Appendix F
Quantum Consequences:

Dear Reader,
The book that I wrote for the text in Physics 303 included a copy of Richard Feynman’s lecture: “Probability and Uncertainty,” from his series: “The Character of Physical Law.” Unfortunately I don’t think I do this any longer. I am allergic to lawsuits. But I want very much for you to watch a video of this lecture, and maybe even buy the complete series in book form. To gain access to these, all you have to do is use Google, and ask for “Richard Feynman.”

Frankly, I didn’t like the previous version of this chapter, the one that appeared in the textbook. It sounded arrogant and combative. This new version, I think, is better, less professorial.

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1. A Bit of History!
That wonderful physicist, Richard Feynman, once asked: If all scientific knowledge were to be destroyed in some cataclysm or other, so that if only one sentence were to survive, what statement would contain the most knowledge in the fewest words? His answer was that: “all things are made of
atoms.” The word: “atom” comes to us from the Greek language: a-tomos, which taken literally means: *indivisible*. Feynman’s “atoms” possessed additional properties; namely, that they attract each other when they are at a little distance apart, but repel each other upon being squeezed into one another. But did he really believe this statement to be true in some absolute, final sense? Certainly not! What he probably meant, was that the belief in their existence had produced a vast intellectual revolution, one that spanned several centuries, and created a tidal wave of scientific discoveries. Thus the atom was truly a seminal concept. But all concepts are merely mental constructs, and thus are subject to revision in the light of experimental results. The atom is no exception. As Feynman himself said: “The principle of science, the definition almost, is the following: *The test of all knowledge is experiment, (my position, exactly!)* Subject to what we have learned from experiment, we must face up to the fact that atoms, in the Greek sense of the word, *do not exist*. “Atoms” are really composite creatures. As we all must know by now, it can be said that atoms consist of massive nuclei, attended by a retinue of electrons. (As long ago as the year 1940, this was common knowledge to me and my friends in the ninth grade at Aptos Junior High School).

A good part of the twentieth century was taken up with the construction of more and more powerful “particle accelerators,” in the hope of probing those massive nuclei, to examine their constituents. The model was the “Russian Doll,” inside of which there was supposed to be other, smaller dolls, and so forth. The goal, (in which we all devoutly believed), was to find the Fundamental Particle, the “tiniest” doll, the one that all the other particles were “made of,” the new Philosopher’s Stone. True, by the 1960s, many physicists were beginning to have their doubts about this way of looking at the world. But the notion had already taken hold, that down at the bottom-most level, there must exist a tiny particle, indivisible, whose properties constitute the cause of everything in the universe; and this notion has developed a vice-like grip on the popular imagination. As a result, physicists *can’t stop* talking that way, even when they know that it’s absurd!

Over that time, a “standard model” has been constructed, whereby we say that atoms are “made of” protons, neutrons and electrons. And protons and neutrons can be thought of as being “made of” entities called “quarks,” which are held together by “gluons,” and so on, (but not ad infinitum). But a certain amount of sophistication has also crept into our way of describing the world, and in the course of this chapter, we shall see that there are limitations, unsuspected, to the meaning of words such as: “substance” and: “made of.” We shall talk about this problem later in the chapter. But first it is useful to examine a bit of history, for the notion of the primacy of “atoms” has had a profound effect upon the Western Mind, ricocheting far beyond the narrow confines of the physics departments.

The doctrine that atoms possess a final explanatory power, is called “radical atomism,” or “materialism.” It implies that “substance” takes the place of “relation.”
2. The Role of the Atom in the Evolution of Materialism

The fifth century BC marked the budding of Greek philosophy, and it was at that time that Democritus of Abdera produced the idea that I shall call: radical atomism, summarized in the epigraph at the heading of this chapter: “By convention sour, by convention sweet, by convention colored, in reality nothing but atoms and the void.” As we have seen in an earlier chapter, an appreciation of Greek language and culture came late to Italian scholars, but at the time of the early Roman Empire, in the first century BC, Titus Lucretius, a Roman, was able not only to demonstrate a firm understanding of atomism, but could set it down beautifully in clear Latin verse, understandable to any educated Italian. The title of his long poem? “On the Nature of Things”—("de Natura Rerum"). After the Empire had collapsed (476AD) there was a millennium-long hiatus, until the poem again came to light in Roman Catholic Europe in the early Renaissance (the year 1417), when it was about as welcome as ants at a picnic). But two centuries later it was clear that Galileo knew all about Lucretius; (though in his writings, he always managed to avoid the ‘a’-word). Instead, he used certain code words, which really meant the same thing). If you read Galileo’s words as quoted in Chapter Two, you will notice they do have a certain chill, depressing tone about them. How to describe this? For one thing, the richness of experience has been reduced to a pale, starved facsimile of the original. Hence the name ‘reductionism,’ a subject we shall discuss later in this chapter.

3. From Atoms to Mechanistic Physics

Let’s start with a simple example. Galileo is doing the kind of physics experiment that makes us all feel comfortable; he is rolling a ball down an inclined plane, measuring how long it takes the ball to roll through a given distance. (This experiment is not as easy as it sounds; for one thing there were no stopwatches in the seventeenth century). Despite this handicap, what he found was that the distance covered by ball varied with the square of the time: a brilliant discovery! He also found that if you slide an object down the inclined plane, that its acceleration does not depend upon its mass! At this point Galileo gets tricky: he recognizes that there is an important limiting case: one where the plane’s angle of inclination is ninety degrees. This, of course, corresponds to free-fall! In this manner he was able to show that the rate of fall of a falling body is independent of its mass! Considering the difficulties that are involved, (air resistance, getting a straight piece of wood for the plane, lubricating the various parts, and Galileo’s failing eyesight), the experiment was a masterpiece. But the real masterwork was his showing that a law of nature could be expressed in simple mathematical terms. He had found a key, and had turned it in a lock, and a magic door had opened.

Once Galileo’s work had been smuggled out of Italy (1640) and had been made known to certain like-minded people in Holland, France and England, ‘the cat was out of the bag.’ In a very short time atomism was combined with Galileo’s science of mechanics to produce the philosophy of Mechanism: the world seen as a machine. One of the very great mathematicians of his time was Blaise Pascal,
(who was also very religious). He was born in 1623 and died in 1662, (when Newton was only 18 years old), but he could already see the full consequences of a disenchanted mechanical universe, one consisting solely of “atoms and the void.” He even exclaimed: “The eternal silence of these infinite spaces terrifies me.”

By the year 1687, Isaac Newton had discovered three laws of mechanics. Of most interest to us here is his Second Law, which states that the acceleration of a body is proportional to the force exerted on it, and inversely proportional to its mass. It looks like this: \( a = \frac{F}{m} \). Here was an even more powerful skeleton key! Knowing the acceleration makes it possible to calculate the velocity; and knowing the velocity gives you the position. Therefore, given the force acting on a body, you can predict its position for all time!

At the beginning of the 19th century there were many great mathematicians in France. But perhaps the greatest of these was Pierre Simon de Laplace, and it was he who wrote the words that were to be the intellectual and psychological “flagship” of the mechanistic materialists who were to hold mental dominion over that century, as well as over a good part of the following one. Here is what Laplace wrote:

“We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.”

This “intellect” is often referred to as Laplace’s demon. Laplace, himself, did not use the word “demon”, which was a later embellishment. In the original French, he simply referred to: “Une intelligence... Rien ne serait incertain pour elle, et l’avenir comme le passé, seraient présent à ses yeux.”

What this means, is that for Laplace the universe is a vast machine, (today we would call it a computer; fashions change), whose parts follow fixed trajectories in time, in accord with strict deterministic laws. One example of this is the motion of planets together with their moons about the sun. Planetary orbits actually functioned psychologically as a sort of “teaching model” for human behavior, and their regularity produced a feeling of comfort that bordered almost on the spiritual. And in this way “Mechanism” became the ruling paradigm. “Just give us the correct equation, and the same initial conditions, and every object will follow the same trajectory.”

The thought that we live in a universe where reality seems to comprise the constant clicking together of deterministic ball-bearings is, to be sure, a dispiriting one (literally), but it has contributed much to the development (and derangement) of the “modern mind,” (at least for the minds of my generation), when
it gave rise to what has been called “the culture of despair.” The reason for this name seems to be that in 1926, in his book: “Why I am Not A Christian,” philosopher Bertrand Russell wrote cheerfully: “…only on the firm foundation of unyielding despair can the soul’s habitation be safely built.”

4. And Now For The Revolution: We Arrive At The Departure Point –From Mechanism

Our first goal is to demonstrate that the search for a primordial atom—a so-called “fundamental particle”—was really an unsuccessful attempt to find a suitable metaphor for Reality. After all, who appointed us “the reality sheriffs” for the universe? We only know what it seems like to us; we don’t know, (in any final sense), what it is. Photons

Let’s start with photons, since they appear to represent the simplest example of the thing I want to show you. Further, let’s use a laser, a device producing waves of essentially the same frequency. Since the energy is related to the frequency by Planck’s equation:

\[ E = hf, \]

Then these photons will all have the same energy. And since the wavelength is related to the frequency by the equation (See Appendix A):

\[ f = c/\lambda, \]

They will all have the same wavelength.

And since the momentum is related to the wavelength by de Broglie’s relation:

\[ p = h/\lambda, \]

the photons will all have the same momentum.

In addition, photons possess a characteristic angular momentum. We can imagine that, as they travel, (always at speed c through a vacuum), the planes of their electric and magnetic fields rotate like a kind of screw. This property is, in a vacuum, called circular polarization. The angular momentum of the photon is \( h/2\pi \), where h is, again, the (now) familiar Planck’s constant. It is important to recognize that every photon has the same angular momentum.

Thus all the intrinsic defining properties of photons depend entirely upon their energy and angular momentum. All photons of a given energy and polarization are absolutely identical. There is absolutely no way to one of these from another: they are perfect clones, bereft of any telltale vestige of personality—of identity².

We may reason further. Since the defining characteristics of the photon are just its energy and polarization, then these, the photon’s only distinguishing attributes, (plus the fact that the photon travels at light-speed in a vacuum), are the photon! Any sentence attributing more qualities to the photon than those, must simply be meaningless, for there is no procedure available to detect the existence of such
extra qualities. That, we might say, is the complete “bar code” of “photon.” When we buy an item at the market, the item carries a “bar code.” In the quantum world there is no “item” beyond the “bar code!” Lesson: A photon is just one example of a quantum. They are all like that: collections of properties. Beyond this, there is “no there there.”

5. Does Causality Still Hold For Quantum-Mechanical Critters?
Let’s think about Galileo, rolling balls down that inclined plane. Every time he repeated a trial, the result had to be the same. If that had not happened, physics would have had a very different, (and undistinguished) history. So we can agree: In the world of classical physics the same causes must always produce the same effects. But there are exceptions to this rule. Let’s look at Airy’s rings.

This is a very simple experiment. We punch a tiny hole in a sheet of aluminum foil, and from the left side of the foil we shine a beam of laser light through the hole in such a manner that it illuminates a screen that has been placed to the right of the sheet of foil. We will see that something peculiar is happening on the screen. See Fig. F1

![Figure F1 Energy levels of positronium.](image)

From the point of view of classical physics we would expect to get a tiny dot of light on the screen: an image of the hole in the aluminum foil. Doesn’t light travel in straight lines? Apparently not! What we see is a kind of bull’s eye pattern of light and dark rings, called Airy Rings, named after the British
scientist, Sir George Airy, who calculated the radii of the rings in 1835. (By the time of Airy’s discovery people had become accustomed to the wave nature of light, and no scandal was reported).

But when we look at the matter from the standpoint of the Quantum Theory it becomes stranger yet. To see why this so, let’s reduce the amplitude of the laser beam until the photons arrive just one at a time, leaving dark specks of silver in the emulsion. After a while we see what is happening. At first the photons seem to strike the screen in a random way. But if we use progressively longer exposure times, (thereby collecting more and more photons), the dark specks begin to coalesce into the familiar Airy rings.

Now here is the astonishing thing. We know that every single one of the photons emitted by a laser is absolutely identical with all the others in its intrinsic attributes. They all propagate at light-speed c, and they all have the same vibrational frequency and their wavelength, is given by:

\[ \lambda = \frac{c}{f}. \]

And from the Planck and the de Broglie relations they all had the same momentum:

\[ E = hf = \frac{hc}{\lambda} = pc. \]

Since h (Planck’s Constant), and c, the speed of light, are measured constants, a look at the algebra should quickly convince you that, (with the exception of polarization), the frequency of the light determines everything there is to know about it: the wavelength, the energy and the momentum!

So, all the photons in the experiment are identical! And yet each one of them was observed to wind up in a different place. Therefore we know all there is to know, and it is still not enough. Classical causality as we know it has broken down. Equal causes no longer produce equal effects. We can no longer trust causality, that mainstay of Western thought. Why? Because the same causes have produced different effects!

6. Another Example: The Electron

Further, the same kind of analysis can be applied to the electron, or, (with a little persistence), to any quantum “particle.” One of the electrons attributes is its “mass,” simply its “rest energy,” (since Einstein has shown “mass” can be given by the famous equation):

\[ E = mc^2. \]

The additional members of the electron’s “bar code” are its electric charge, e, its angular momentum \( \frac{\hbar}{4\pi} \), where \( \hbar \) is the inevitable Planck’s constant--and one further number that arises when a nucleus requires the presence of an electron in order to be part of an internal “decay” of a neutron. And that is the electron’s complete “bar code”! All electrons have these intrinsic attributes, and no others; they are all identical clones! They are just “bar codes.”
You might ask: “Aren’t they particles? Aren’t they round and plump, with a fixed radius?” And I will reply: “If you make them behave like particles, they will. If the electron impinges upon a target, it will do so at what appears to be a single point. But if you make them act like waves, by performing a double slit experiment with them, they will act like waves, in the same manner as photons. You ask a “particle question,” and you get a “particle answer.” It is likewise with wave questions. *We do not see nature in any other way than in the manner in which it interacts with our macroscopic detection apparatus.*” And the radius of the electron? Have patience! We shall talk about this matter shortly. But be prepared for a surprise!

### 7. Nuclei, and other gross things

Without much error, one can speak of the atomic nucleus as being “made of” protons and neutrons. Each of these latter two types of “particle” is approximately 1833 times as massive as an electron, a fact that accounts for most of the mass of an atom. In the early 1960’s it was discovered that one could speak of each proton or neutron as being made up of “kinds” of particles called quarks; and it was to these, the quarks, that physicists looked, to account for the properties of protons and neutrons. They were to be disappointed.

And it gets worse. In the mechanistic tradition it had been assumed that the mass of, say, the proton, would turn out to be the sum of the masses of its constituent quarks. Instead it was discovered that the rest mass of the quarks produces at most a tiny fraction of the mass of the proton. The remainder of the mass of the proton is due to the energy of the extremely rapidly moving quarks. Why is this so? Recall: that by Einstein’s famous formula, mass equals energy divided by the square of the speed of light. There seems to be so much energy stored in the force-field that holds them together, that enough mass seems to be produced to account for what we see when we actually weigh a proton.

Clearly, we need to get out of the habit of thinking about mass as a fundamental feature of the universe. For the past thirty years this heretical thought has simmered on the back burner of science, but now it has come to a boil. In the words of Frank Wilczek, who was a member of the Nobel Prize-winning team that “weighed the quark:” “We’ve come a long way toward dethroning mass as a primary, irreducible property of matter.”

It is helpful to practice thinking like Michael Faraday (Ch. 8). It was he who stopped thinking of particles and started drawing maps of their effects in the surrounding spaces. These effects produced regions where the “state of affairs” was changed, vis-à-vis the way they had been in the absence of the charges. He called affected regions: “fields.” This became the way we quantum people think about the world. (1) The universe is a playground of quantized fields. (2) What we observe as “particles” are merely the energy quanta of these fields. (3) They only manifest themselves to us by interacting with us. So: “Get used to it!”
Now let’s return to the subject of mass. In order to find a place for the concept of mass, it was thought that there may be a kind of field—one which acts upon other fields, conferring a kind of inertia upon their energy quanta—and that this inertia would in turn be detectable in the laboratory as: mass. Further, since associated with every field is a quantum, one that can be discerned as a particle, we should make an effort to find that particle. Several years and billions of euros later, the particle was found, and was named the “Higgs particle” after the man who predicted its existence.

Lesson: There is no intrinsic property of “objects” called mass. It is conferred upon most “objects” by their interactions with the Higgs field. This is one of the facts of life.

8. What Happens When We Think About Angular Momentum?
In the world of classical objects, angular momentum is a property that they have when they rotate. I believe that we can discuss angular momentum without using the customary mathematical apparatus, simply by appealing to your intuition, gained from your experience in sports. So it’s useful to think about spinning baseballs, footballs, and the “English” that we place on ping-pong balls. These balls are all rotating objects; they have finite radii, they have mass, and they spin.

First, let’s think about the photon. It has no radius, and no mass. But it does have a polarization vector with certain corkscrew properties, i.e., the vector rotates. This fact gives it an angular momentum \( \frac{\hbar}{2\pi} \). When we talked about electrons I warned you that a surprise was coming. It is here already, and we are only talking about photons, which we thought we understood. So, we had become accustomed to associating angular momentum with massive rotating objects, (5.5 oz. baseballs) and now here is the mass-less photon….

Next let’s examine the electron. If we want to retain our grasp on the familiar ways of Newtonian physics, we will find little comfort here. The electron does have a mass, indeed. But years of effort have been unable to disclose a radius for the beast. Any particle-like experiment reveals the electron as a dimensionless point. And yet it spins, with angular momentum \( \frac{\hbar}{4\pi} \)! A spinning point!

From the classical Newtonian point of view, it seems correct to say that angular momentum is a property of bodies that possess mass, and a finite radius, and just happen to be rotating. That’s the way we always talk. But experiments have driven us to the conclusion that it is really the other way around: that angular momentum often manifests itself in the behavior of gross classical objects, but its connection to them is not a necessary one! It exists all by itself!
Angular momentum is not a kind of “thing;” it is an attribute. It is autonomous. Spinning balls are creatures of angular momentum, not the other way around. Therefore we cannot really avoid the conclusion that what is happening in the universe is really a set of relations between “bar codes.”

9. Returning to the question: “What Are Things Made Of?”

Shortly before the year 1940, scientists came to realize that if two protons and two neutrons came together under the proper conditions, the element Helium was produced. What was noticeable was that the mass of the resulting Helium atom is less than that of the original ingredients: the two protons and two neutrons—by about seven parts in a thousand. (This figure is remarkable in its own right, for if it were to differ appreciably from its actual value, the universe as we know it, would not exist). What is striking about this is that it is counter-intuitive. Aren’t objects supposed merely to be the sum of their parts?

With the development of the first mammoth particle accelerators during the 1950s, matters only grew worse. After that time it became possible to arrange for one proton to collide with another, using energies markedly greater than the rest energy of an individual proton. Below are two examples a bizarre kind of reaction, one that became extremely common with the passage of time.

\[ p + p \rightarrow p + p + p + p \]

Here the symbol \( p \) denotes a particle called an anti-proton. It “looks” just like a proton, except its charge is negative, (and, given the opportunity, the proton ad its “anti-” will annihilate each other). A slightly more extreme event looks like:

\[ p + p \rightarrow p + p + p + p + \pi^+ + \pi^- \]

In the second example, the particles labeled: “\( \pi \)” are called \( \pi \)-mesons, (or simply pions) and constitute just one example of the various kinds of exotic beasts that emerged from the quantum jungle to bedevil physicists during the second half of the twentieth century. Today, events occurring in “high-end” accelerators feature hundreds of these and other exotic interlopers, none of which were “on stage” before the collision that produced them. It is not unreasonable to say that they were “created.”

There is absolutely no precedent for this kind of thing in our everyday life. If we examine the debris left over from firing two grandfather clocks at each other from cannons, we will find a shower of loose cog-wheels, springs, pendulums and broken glass; but what we won’t get is a barrage of alarm clocks and wristwatches. Toward the end of his life Werner Heisenberg expressed the problem with his usual forcefulness:

I will discuss that development of theoretical particle physics that, I believe, begins with the wrong questions. First of all there is the thesis that the observed particles such as the proton—consist of smaller particles: quarks—or whatever else, none of which have
been observed. Apparently here the question was asked: What does a proton consist of? But the questioners appear to have forgotten that the phrase ‘consist of’ has a tolerably clear meaning only if the particle can be divided into pieces with a small amount of energy, much smaller than the rest mass of the particle itself.

From the above discussion we can see that by the second half of the twentieth century, the traditional metaphors of Western Philosophy, had become incoherent! (We had to use one kind of logic for going to the grocery store, and quite another one, when we want to learn some of the innermost secrets of nature).

Once again we turn to Werner Heisenberg, who summed up this position admirably, (together with the tension that it has inevitably produced):

One extreme is the idea of an objective world, pursuing its regular course in space and time, independently of any kind of observing subject; this has been the guiding image from modern science. At the other extreme is the idea of a subject, mystically experiencing the unity of the world and no longer confronted by an object or an objective world; this has been the guiding image of Asian mysticism. Our thinking moves somewhere in the middle, between these two limiting conceptions; we should maintain the tension resulting from these opposites.

10. The Quantum and the Particle: When is a Particle?\(^6\)

Sidney Drell of Stanford University asked the above question in the title to an article appearing in *The American Journal of Physics*. The search for particles, together with what were supposed to be their inherent properties, was a kind of linguistic entrapment that had had its origin in early Greek philosophy. During the late 1940s and throughout the 50’s and early 60’s regiments of physicists around the world were engaged in an unrelenting search for new particles, (of which there were more than anyone had ever hoped for). At the same time they were trying to make sense of the plethora of particles that had already been discovered. The purpose of this search had been to find the truly Fundamental Particle—the one that all the others may be said to “consist of.” By the time Drell had written his famous article, the physics community had, by and large, arrived at the realization that Heisenberg had been right—that it didn’t really make sense to ask: “What does matter consist of?” (But under the tyranny of habit they often went ahead and did it anyway. And they still do, because they can’t help it! As the scorpion said in the fable: It’s my nature!)

In the early years of particle physics it had been taken for granted that you could treat sub-atomic particles in the same way you could treat gross, macroscopic objects. My main purpose in writing this chapter is to show you that this approach doesn’t make sense. After the middle of the 20\(^{th}\) century
powerful particle accelerators had already produced an undigestibly large menu of these quantum entities, a fact which prompted Enrico Fermi, one of the truly great physicists, to exclaim: “If I knew the names of all the particles, I would be a botanist!”

What is the Higgs Particle? For some time now, physicists have noticed that people had given too much reverence to the idea that mass is ‘permanent.’ The principle complaint about mass is, of course, its convertibility into energy. Once you have watched the tracks of an electron and a positron as they meet and annihilate, mass no longer has the grasp on your imagination that it had when it was supposed to be an eternal fixture of reality. If you have been taught that the universe is made up of small ball bearing-like entities, the evanescence of mass brings about a crisis of faith. But then, how do you explain away the existence of mass?

Well, after more than a century of the Quantum Theory, we have been conditioned to think of the world in terms of ‘quantum fields.’ Peter Higgs reasoned that there must be some kind of quantum field that interacts with other quanta to bestow mass on some of them. And so the chase was on. The quantum of the ‘Higgs field’ had to manifest itself as a ‘particle’ in the context of a collision. So you can imagine the rest. Thousands of people worked together, sources of money were found, (I’ll skip the political ramifications), and after years of searching, the Higgs particle was found (at an energy of about 125 Gev).

So what does this show? It shows that ‘mass’ is like a disease; you catch it from Higgs field. If Democritus were alive, he’d be embarrassed.

But by the 1960’s some degree of order was beginning to appear; it had been possible to arrange these particles according to the symmetries of their attributes, and to study the ways in which one particle could decay to form another one. The emergent pattern looked strangely familiar; and we would do well to explore its outline by comparing two examples.

11. We Look Again at the Electron

We should all feel fairly comfortable around electrons by now, since they are absolutely indispensable to the functioning of our bodies, as well as our computers! But there is another thing…. It turns out that the electron has a twin, called the “positron.” It is identical to the electron in every respect save one; it carries a positive charge. Under the proper circumstances the electron and the positron can be made to orbit each other7, in a manner similar to the hydrogen atom, (the one we studied when we were following the adventures of Niels Bohr). In that case the electron and the hydrogen nucleus were doing a kind of dance. So, the positron and the electron form a kind of atom—and they, too, are doing a dance, one called “positronium”—except this time the positronium dance is truly a dance of death8, culminating rapidly in mutual annihilation of the dancers, for this is what always happens when particles and antiparticles meet.
But the dance does manage to last long enough for us to be able to study the various dance steps—that is, the transitions occurring between various “states,” i.e., energy levels. These transitions constitute the “spectrum” of positronium, in a manner entirely analogous to the spectrum of hydrogen unraveled by Niels Bohr in Chapter 9 of this book. See figure F2, below.

![Figure F2](image)

Figure F2: Energy levels of charmonium labeled by their quantum numbers.

The transitions are accompanied by the emission and absorption of photons, just as we saw when we looked at the spectrum of hydrogen (Figure 9-2). They occur between quantum states that are exactly analogous to those we encountered previously. That is why Sidney Drell chose positronium as an example.

So, here is something to remember: The energy differences between the states are very small compared to the rest energies ($E = mc^2$) of the electron and the positron. But they are still there! Therefore, an electron or positron in a higher energy state has a mass that is a tiny bit larger than the mass of the “same” particle in a lower energy state. Thus, if we wanted to define a particle by its mass, then the above diagram would be a mass spectrum!

But we talk about energies instead, because people who studied atomic spectra found it convenient to use that terminology. Now let’s look at an example that exhibits some minor differences, is essentially analogous to what we have seen in the case of positronium.

12. The Charms of Charmonium

Here is an example, now involving π-mesons, particles that we have met briefly before. They have acquired the name: mesons, because they were initially found to be intermediate in mass between lightweights like the electrons and more serious particles, such as protons or neutrons.
In a brilliant piece of work done in the early ’60s, Murray Gell-Mann and George Zweig were able to show (among many other things) that we can talk about the meson as a composite of a quark and an anti-quark. (Note the analogy with positronium). These quarks also execute a dance, and exhibit a spectrum just as positronium does. Although the details of the spectra will differ, there remains an underlying similarity, because the two cases are analogous. The important thing is for us to see where that analogy holds.

The point of Drell’s argument is that there is a similarity between the patterns in the positronium diagram and those that we shall see when we look at the charmonium diagram. While the similarity is not quite perfect, it is close enough so that we can discern that the same kind of thing is happening in both cases. Behold! Fig. F3

![Figure F3](image)

The only difference is that: states of charmonium represent a considerably greater investment in mass-energy than those of positronium; and so it became fashionable to refer to the states of the former as “particles.” And this is precisely my point: that the animal we have become accustomed to speak of as a “particle,” (a word that triggers off the mental image of a billiard ball), can better be regarded as a quantum state, (an energy state belonging to a quantum field). This idea is to be treasured, for it is revolutionary, and beautiful. It may seem peculiar to you, (as it did to me when I was younger). But it is correct.

13. A Kind of Cosmic Jell-O
What, then, is a quantum field? This notion is an abstract one, but it will be helpful for us to use our imaginations. Many, (after a few puffs), have found it profitable to look upon the quantum field as a set of incredibly fine, invisible, ethereal interlocking bed springs! A Cosmic Jell-O, but with an essential difference: the quantum field cannot be said to be made of “matter”; it is not “stuff;” rather, it is a Jell-O of pure possibility! the very stuff of the Schroedinger waves. If the quantum Jell-O is caused to vibrate, the corresponding quantum state can be regarded as being filled by a “particle.” In the final analysis it is a matter of language. But the words have been chosen to describe a picture in our minds. But is there
an underlying reality that, if known, will give us the “correct picture?” The answer seems to be: “No.” Do you find this disturbing? It is good to remember Bohr’s admonition: “Anyone who is not disturbed by the Quantum Theory has not understood a word of it.”

14. The Problem of the Void
We have seen that the mechanistic philosophers of the 17th and 18th centuries had conceived of the spaces of the universe as a cold, empty, dead expanse: a void. In the 19th century an attempt was made to fill the void with a rarified material medium called the æther; (to accommodate the newly-found electric and magnetic fields). After Michelson and Morley had shown that there is no evidence indicating the existence of a material æther, the door was open for Einstein’s Theory of Relativity, which described space-time as a continuum, space and time being treated as inter-convertible. However, space-time didn’t appear to make the vast spaces of the universe appear any the less void.

15. The Mysterious Quantum Vacuum: “That Jello Again?”
When we look up at the sky on a clear, moonless night, we can observe the light of several thousand stars. This light, in the form of electromagnetic waves, is propagated through a space that seems to be nearly empty of matter. Yet, as the classical physicists of the 19th century had noticed, a wave is an oscillation, so something really must be oscillating. But if there is no material æther what can it be that is oscillating like that? In the early days of the Quantum Theory physicists reasoned that the electromagnetic field must itself be quantized. The conclusion reached was that:

(1) “Empty” space must be full of ghostly oscillators, and
(2) These oscillators must oscillate in strict obedience to the laws of quantum mechanics.

Thus, even in the absence of “real matter,” that which had formerly been regarded as “empty space” must really obey the Heisenberg Uncertainty Principle. One consequence of this is that there must always be an uncertainty in the amount of energy present in a given volume of space. Thus energy may, in a sense, be “borrowed,” and for short periods of time, this will go un-noticed!

From Appendix B we see that the “energy form” of the Uncertainty Principle is:

\[ \Delta E \Delta t \geq \frac{h}{2\pi} \]

From this we can reason further, and see that for very short periods of time, it is actually possible to borrow enough energy to create (on credit) a particle-antiparticle pair. These fluctuations in the vacuum energy produce “virtual particles” which are continually coming into, and going out of existence, back into the eerie, probabilistic half-world from which they issued: the Quantum Vacuum.

As an aid in visualizing the Quantum Vacuum it is useful to imagine yourself in an airplane, flying over the ocean. From an altitude of 37,000 feet the surface of the ocean appears to be as smooth as a billiard table. But a person traveling aboard a ship may experience monstrous waves roiling the surface of that ocean, tossing the vessel wildly from side to side. The Quantum Vacuum is like this, and the
fluctuations of the quantum oscillators are like waves on the surface of a quantum sea. Some fluctuations have enough energy to create virtual particle-antiparticle pairs, such as electrons and positrons. If there is enough energy in one of the collisions produced by a particle accelerator to “pay back the bank,” those virtual particles will become “real,” and will leave a record of their existence. According to the great physicist John Archibald Wheeler:

No point is more central than this, that empty space is not empty. It is the seat of the most violent physics.

Why is this so? We have seen that space can be thought of as packed full of quantum oscillators, in the same sense we spoke of in connection with the Blackbody radiation problem—the one that had make the Quantum Theory necessary in the first place, (See Chapter 8). For another thing, every quantum oscillator possesses energy, even if it is in its lowest possible quantum state. Thus the total amount of energy that seems to be stored in the Quantum Vacuum is greater than the rest energy of all the “matter” in the known universe—all the stuff—the billions of galaxies, each with its billions of stars. Wheeler expresses this idea in the following manner:

Elementary particles do not form a really basic starting point for the description of nature. Instead, they represent a first-order correction to vacuum physics.

In some mysterious way, all the apparent stability of the world is built upon this orgy of creation and annihilation. Millennia ago the Hindus intuited the true impermanence of the world in the myth of the Dance of Shiva, in which the god calls worlds into existence—worlds that might endure for eons, ultimately to be snuffed out, only to have other worlds rise from their ashes. Astonishingly, this view seems in accord with current thinking in the field of cosmology. The Dance of Shiva is an apt metaphor for the dynamic, impermanent nature of the universe—a dream, one that can be obliterated in the blink of an eye.

16. What is the evidence for the Quantum Vacuum?
The first experimental evidence for the Quantum Vacuum was an extraordinarily small correction to the Balmer Series in the hydrogen spectrum. First observed in 1947, this correction, called the Lamb Shift, was only one part in $10^{11}$. But since that time other effects have been detected—the most noticeable among them being the Casimir Force. If you wish to know how this works, you have to understand that electromagnetic waves exert a pressure on material objects. To measure the Casimir Force we place two metal plates at a very small distance from each other. We then discover that they will experience an attractive force. The reason for this is that the region between the plates can’t accommodate as many waves as can the region outside the plates. And electromagnetic waves exert a force proportional to the number of waves.
17. The Buddhist View and Heisenberg’s Middle Way

Since the Scientific Revolution of the 17th century until recent times, the dominant themes in the thinking of scientists have emerged almost wholly from Western Europe. What I am tempted to say, is that this mental set has really been an offshoot of European colonialism. So, when the progenitors of quantum physics grappled with their inability to harmonize the strangeness of their new subject matter with their old ways of thinking, they were forced to reposition the pillars of their philosophical foundations. Fortunately, students in Europe and America scholars had begun to discover the intellectual and spiritual treasures of Asia as early as the 18th century, so some of these concepts were no longer considered to be exotic.

Bohr, Schroedinger and Heisenberg all found certain aspects of what is recognized as “Eastern Philosophy” to be more in harmony with the Quantum Theory than anything that could be found in the Western Rationalistic Tradition. We must always reason in a manner ruthlessly consistent with the empirical data. This has been the scientific ideal: (Good luck with that). But this time our investigations have led us to a strange place. As Heisenberg put it:

The hope that new experiments will lead us back to objective events in time and space is about as well founded as the hope of discovering the end of the world in the unexplored regions of the Antarctic.

So, we have to look at traditions where objective events tend to be absent, and one such place is Buddhism. The central insight of Buddhist philosophy is: the non-inherent existence of all phenomena. According to this teaching, what we observe in the world is purely relative in nature, and nothing around us has any true, final, self-nature. All that we actually perceive are relations. The “things” between which the relations seem to occur are as evanescent as smoke, because they exist only insofar as they participate in those relations. When we intellectualize features of our experience, we are inevitably driven to make distinctions. In doing so, we must create “pairs of opposites,” (this and not that), where before then there had been a seamless whole. The Tantric Buddhist Lama Anagarika Govinda expressed this principle in the following way:

The Buddhist does not believe in an independent or separately existing external world, into whose dynamic forces he could insert himself. The external world and his internal world are for him only two sides of the same fabric, in which the threads of all forces and of all events, of all forms of consciousness and of their objects, are woven into an inseparable net of endless, mutually conditioned relations.

According to Buddhist analysis, belief in the inherent existence of phenomena feeds back into us, creating the illusion of the inherent existence of the human ego. In the words of the Dalai Lama:
How do self-attachment and so forth arise in such great force? Because of beginning-less conditioning, the mind holds tightly to “I”, “I” even in dreams; and through the power of this conception, self-attachment and so forth occur. This false conception of “I” arises because of one’s lack of knowledge concerning the mode of existence of things. The fact that all objects are empty of inherent existence is obscured, and one conceives things to exist inherently, the strong conception of “I” derives from this. Therefore, the conception that the phenomena inherently exist is the afflicting ignorance that is the ultimate root of all afflictions.

An important result of Quantum Theory is that no observation can ever be made of the world, or of any interaction within it, without the exchange of at least one photon—the bare minimum requirement. Further, the properties of a quantum entity depend crucially upon which properties we choose to measure. And what is a measurement, or an observation—but a relation? From this we can appreciate the Buddhist point of view. One is even tempted to say that if there had been no Buddhism, quantum physicists would have had to invent it. We only observe relations, not “things.”

The relative character of phenomena has been expressed by quantum theorist Henry Stapp in the following way:

The observed system is required to be isolated in order to be defined, yet interacting in order to be observed.

Unsurprisingly, this is in accord with a remark by Werner Heisenberg:

What we observe is not nature itself, but nature as exposed to our method of questioning.

Notes to Appendix F:

1. “La silence éternel de ces espaces infinis m’effraie.
Pensees 206.

2. A supporter of Einstein probably would have said: “Wait! This is impossible! There must be some mysterious ‘wheels within wheels’ inside the photon: hidden variables, because in classical physics, similar causes always have similar results.” But as we saw in Chapter 12, the search for hidden variables has been a failure.

4. Classically, the angular momentum of a rotating object can be thought of as that property which makes it impossible to diminish the speed of rotation without “torquing” the object. You can’t ever change angular momentum without applying a torque. You will note that speaking classically, angular momentum is expressed as the inherent property of a rotating massive object. Quantum-mechanically, this is nonsense.

5. For a more technical classical treatment, see the excellent: *Classical Dynamics of Particles and Systems*, by Marion and Thornton, Harcourt, Brace and Jovanovich, NY, 1988.


7. When the electron and the positron get into each other’s proximity, they proceed to annihilate each other, producing a pair of extremely energetic photons. This fact “speaks worlds” about the self-nature of things….

8. Actually, they orbit their common center of mass.

9. Drell points out that, since quarks cannot be produced as isolated particles, their existence can be compared to that of magnetic poles: a kind of phenomenon, incapable of being observed in an isolated form.

10. This magnificent theory was worked out during the years between 1925 and 1932, by Born, Heisenberg, Jordan and Pauli.

11. To get an intuitive feeling for an oscillator, think of a mass hanging from a spring, and bobbing up and down.

12. This result is a necessary consequence of Heisenberg’s Uncertainty Principle, which states that the uncertainty in energy, multiplied by the uncertainty in time, cannot be less than Planck’s Constant divided by $2\pi$. Thus the Quantum Vacuum can be described as a vast Energy Bank—really Too Big To Fail! It is possible to make small withdrawals for reasonable periods of time; large withdrawals however, can only be made for short periods.

13. Virtual particles cannot become “real” in the absence of an interaction/observation. Thus they reside in the same limbo as the rest of the Schroedinger wave functions.

14. This force has been measured by Steven Lamoureax at Los Alamos National Laboratory, who obtained a result that differed from the predicted one by less than five percent, while the force that was being measured was less than a quarter of a billionth of a pound! An astonishing accomplishment. See the magazine: *Science*, Vol. 275, page 158, 10 January 1997.

15. In the 1780s an English judge, Sir William Jones, serving in Calcutta, discovered that the Indians were speaking and writing in a language related to those of Europe. Hindi is related to Sanskrit much as Italian is related to Latin. Sanskrit and English have a lot in common! They are called “Indo–European languages.” In the 19th century these commonalities attracted the interest of German thinkers, resulting in the development of the science of philology.