roots are. Then, and then only, we will get to the juicy part of quantum physics.

The Submicroscopic World

In classical physics, we do have the concepts of atoms and molecules, and even that of elementary particles such as electrons, and these concepts have greatly helped in developing a successful reductionist picture of thermal physics and the physics of electricity and magnetism, for example (as you have amply seen in Volume I of this book). With new breakthroughs in experimental technology in the 20th century when it was possible to delve deeply into the heart of matter, we began to be more acquainted with our postulated objects—molecules, atoms, and elementary particles. And there came many surprises.

The first surprise was, as mentioned already, that some of the ideas of classical physics do not work in this new realm of physics and new ideas have to be introduced. Above

I mentioned the breakdown of the principle of continuity in the exchange of energy in the phenomenon of radiation from incandescent bodies, and the introduction of the energy quanta—discrete bits of energy—but that is just the tip of the iceberg. When the idea of discreteness and quanta was introduced in our theories of the atom, the problem of emission of light from atoms became tractable—so much so that we have managed to manipulate it to make the emission in special cases very special, laser light for example (see Chapter 9). The discrete nomenclature of the states of the atom solved the anomalous problem of the periodic table in chemistry as well (see Chapter 10).

A second surprise. The movement of quanta was found to be shrouded by a cloud of uncertainty, which gave rise to some strange phenomena. Electrons and other subatomic particles are able to jump over hurdles, even though they don't have enough energy to jump. They can borrow some energy, taking advantage of the uncertainty in maintaining nature's energy ledger. This barrier penetration ability of the electrons, when suitably manipulated, gave us the new and wonderful technology of the transistors, beginning the solid state revolution that includes our precious computers (see Chapter 13).

Uncertainty breeds probability. This probabilistic behavior explained the anomaly of radioactivity—radioactive decay is probabilistic. Radioactivity involves the core of atoms—atomic nuclei. How do parts of the nucleus escape the bondage of the rest spontaneously? Barrier penetration, again, is the answer (see Chapter 11).

A third surprise. A novel change took place in how we look at forces and force fields between elementary particles. The idea was developed that the force fields themselves consist of quanta, and a force happens when these quanta are exchanged between two bodies. This way of looking at force fields began a program of unification of physics via a unified way of looking at all the fundamental forces between material objects that nobody could have guessed except Einstein (although in a different context). This program defines the heart of today's research in elementary particle physics (see Chapter 12).

The Radicalness of Quantum Physics

But all these surprises seem to be esoteric, only appreciated in the context of physics and its problems. The idea of quanta alone does not seem to be *that* radical conceptually, at least to the nonspecialist. You don't see yet why this idea forces you to abandon your very way of thinking about the world.

Let me try to give you a quick introduction to the radicalness of quantum physics in a few paragraphs. You know that physical laws of motion enable us to solve the fundamental question of movement of an object: Where is the object when? Classical physics is deterministic because it exactly tells us where an object is when. But quantum physics equivocates. It gives us probabilities that an object should appear in some possible places, but says nothing more definite. So at first people thought that quantum physics was probabilistic, and it applied only to large ensembles of objects, not to the objects themselves. It was a little disappointing, but certainly one could make do. In atomic and subatomic physics, where quantum laws are necessary in order to explain the anomalous data referred to above, we almost always have large ensembles of objects. You remember that a spoonful of a substance has some 10^{23} atoms in it.

But detailed analysis of experimental data revealed the possibility of revolutionary radicalness—the quantum laws do apply to individual objects. The motion of every quantum object must be depicted as a wave of possibility, a superposition of many possible actualities. Gone is the unique-actuality depiction of Newtonian physics. An electron is a possibility object with calculable probabilities to manifest in this, that, and the other place at this time. This is what the laws of quantum physics enable us to figure out: the possibilities and the probabilities associated with each possibility.

Now the radicalness. When we do experiments with quantum objects, we do not find the objects smeared out in all those possible places of quantum prediction, but instead quite actualized in only one of its possible places, much like Newtonian objects. To be sure, if we do many experiments, the object shows up actualized in all of its possible places with probabilities that agree with quantum calculations. But quantum mathematics cannot predict the outcome of a single measurement event. So how do we connect quantum theory with experiment? A postulate—called the measurement postulate—is necessary as part and parcel of quantum physics. Our observation collapses the quantum wave of possibility to a unique particle of actuality or, using slightly different words, our experiment reduces the superposition of many possibilities (technically called a wave function) to a unique actuality. There is no mechanism for collapse, no algorithm for it can be given, no causal description. The collapse of the quantum wave of possibility is truly a discontinuous affair and *we* have something to do with it.

I hope you now see the radicalness of quantum physics. Who or what collapses the quantum possibility wave into one actuality from behind the veil of discontinuity? Who or what considers these possibilities and chooses from them? This kind of question can most easily lead to seeing a role for the observer, a genuine observer effect, or an effect that consciousness imposes on objects. A consistent answer to the question of collapse is this: quantum possibilities are possibilities within our consciousness, and consciousness chooses the unique actuality from the possibility spectrum in each event of quantum measurement. Since there is no mechanism, no algorithm for the event of discontinuous collapse, the choice can be free—it can be creative! So not only does consciousness enter physics, but free will and creativity do as well.

So this is the radical message of quantum physics. Elementary particles and their interactions, upward causation, are important for shaping the world around us, no doubt. But upward causation produces only possibilities within consciousness. Consciousness has the power of ***downward causation*** to choose among the possibilities and make actualities of the world that we experience.

In summary, there is continuous and deterministic movement in quantum physics, the development of waves of possibility in time. The general acceptance of quantum physics as the ultimate physics of matter comes from its ability to predict this aspect of quantum movement with unprecedented accuracy. But there is also discontinuous movement, the event of collapse. For this, there is no mathematics, no algorithm for prediction. Here consciousness is needed, and free will and creativity find room.

But it is a long way from here to show that consciousness, normally regarded as a concept of neurophysiology and psychology, is really needed in the quantum context, to solve the problem of discontinuous quantum collapse. Should we let ideas of neurophysiology and psychology invade physics, while physics has long been regarded as the funda-

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