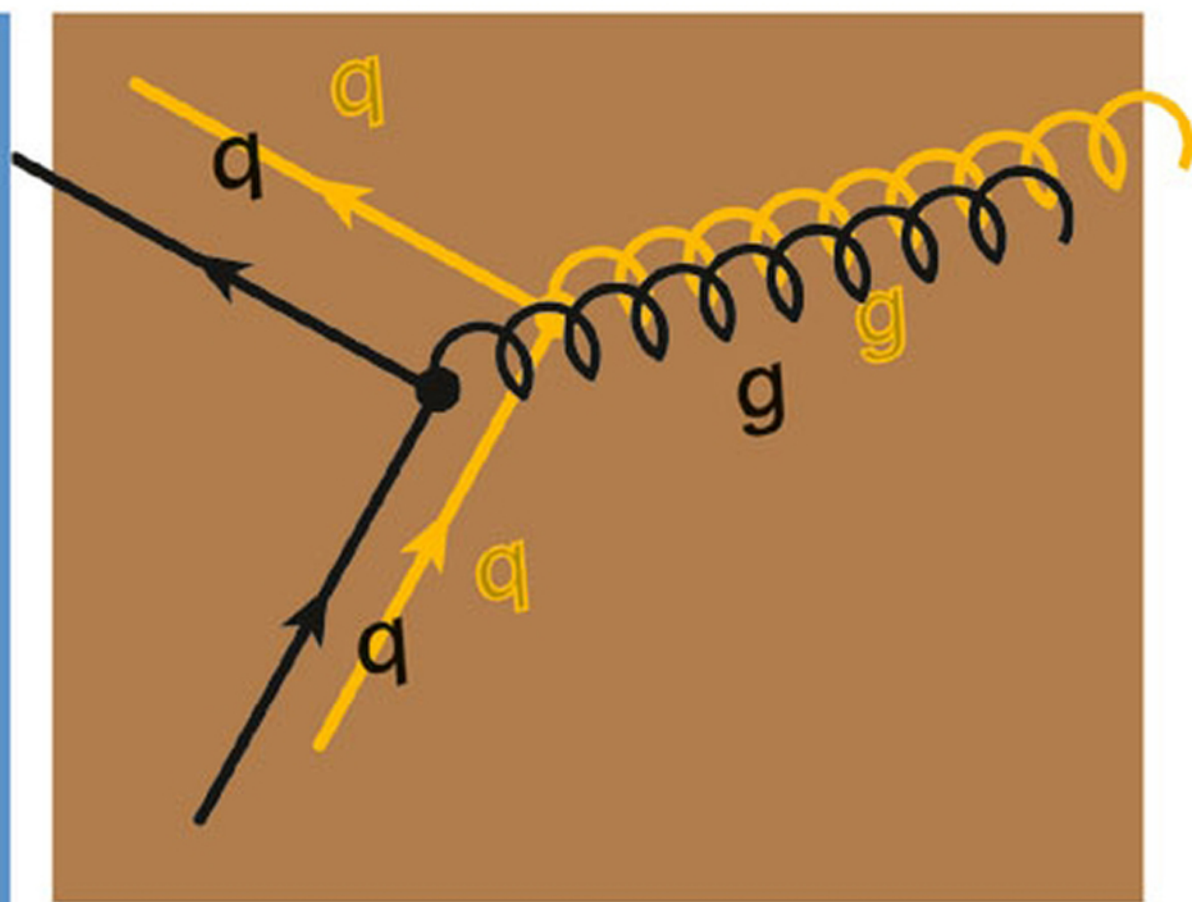


# Introduction to Elementary Particles





# INTRODUCTION TO ELEMENTARY PARTICLES

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**David Griffiths**

Reed College



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# PREFACE

This introduction to the theory of elementary particles is intended primarily for advanced undergraduates who are majoring in physics. Most of my colleagues consider this subject inappropriate for such an audience—mathematically too sophisticated, phenomenologically too cluttered, insecure in its foundations, and uncertain in its future. Ten years ago I would have agreed. But in the last decade the dust has settled to an astonishing degree, and it is fair to say that elementary particle physics has come of age. Although we obviously have much more to learn, there now exists a coherent and unified theoretical structure that is simply too exciting and important to save for graduate school or to serve up in diluted qualitative form as a subunit of modern physics. I believe the time has come to integrate elementary particle physics into the standard undergraduate curriculum.

Unfortunately, the research literature in this field is clearly inaccessible to undergraduates, and although there are now several excellent graduate texts, these call for a strong preparation in advanced quantum mechanics, if not quantum field theory. At the other extreme, there are many fine popular books and a number of outstanding *Scientific American* articles. But very little has been written specifically for the undergraduate. This book is an effort to fill that need. It grew out of a one-semester elementary particles course I have taught from time to time at Reed College. The students typically had under their belts a semester of electromagnetism (at the level of Lorrain and Corson), a semester of quantum mechanics (at the level of Park), and a fairly strong background in special relativity.

In addition to its principal audience, I hope this book will be of use to beginning graduate students, either as a primary text, or as preparation for a more sophisticated treatment. With this in mind, and in the interest of greater completeness and flexibility, I have included more material here than one can comfortably cover in a single semester. (In my own courses I ask the students to read Chapters 1 and 2 on their own, and begin the lectures with Chapter 3. I skip Chapter 5 altogether, concentrate on Chapters 6 and 7, discuss the first two sections of Chapter 8, and then jump to Chapter 10). To assist the reader (and the teacher) I begin each chapter with a brief indication of its purpose and content, its prerequisites, and its role in what follows.

This book was written while I was on sabbatical at the Stanford Linear Accelerator Center, and I would like to thank Professor Sidney Drell and the other members of the Theory Group for their hospitality.

DAVID GRIFFITHS



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# Introduction

## ELEMENTARY PARTICLE PHYSICS

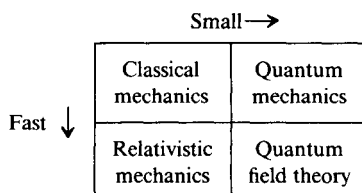
Elementary particle physics addresses the question, “What is matter made of?” on the most fundamental level—which is to say, on the smallest scale of size. It’s a remarkable fact that matter at the subatomic level consists of tiny chunks, with vast empty spaces in between. Even more remarkable, these tiny chunks come in a small number of different types (electrons, protons, neutrons, pi mesons, neutrinos, and so on), which are then replicated in astronomical quantities to make all the “stuff” around us. And these replicas are absolutely perfect copies—not just “pretty similar,” like two Fords coming off the same assembly line, but utterly *indistinguishable*. You can’t stamp an identification number on an electron, or paint a spot on it—if you’ve seen one, you’ve seen them all. This quality of absolute identicalness has no analog in the macroscopic world. (In quantum mechanics it is reflected in the Pauli exclusion principle.) It enormously simplifies the task of elementary particle physics: we don’t have to worry about big electrons and little ones, or new electrons and old ones—an electron is an electron. It didn’t have to be so easy.

My first job, then, is to introduce you to the various kinds of elementary particles, the actors, if you will, in the drama. I could simply *list* them, and tell you their properties (mass, electric charge, spin, etc.), but I think it is better in this case to adopt a historical perspective, and explain how each particle first came on the scene. This will serve to endow them with character and personality, making them easier to remember and more interesting to watch. Moreover, some of the stories are delightful in their own right.

Once the particles have been introduced, in Chapter 1, the issue becomes, “How do they interact with one another?” This question, directly or indirectly, will occupy us for the rest of the book. If you were dealing with two *macroscopic*

objects, and you wanted to know how they interact, you would probably begin by suspending them at various separation distances and measuring the force between them. That's how Coulomb determined the law of electrical repulsion between two charged pith balls, and how Cavendish measured the gravitational attraction of two lead weights. But you can't pick up a proton with tweezers or tie an electron onto the end of a piece of string; they're just too small. For practical reasons, therefore, we have to resort to less direct means to probe the interactions of elementary particles. As it turns out, almost all our experimental information comes from three sources: (1) scattering events, in which we fire one particle at another and record (for instance) the angle of deflection; (2) decays, in which a particle spontaneously disintegrates and we examine the debris; and (3) bound states, in which two or more particles stick together, and we study the properties of the composite object. Needless to say, determining the interaction law from such indirect evidence is not a trivial task. Ordinarily, the procedure is to *guess* a form for the interaction and compare the resulting theoretical calculations with the experimental data.

The formulation of such a guess ("model" is a more respectable term for it) is guided by certain general principles, in particular, special relativity and quantum mechanics. In the diagram below I have indicated the four realms of mechanics:



The world of everyday life, of course, is governed by classical mechanics. But for objects that travel very fast (at speeds comparable to  $c$ ), the classical rules are modified by special relativity, and for objects that are very small (comparable to the size of atoms, roughly speaking), classical mechanics is superseded by quantum mechanics. Finally, for things that are both fast *and* small, we require a theory that incorporates relativity and quantum principles: quantum field theory. Now, elementary particles *are* extremely small, of course, and typically they are also very fast. So elementary particle physics naturally falls under the dominion of quantum field theory.

Please observe the distinction here between a *type of mechanics* and a *particular force law*. Newton's law of universal gravitation, for example, describes a specific interaction (gravity), whereas Newton's three laws of motion define a mechanical system (classical mechanics), which (within its jurisdiction) governs *all* interactions. The force law tells you what  $F$  is, in the case at hand; the mechanics tells you how to *use*  $F$  to determine the motion. The goal of elementary particle dynamics, then, is to guess a set of force laws which, within the context of quantum field theory, correctly describe particle behavior.

However, some general features of this behavior have nothing to do with the detailed form of the interactions. Instead they follow directly from relativity,

from quantum mechanics, or from the combination of the two. For example, in relativity, energy and momentum are always conserved, but (rest) mass is not. Thus the decay  $\Delta \rightarrow p + \pi$  is perfectly acceptable, even though the  $\Delta$  weighs more than the sum of  $p$  plus  $\pi$ . Such a process would not be possible in classical mechanics, where mass is strictly conserved. Moreover, relativity allows for particles of zero (rest) mass—the very idea of a massless particle is nonsense in classical mechanics—and as we shall see, photons, neutrinos, and gluons are all (apparently) massless.

In quantum mechanics a physical system is described by its *state*,  $s$  (represented by the wave function  $\psi_s$  in Schrodinger's formulation, or by the *ket*  $|s\rangle$  in Dirac's). A physical process, such as scattering or decay, consists of a *transition* from one state to another. But in quantum mechanics the outcome is not uniquely determined by the initial conditions; all we can hope to calculate, in general, is the *probability* for a given transition to occur. This indeterminacy is reflected in the observed behavior of particles. For example, the charged pi meson ordinarily disintegrates into a muon plus a neutrino, but occasionally one will decay into an *electron* plus a neutrino. There's no difference in the original pi mesons; they're all identical. It is simply a fact of nature that a given particle can go either way.

Finally, the union of relativity and quantum mechanics brings certain extra dividends that neither one by itself can offer: the existence of antiparticles, a proof of the Pauli exclusion principle (which in nonrelativistic quantum mechanics is simply an ad hoc hypothesis), and the so-called *TCP theorem*. I'll tell you more about these later on; my purpose in mentioning them here is to emphasize that these are features of the mechanical system itself, not of the particular model. Short of a catastrophic revolution, they are untouchable. By the way, quantum field theory in all its glory is difficult and deep, but don't be alarmed: Feynman invented a beautiful and intuitively satisfying formulation that is not hard to learn; we'll come to that in Chapter 6. (The *derivation* of Feynman's rules from the underlying quantum field theory is a different matter, which can easily consume the better part of an advanced graduate course, but this need not concern us here.)

In the last few years a theory has emerged that describes all of the known elementary particle interactions except gravity. (As far as we can tell, gravity is much too weak to play any significant role in ordinary particle processes.) This theory—or, more accurately, this collection of related theories, incorporating quantum electrodynamics, the Glashow–Weinberg–Salam theory of electroweak processes, and quantum chromodynamics—has come to be called the *Standard Model*. No one pretends that the Standard Model is the final word on the subject, but at least we now have (for the first time) a full deck of cards to play with. Since 1978, when the Standard Model achieved the status of “orthodoxy,” it has met every experimental test. It has, moreover, an attractive aesthetic feature: in the Standard Model all of the fundamental interactions derive from a single general principle, the requirement of *local gauge invariance*. It seems likely that future developments will involve extensions of the Standard Model, not its repudiation. This book might be called an “Introduction to the Standard Model.”

As that alternative title suggests, this is a book about elementary particle *theory*, with very little on experimental methods or instrumentation. These are important matters, and an argument can be made for integrating them into a text such as this, but they can also be distracting and interfere with the clarity and elegance of the theory itself. (I encourage you to read about experimental aspects of the subject, and from time to time I will refer you to particularly accessible accounts.) For now, I'll confine myself to scandalously brief answers to the two most obvious experimental questions.

## HOW DO YOU *PRODUCE* ELEMENTARY PARTICLES?

Electrons and protons are no problem; these are the stable constituents of ordinary matter. To produce electrons one simply heats up a piece of metal, and they come boiling off. If one wants a *beam* of electrons, one then sets up a positively charged plate nearby, to attract them over, and cuts a small hole in it; the electrons that make it through the hole constitute the beam. Such an *electron gun* is the starting element in a television tube or an oscilloscope or an electron accelerator (Fig. I.1).

To obtain protons you ionize hydrogen (in other words, strip off the electron). In fact, if you're using the protons as a *target*, you don't even need to bother about the electrons; they're so light that an energetic particle coming in will knock them out of the way. Thus, a tank of hydrogen *is* essentially a tank of protons. For more exotic particles there are three main sources: cosmic rays, nuclear reactors, and particle accelerators.

**Cosmic Rays** The earth is constantly bombarded with high-energy particles (principally protons) coming from outer space. What the source of these particles might be remains something of a mystery; at any rate, when they hit atoms in the upper atmosphere they produce showers of secondary particles (mostly muons, by the time they reach ground level), which rain down on us all the time. As a source of elementary particles, cosmic rays have two virtues: they are free, and their energies can be enormous—far greater than we could possibly produce in the laboratory. But they have two major disadvantages: The rate at which they strike any detector of reasonable size is very low, and they are completely uncontrollable. So cosmic ray experiments call for patience and luck.

**Nuclear Reactors** When a radioactive nucleus disintegrates, it may emit a variety of particles—neutrons, neutrinos, and what used to be called alpha rays (actually, *alpha particles*, which are bound states of two neutrons plus two protons), beta rays (actually, electrons or positrons), and gamma rays (actually, photons).

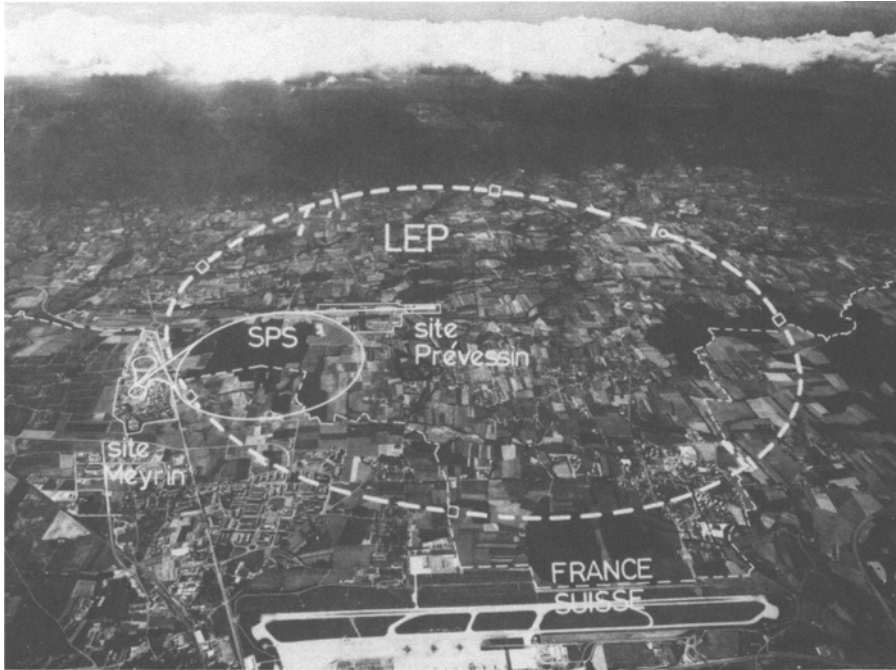
**Particle Accelerators** You start with electrons or protons, accelerate them to high energy, and smash them into a target. By skillful arrangements of absorbers and magnets, you can separate out of the resulting debris the particle species you wish to study. Nowadays it is possible in this way to generate intense sec-



**Figure I.1** The Stanford Linear Accelerator Center (SLAC). Electrons and positrons are accelerated down a straight tube 2 miles long, reaching energies as high as 45 GeV. (Photo courtesy of SLAC.)

ondary beams of positrons, muons, pions, kaons, and antiprotons, which in turn can be fired at another target. The stable particles—electrons, protons, positrons, and antiprotons—can even be fed into giant *storage rings* in which, guided by powerful magnets, they circulate at high speed for hours at a time, to be extracted and used at the required moment (Fig. I.2).

In general, the heavier the particle you want to produce, the higher must



**Figure I.2** CERN, outside Geneva, Switzerland. SPS is the 450 GeV Super Proton Synchrotron, later modified to make a proton–antiproton collider; LEP is a 50 GeV electron–positron storage ring now under construction. (Photo courtesy of CERN.)

be the energy of the collision. That’s why, historically, lightweight particles tend to be discovered first, and as time goes on, and accelerators become more powerful, heavier and heavier particles are found. At present, the heaviest known particle is the  $Z^0$ , with nearly 100 times the mass of the proton. It turns out that the particle gains enormously in energy if you collide two high-speed particles head-on, as opposed to firing one particle at a stationary target. (Of course, this calls for much better aim!) Therefore, most contemporary experiments involve colliding beams from intersecting storage rings; if the particles miss on the first pass, they can try again the next time around. Indeed, with electrons and positrons (or protons and antiprotons) the *same ring* can be used, with the plus charges circulating in one direction and the minus charges in the other.

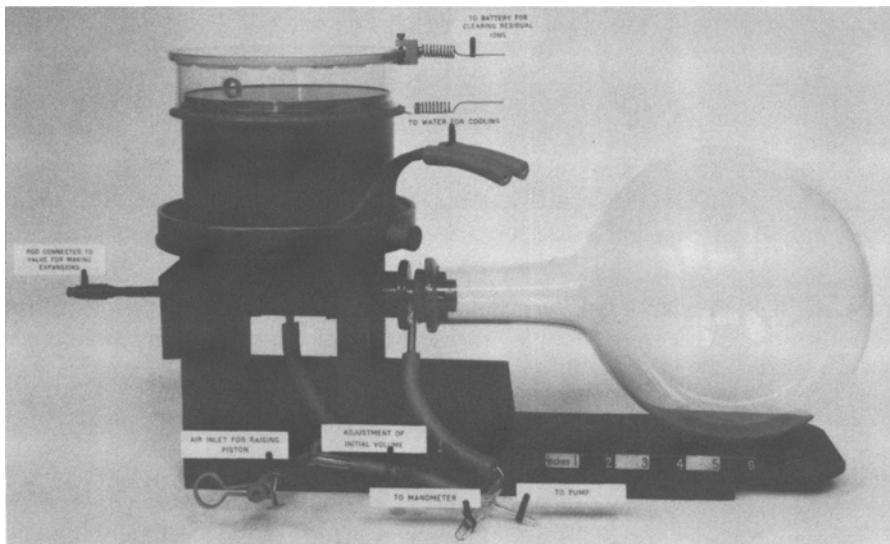
There is another reason why particle physicists are always pushing for higher energies: In general, the higher the energy of the collision, the closer the two particles come to one another. So if you want to study the interaction at very short range, you need very energetic particles. In quantum-mechanical terms, a particle of momentum  $p$  has an associated wavelength  $\lambda$  given by the de Broglie formula  $\lambda = h/p$ , where  $h$  is Planck’s constant. At large wavelengths (low momenta) you can only hope to resolve relatively large structures; in order to examine something extremely small, you need comparably short wavelengths, and hence high momenta. If you like, consider this a manifestation of the uncertainty principle ( $\Delta x \Delta p \geq h/4\pi$ )—to make  $\Delta x$  small,  $\Delta p$  must be large. However you



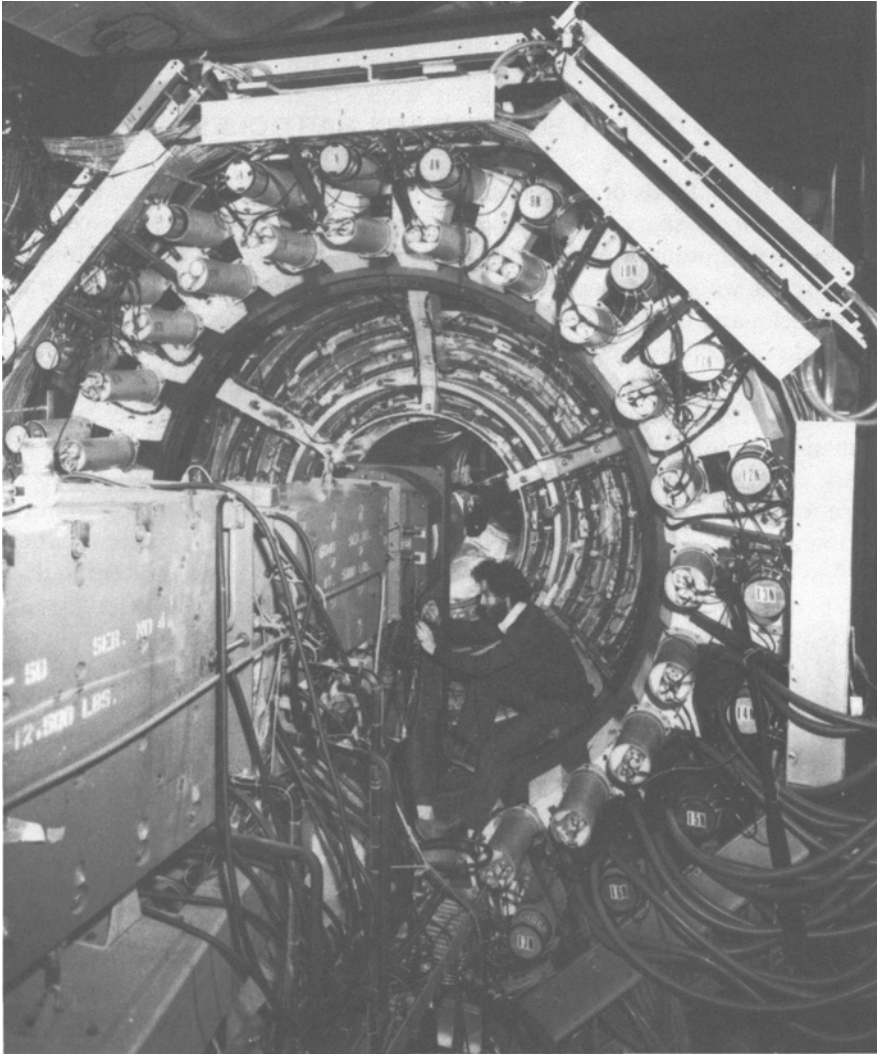
look at it, the conclusion is the same: to probe *small distances* you need *high energies*.

## HOW DO YOU DETECT ELEMENTARY PARTICLES?

There are many kinds of particle detectors—Geiger counters, cloud chambers, bubble chambers, spark chambers, photographic emulsions, Čerenkov counters, scintillators, photomultipliers, and so on (Fig. I.3). Actually, a typical modern detector has whole arrays of these devices, wired up to a computer that tracks the particles and displays their trajectories on a television screen (Fig. I.4). The details do not concern us, but there is one thing to be aware of: Most detection mechanisms rely on the fact that when high-energy charged particles pass through matter they ionize atoms along their path. The ions then act as “seeds” in the formation of droplets (cloud chamber) or bubbles (bubble chamber) or sparks (spark chamber), as the case may be. But electrically *neutral* particles do not cause ionization, and they leave no tracks. If you look at the bubble chamber photograph in Fig. 1.11, for instance, you will see that the five neutral particles are “invisible”; their paths have been reconstructed by analyzing the tracks of the *charged* particles in the picture and invoking conservation of energy and momentum at each vertex. Notice also that most of the tracks in the picture are *curved* (actually, *all* of them are, to some extent; try holding a ruler up to one you think is straight). Evidently the bubble chamber was placed between the poles of a giant magnet. In a magnetic field  $B$ , a particle of charge  $q$  and momentum  $p$  will move in a circle of radius  $R$  given by the famous *cyclotron formula*:  $R = pc/qB$ , where  $c$  is the speed of light. The curvature of the track in a known



**Figure I.3** An early particle detector: Wilson’s cloud chamber (ca. 1900). (Photo courtesy Science Museum, London.)



**Figure I.4** A modern particle detector: The Mark I, at SLAC. (Photo courtesy SLAC.)

magnetic field thus affords a very simple measure of the particle's momentum. Moreover, we can immediately tell the *sign* of the charge from the *direction* of the curve.

## UNITS

Elementary particles are small, so for our purposes the *normal* mechanical units—grams, ergs, joules, and so on—are inconveniently large. Atomic physicists introduced the *electron volt*—the energy acquired by an electron when accelerated

through a potential difference of 1 volt:  $1 \text{ eV} = 1.6 \times 10^{-19}$  joules. For us the eV is inconveniently *small*, but we're stuck with it. Nuclear physicists use keV ( $10^3$  eV); typical energies in particle physics are MeV ( $10^6$  eV), GeV ( $10^9$  eV), or even TeV ( $10^{12}$  eV). Momenta are measured in MeV/c (or GeV/c, or whatever), and masses in MeV/c<sup>2</sup>. Thus the proton weighs  $938 \text{ MeV}/c^2 = 1.67 \times 10^{-24}$  g.

Actually, particle theorists are lazy (or clever, depending on your point of view)—they seldom include the  $c$ 's and  $\hbar$ 's ( $\hbar \equiv h/2\pi$ ) in their formulas. You're just supposed to fit them in for yourself at the end, to make the dimensions come out right. As they say in the business, "set  $c = \hbar = 1$ ." This amounts to working in units such that time is measured in centimeters and mass and energy in inverse centimeters; the unit of time is the time it takes light to travel 1 centimeter, and the unit of energy is the energy of a photon whose wavelength is  $2\pi$  centimeters. Only at the end of the problem do we revert to conventional units. This makes everything look very elegant, but I thought it would be wiser in this book to keep all the  $c$ 's and  $\hbar$ 's where they belong, so that you can check for dimensional consistency as you go along. (If this offends you, remember that it is easier for you to ignore an  $\hbar$  you don't like than for someone else to conjure one up in just the right place.)

Finally, there is the question of what units to use for electric charge. In introductory physics courses most instructors favor the *SI* system, in which charge is measured in *coulombs*, and Coulomb's law reads

$$F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \quad (\text{SI})$$

Most advanced work is done in the *Gaussian* system, in which charge is measured in *electrostatic units* (esu), and Coulomb's law is written

$$F = \frac{q_1 q_2}{r^2} \quad (\text{G})$$

But elementary particle physicists prefer the *Heaviside-Lorentz* system, in which Coulomb's law takes the form

$$F = \frac{1}{4\pi} \frac{q_1 q_2}{r^2} \quad (\text{HL})$$

The three units of charge are related as shown:

$$q_{\text{HL}} = \sqrt{4\pi} q_{\text{G}} = \frac{1}{\sqrt{\epsilon_0}} q_{\text{SI}}$$

In this book I shall use Gaussian units exclusively, in order to avoid unnecessary confusion in an already difficult subject. Whenever possible I will express results in terms of the *fine structure constant*

$$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137}$$

where  $e$  is the charge of the electron in Gaussian units. Most elementary particle

texts write this as  $e^2/4\pi$ , because they are measuring charge in Heaviside–Lorentz units and setting  $c = \hbar = 1$ ; but everyone agrees that the *number* is  $\frac{1}{137}$ .

## REFERENCES AND NOTES

This book is a brief survey of an enormous and rapidly changing subject. My aim is to introduce you to some important ideas and methods, to give you a sense of what's out there to be learned, and perhaps to stimulate your appetite for more. If you want to read further in quantum field theory, I particularly recommend:

Bjorken, J. D., and S. D. Drell. *Relativistic Quantum Mechanics and Relativistic Quantum Fields*. New York: McGraw-Hill, 1964.

Sakurai, J. J. *Advanced Quantum Mechanics*. Reading, MA: Addison-Wesley, 1967.

Itzykson, C., and J.-B. Zuber. *Quantum Field Theory*. New York: McGraw-Hill, 1980.

I warn you, however, that these are all difficult and advanced books. For elementary particle physics itself, the following books (listed in order of increasing difficulty) are especially useful:

Gottfried, K., and V. F. Weisskopf. *Concepts of Particle Physics*. Oxford: Oxford University Press, 1984.

Frauenfelder, H., and E. M. Henley. *Subatomic Physics*. Englewood Cliffs, NJ: Prentice-Hall, 1974.

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# Chapter 1

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## Historical Introduction to the Elementary Particles

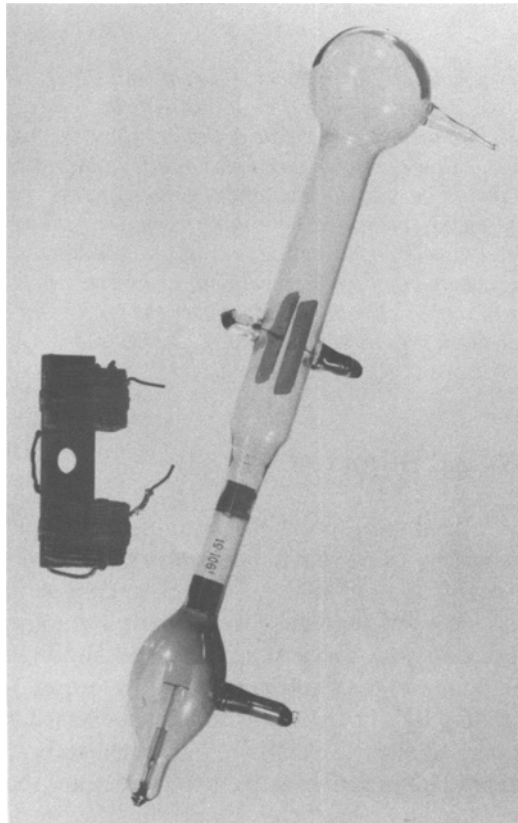
*This chapter is a kind of “folk history” of elementary particle physics. Its purpose is to provide a sense of how the various particles were first discovered, and how they fit into the overall scheme of things. Along the way some of the fundamental ideas that dominate elementary particle theory are explained. This material should be read quickly, as background to the rest of the book. (As history, the picture presented here is certainly misleading, for it sticks closely to the main track, ignoring the false starts and blind alleys that accompany the development of any science. That’s why I call it “folk” history—it’s the way particle physicists like to remember the subject—a succession of brilliant insights and heroic triumphs unmarred by foolish mistakes, confusion, and frustration. It wasn’t really quite so easy.)*

### 1.1 THE CLASSICAL ERA (1897–1932)

It is always a little artificial to pinpoint such things, but I’d say that elementary particle physics was born in 1897, with J. J. Thomson’s discovery of the electron.<sup>1</sup> (It is fashionable to carry the story all the way back to Democritus and the Greek atomists, but apart from a few suggestive words their metaphysical speculations have nothing in common with modern science, and although they may be of modest antiquarian interest, their relevance is infinitesimal.) Thomson knew that *cathode rays* emitted by a hot filament could be deflected by a magnet. This suggested that they carried electric charge; in fact, the direction of the curvature required that the charge be negative. It seemed, therefore, that these were not rays at all, but rather streams of particles. By passing the beam through crossed electric and magnetic fields, and adjusting the field strength until the net deflection was zero, Thomson was able to determine the velocity of the particles (about a

tenth the speed of light) as well as their charge-to-mass ratio. (See Fig. 1.1 and Problem 1.1). This ratio turned out to be enormously greater than for any known ion, indicating that either the charge was extremely large or the mass was very small. Indirect evidence pointed to the second conclusion. Thomson called the particles *corpuscles*, and their charge the *electron*. Later the word electron was applied to the particles themselves.

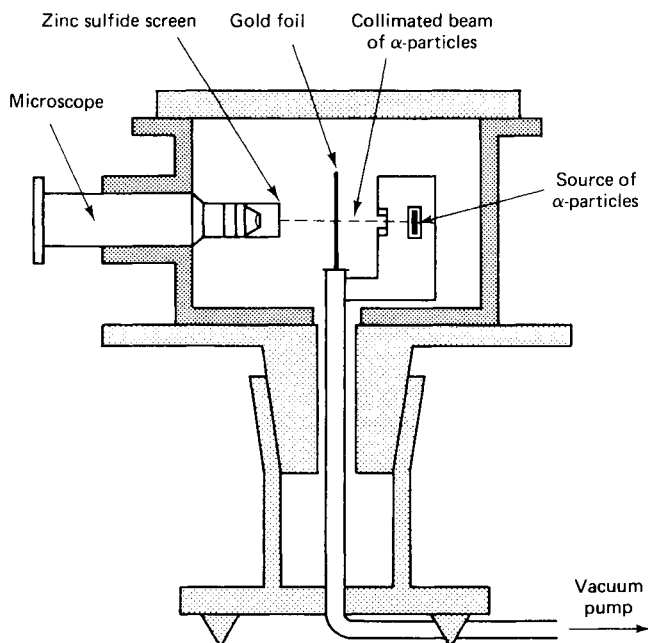
Thomson correctly surmised that these electrons were essential constituents of atoms; however, since atoms as a whole are electrically neutral and very much heavier than electrons, there immediately arose the problem of how the compensating plus charge—and the bulk of the mass—is distributed within an atom. Thomson himself imagined that the electrons were suspended in a heavy, positively charged paste, like (as he put it) the plums in a pudding. But Thomson's model was decisively repudiated by Rutherford's famous scattering experiment, which showed that the positive charge, and most of the mass, was concentrated in a tiny core, or *nucleus*, at the center of the atom. Rutherford demonstrated this by firing a beam of  $\alpha$ -particles (ionized helium atoms) into a thin sheet of



**Figure 1.1** The apparatus with which J. J. Thomson discovered the electron. (Photo courtesy Science Museum, London.)

gold foil (see Fig. 1.2). Had the gold atoms consisted of rather diffuse spheres, as Thomson supposed, then all of the  $\alpha$ -particles should have been deflected a bit, but none would have been deflected much—any more than a bullet is deflected much when it passes, say, through a bag of sawdust. What in *fact* occurred was that *most* of the  $\alpha$ -particles passed through the gold completely undisturbed, but a few of them bounced off at wild angles. Rutherford's conclusion was that the  $\alpha$ -particles had encountered something very small, very hard, and very heavy. Evidently the positive charge, and virtually all of the mass, was concentrated at the center, occupying only a tiny fraction of the volume of the atom (the electrons are too light to play any role in the scattering; they are knocked right out of the way by the much heavier  $\alpha$ -particles).

The nucleus of the lightest atom (hydrogen) was given the name *proton* by Rutherford. In 1914 Niels Bohr proposed a model for hydrogen consisting of a single electron circling the proton, rather like a planet going around the sun, held in orbit by the mutual attraction of opposite charges. Using a primitive version of the quantum theory, Bohr was able to calculate the spectrum of hydrogen, and the agreement with experiment was nothing short of spectacular. It was natural then to suppose that the nuclei of heavier atoms were composed of two or more protons bound together, supporting a like number of orbiting electrons. Unfortunately, the next heavier atom (helium), although it does indeed carry two electrons, weighs *four* times as much as hydrogen, and lithium (three electrons) is *seven* times the weight of hydrogen, and so it goes. This dilemma



**Figure 1.2** Schematic diagram of the apparatus used in the Rutherford scattering experiment. Alpha particles scattered by the gold foil strike a fluorescent screen, giving off a flash of light, which is observed visually through a microscope.

was finally resolved in 1932 with Chadwick's discovery of the neutron—an electrically neutral twin to the proton. The helium nucleus, it turns out, contains two neutrons in addition to the two protons; lithium evidently includes four; and in general the heavier nuclei carry very roughly the same number of neutrons as protons. (The number of neutrons is in fact somewhat flexible: the same atom, chemically speaking, may come in several different *isotopes*, all with the same number of protons, but with varying numbers of neutrons.)

The discovery of the neutron put the final touch on what we might call the *classical period* in elementary particle physics. Never before (and I'm sorry to say never since) has physics offered so simple and satisfying an answer to the question, "What is matter made of?" In 1932 it was all just protons, neutrons, and electrons. But already the seeds were planted for the three great ideas that were to dominate the *middle period* (1930–1960) in particle physics: Yukawa's meson, Dirac's positron, and Pauli's neutrino. Before we come to that, however, I must back up for a moment to introduce the photon.

## 1.2 THE PHOTON (1900–1924)

In some respects the photon is a very "modern" particle, having more in common with the  $W$  and  $Z$  (which were not discovered until 1983) than with the classical trio. Moreover, it's hard to say exactly when or by whom the photon was really "discovered," although the essential stages in the process are clear enough. The first contribution was made by Planck in 1900. Planck was attempting to explain the so-called *blackbody spectrum* for the electromagnetic radiation emitted by a hot object. Statistical mechanics, which had proved brilliantly successful in explaining other thermal processes, yielded nonsensical results when applied to electromagnetic fields. In particular, it led to the famous "ultraviolet catastrophe," predicting that the total power radiated should be *infinite*. Planck found that he could escape the ultraviolet catastrophe—and fit the experimental curve—if he assumed that electromagnetic radiation is *quantized*, coming in little "packages" of energy

$$E = h\nu \tag{1.1}$$

where  $\nu$  is the frequency of the radiation and  $h$  is a constant, which Planck adjusted to fit the data. The modern value of Planck's constant is

$$h = 6.626 \times 10^{-27} \text{ erg s} \tag{1.2}$$

Planck did not profess to know *why* the radiation was quantized; he assumed that it was due to a peculiarity in the emission process: For some reason a hot surface only gives off light\* in little squirts.

Einstein, in 1905, put forward a far more radical view. He argued that quantization was a feature of the electromagnetic field itself, having nothing to

\* In this book the word *light* stands for *electromagnetic radiation*, whether or not it happens to fall in the visible region.



do with the emission mechanism. With this new twist, Einstein adapted Planck's idea, and his formula, to explain the *photoelectric effect*: When electromagnetic radiation strikes a metal surface, electrons come popping out. Einstein suggested that an incoming light quantum hits an electron in the metal, giving up its energy ( $h\nu$ ); the excited electron then breaks through the metal surface, losing in the process an energy  $w$  (the so-called *work function* of the material—an empirical constant that depends on the particular metal involved). The electron thus emerges with an energy

$$E \leq h\nu - w \quad (1.3)$$

(It may lose some energy before reaching the surface. That's the reason for using  $\leq$ , instead of  $=$ .) Einstein's formula (1.3) is pretty trivial to *derive*, but it carries an extraordinary implication: The maximum electron energy is *independent of the intensity of the light* and depends only on its *color* (frequency). To be sure, a more intense beam will knock out *more* electrons, but their *energies* will be the same.

Unlike Planck's theory, Einstein's theory met a hostile reception, and over the next 20 years he was to wage a lonely battle for the *light quantum*.<sup>2</sup> In saying that electromagnetic radiation is *by its nature* quantized, regardless of the emission mechanism, Einstein came dangerously close to resurrecting the discredited particle theory of light. Newton, of course, had introduced such a *corpuscular* model, but a major achievement of nineteenth-century physics was the decisive repudiation of Newton's idea in favor of the rival wave theory. No one was prepared to see that accomplishment called into question, even when the experiments came down on Einstein's side. In 1916 Millikan completed an exhaustive study of the photoelectric effect and was obliged to report that "Einstein's photoelectric equation . . . appears in every case to predict exactly the observed results. . . . Yet the semicorpuscular theory by which Einstein arrived at his equation seems at present wholly untenable."<sup>3</sup>

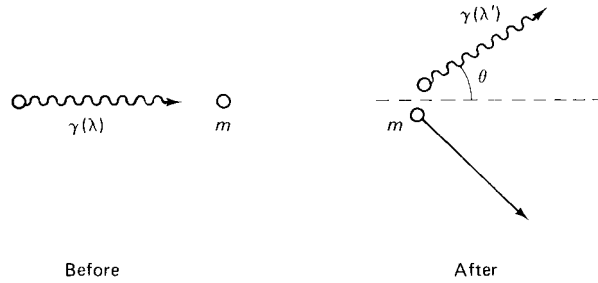
What finally settled the issue was an experiment conducted by A. H. Compton in 1923. Compton found that the light scattered from a particle at rest is shifted in wavelength, according the equation

$$\lambda' = \lambda + \lambda_c(1 - \cos \theta) \quad (1.4)$$

where  $\lambda$  is the incident wavelength,  $\lambda'$  is the scattered wavelength,  $\theta$  is the scattering angle, and

$$\lambda_c = h/mc \quad (1.5)$$

is the so-called *Compton wavelength* of the target particle (mass  $m$ ). Now, this is *precisely* the formula you get (Problem 3.24) if you treat light as a particle of zero rest mass with energy given by Planck's equation, and apply the laws of conservation of (relativistic) energy and momentum—just as you would for an ordinary elastic collision (Fig. 1.3). That clinched it; here was direct and incontrovertible experimental evidence that light behaves as a particle, on the subatomic scale. We call this particle the *photon* (a name suggested by the chemist Gilbert Lewis, in 1926); the symbol for a photon is  $\gamma$  (from *gamma ray*). How



**Figure 1.3** Compton scattering. A photon of wavelength  $\lambda$  scatters off a particle, initially at rest, of mass  $m$ . The scattered photon carries wavelength  $\lambda'$  given by equation (1.4).

the particle nature of light on this level is to be reconciled with its well-established wave behavior on the macroscopic scale (exhibited in the phenomena of interference and diffraction) is a story I'll leave to the quantum texts.

Although the photon initially *forced* itself on an unreceptive community of physicists, it eventually found a natural place in quantum field theory, and was to offer a whole new perspective on electromagnetic interactions. In classical electrodynamics, we attribute the electrical repulsion of two electrons, say, to the electric field surrounding them; each electron contributes to the field, and each one responds to the field. But in quantum field theory, the electric field is *quantized* (in the form of photons), and we may picture the interaction as consisting of a stream of photons passing back and forth between the two charges, each electron continually emitting them and continually absorbing them. And the same goes for *any* noncontact force: where classically we interpret “action at a distance” as “mediated” by a *field*, we now say that it is mediated by an *exchange of particles* (the *quanta* of the field). In the case of electrodynamics, the mediator is the photon; for gravity, it is called the *graviton* (though a fully successful quantum theory of gravity has yet to be developed and it may well be centuries before anyone detects a graviton experimentally).

You will see later on how these ideas are implemented in practice, but for now I want to dispel one common misapprehension. When I say that every force is mediated by the exchange of particles, I am *not* speaking of a merely *kinematic* phenomenon. Two ice skaters throwing snowballs back and forth will of course move apart with the succession of recoils; they “repel one another by exchange of snowballs,” if you like. But that's *not* what is involved here. For one thing, this mechanism would have a hard time accounting for an *attractive* force. You might think of the mediating particles, rather, as “messengers,” and the message can just as well be “come a little closer” as “go away.”

I said earlier that in the “classical” picture ordinary matter is made of atoms, in which electrons are held in orbit around a nucleus of protons and neutrons by the electrical attraction of opposite charges. We can now give this model a more sophisticated formulation by attributing the binding force to the exchange of photons between the electrons and the protons in the nucleus. However, for the purposes of atomic physics this is overkill, for in this context quantization of the electromagnetic field produces only minute effects (notably the

Lamb shift and the anomalous magnetic moment of the electron). To excellent approximation we can pretend that the forces are given by Coulomb's law (together with various magnetic dipole couplings). The point is that in a bound state enormous numbers of photons are continually streaming back and forth, so that the "lumpiness" of the field is effectively smoothed out, and classical electrodynamics is a suitable approximation to the truth. But in *most* elementary particle processes, such as the photoelectric effect or Compton scattering, *individual* photons are involved, and quantization can no longer be ignored.

### 1.3 MESONS (1934–1947)

Now there is one conspicuous problem to which the "classical" model does not address itself at all: What holds the *nucleus* together? After all, the positively charged protons should repel one another violently, packed together as they are in such close proximity. Evidently there must be some other force, more powerful than the force of electrical repulsion, that binds the protons (and neutrons) together; physicists of that less imaginative age called it, simply, the *strong force*. But if there exists such a potent force in nature, why don't we notice it in everyday life? The *fact* is that virtually every force we experience directly, from the contraction of a muscle to the explosion of dynamite is electromagnetic in origin; the only exception, outside a nuclear reactor or an atomic bomb, is gravity. The answer must be that, powerful though it is, the strong force is of very short *range*. (The range of a force is like the arm's reach of a boxer—beyond that distance its influence falls off rapidly to zero. Gravitational and electromagnetic forces have *infinite* range, but the range of the strong force is about the size of the nucleus itself.)\*

The first significant theory of the strong force was proposed by Yukawa in 1934. Yukawa assumed that the proton and neutron are attracted to one another by some sort of *field*, just as the electron is attracted to the nucleus by an electric field and the moon to the earth by a gravitational field. This field should properly be quantized, and Yukawa asked the question: What must be the properties of its *quantum*—the particle (analogous to the photon) whose exchange would account for the known features of the strong force? For example, the short range of the force indicated that the mediator would be rather heavy; Yukawa calculated that its mass should be nearly 300 times that of the electron, or about a sixth the mass of a proton. (See Problem 1.2.) Because it fell between the electron and the proton, Yukawa's particle came to be known as the *meson* (meaning "middle-weight"). [In the same spirit the electron is called a *lepton* ("light-weight"), whereas the proton and neutron are *baryons* ("heavy-weight").] Now, Yukawa knew that no such particle had ever been observed in the laboratory, and he therefore assumed his theory was wrong. But at the time a number of systematic studies

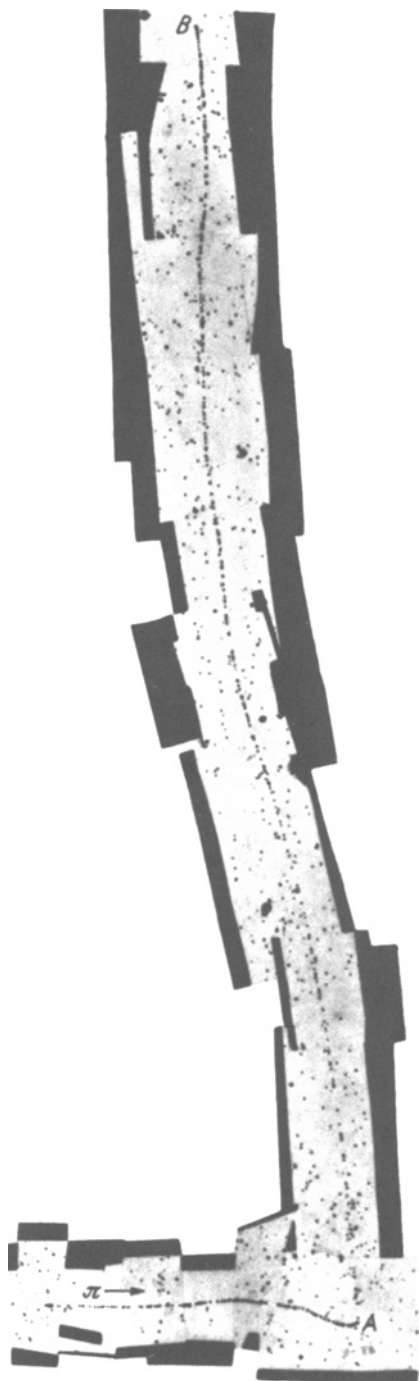
\* This is a bit of an oversimplification. Typically, the forces go like  $e^{-(r/a)}/r^2$ , where  $a$  is the "range." For Coulomb's law and Newton's law of universal gravitation,  $a = \infty$ ; for the strong force  $a$  is about  $10^{-13}$  cm (one fermi).

of cosmic rays were in progress, and by 1937 two separate groups (Anderson and Neddermeyer on the West Coast, and Street and Stevenson on the East) had identified particles matching Yukawa's description. Indeed, the cosmic rays with which you are being bombarded every few seconds as you read this consist primarily of just such middle-weight particles.

For a while everything seemed to be in order. But as more detailed studies of the cosmic ray particles were undertaken, disturbing discrepancies began to appear. They had the wrong lifetime and they seemed to be significantly lighter than Yukawa had predicted; worse still, different mass measurements were not consistent with one another. In 1946 (after a period in which physicists were engaged in a less savory business) decisive experiments were carried out in Rome demonstrating that the cosmic ray particles interacted very weakly with atomic nuclei.<sup>4</sup> If this was really Yukawa's meson, the transmitter of the strong force, the interaction should have been dramatic. The puzzle was finally resolved in 1947, when Powell and his co-workers at Bristol<sup>5</sup> discovered that there are actually *two* middle-weight particles in cosmic rays, which they called  $\pi$  (or "pion") and  $\mu$  (or "muon"). (Marshak reached the same conclusion simultaneously, on theoretical grounds.<sup>6</sup>) The true Yukawa meson is the  $\pi$ ; it is produced copiously in the upper atmosphere, but ordinarily disintegrates long before reaching the ground. (See Problem 3.4.) Powell's group exposed their photographic emulsions on mountain tops (see Fig. 1.4). One of the decay products is the lighter (and longer-lived)  $\mu$ , and it is primarily muons that one observes at sea level. In the search for Yukawa's meson, then, the muon was simply an imposter, having nothing whatever to do with the strong interactions. In fact, it behaves in every way like a heavier version of the electron and properly belongs in the *lepton* family (though some people to this day call it the "mu-meson" by force of habit).

#### 1.4 ANTIPARTICLES (1930–1956)

Nonrelativistic quantum mechanics was completed in the astonishingly brief period 1923–1926, but the relativistic version proved to be a much thornier problem. The first major achievement was Dirac's discovery, in 1927, of the equation that bears his name. The Dirac equation was supposed to describe free electrons with energy given by the relativistic formula  $E^2 - \mathbf{p}^2c^2 = m^2c^4$ . But it had a very troubling feature: For every positive-energy solution ( $E = +\sqrt{\mathbf{p}^2c^2 + m^2c^4}$ ) it admitted a corresponding solution with *negative* energy ( $E = -\sqrt{\mathbf{p}^2c^2 + m^2c^4}$ ). This meant, given the natural tendency of every system to evolve in the direction of lower energy, that the electron should "runaway" to increasingly negative states, radiating off an infinite amount of energy in the process. To rescue his equation, Dirac proposed a resolution that made up in brilliance for what it lacked in plausibility: He postulated that the negative energy states are all filled by an infinite "sea" of electrons. Because this sea is always there, and perfectly uniform, it exerts no net force on anything, and we are not normally aware of it. Dirac then invoked the Pauli exclusion principle (which says that no two electrons can occupy the same state), to "explain" why the



**Figure 1.4** One of Powell's earliest pictures showing the track of a pion in a photographic emulsion exposed to cosmic rays at high altitude. The pion (entering from the left) decays into a muon and a neutrino (the latter is electrically neutral, and leaves no track). Reprinted by permission from C. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (New York: Pergamon, 1959). First published in *Nature* **159**, 694 (1947).

electrons we *do* observe are confined to the positive energy states. But if this is true, then what happens when we impart to one of the electrons in the “sea” an energy sufficient to knock it into a positive energy state? The *absence* of the

“expected” electron in the sea would be interpreted as a net positive charge in that location, and the absence of its expected negative energy would be seen as a net positive energy. Thus a “hole in the sea” would function as an ordinary particle with *positive* energy and *positive* charge. Dirac at first hoped that these holes might be *protons*, but it was soon apparent that they had to carry the same mass as the electron itself—2000 times too light to be a proton. No such particle was known at the time, and Dirac’s theory appeared to be in trouble. What may have seemed a fatal defect in 1930, however, turned into a spectacular triumph in late 1931, with Anderson’s discovery of the *positron* (Fig. 1.5), a positively charged twin for the electron, with precisely the attributes Dirac required.<sup>7</sup>



**Figure 1.5** The positron. In 1932, Anderson took this photograph of the track left in a cloud chamber by a cosmic ray particle. The chamber was placed in a magnetic field (pointing into the page) which caused the particle to travel in a curve. But was it a negative charge traveling downward, or a positive charge traveling upward? In order to tell, Anderson had placed a lead plate across the center of the chamber (the thick horizontal line in the photograph). A particle passing through the plate slows down, and subsequently moves in a tighter circle. By inspection of the curves, it is clear that this particle traveled upward, and hence must have been positively charged. From the curvature of the track, and from its texture, Anderson was able to show that the mass of the particle was close to that of the electron. (Photo courtesy California Institute of Technology)