Search for a Supertheory

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Preface

What is the universe made of? What forces hold it together? And how are they related? These are questions that have puzzled scientists for decades. Today, scientists believe they are close to an answer. It is not yet a complete answer, but tremendous strides have been made. *Search for a Supertheory* is the story of what these advances are and how they were made. But it is also the story of the scientists involved in the search, their frustrations, hardships, hopes, and joy when great discoveries are made. It traces the advances in particle physics from the discovery of the atom and its components through to today's most exciting theory—Superstring Theory. And although it has the same theme as my earlier book *Einstein's Dream,* namely, the search for unity, the emphasis is quite different. In that book I emphasized the macrocosm; in this book I emphasize particles and fields. In the early chapters of the book you may, in fact, be overwhelmed by the large number of seemingly unrelated particles that have been discovered. This is, of course, exactly the way scientists felt at the time. But as you continue you will see how everything eventually came together and began to make sense. And you will also, I hope, share some of the excitement that physicists are now experiencing as the last pieces of this great scientific adventure are being put in place.

There is no mathematics in the book but it is impossible to talk about science without using scientific terms, and it is likely that you will not be familiar with some of them. I have attempted to define each of these terms as it appears, but for the benefit of those who are new to science I have added a glossary. Very large and very small numbers are also needed occasionally and I have used scientific notation to designate them. The notation 10^{30}, for example, represents the large number one with 30 zeros after it. Similarly, 10^{-30} represents the small number one divided by 10^{30}.

Also used extensively is the energy unit, the electron volt. It is the energy an electron acquires in moving through a potential difference of one volt—roughly the voltage of a flashlight battery. Most of the accelerators discussed accelerate particles to millions (MeV) or billions of electron volts (GeV).

The sketches of the physicists were done by Lori Scoffield,* and the line drawings by Sandra Carnahan. I would like to thank both of them for an excellent job. I would also like to thank Murray Gell-Mann for several helpful suggestions and Julius Wess for the interview. And finally I would like to thank Linda Greenspan Regan, Victoria Cherney, and the staff of Plenum Publishing for their assistance in bringing the text into its final form.

Barry Parker

*The sketches of the physicists were adapted from Weber, White, and Manning, 1956, *College Physics*, with permission from McGraw-Hill.

Contents

CHAPTER 1

Introduction

In the last few years scientists have been sifting through an ocean of scientific facts, organizing them, trying to make sense out of them, trying to extract from them an ultimate understanding of nature. And their efforts are finally beginning to pay off; they have brought us to the verge of one of the greatest breakthroughs science has ever seen. We are, even now, getting the first glimpse of a theory that will show us in detail how the universe came into being, what it is made of, and how it is put together. Once achieved, this theory will unify all of nature, from gigantic clusters of galaxies down to tiny elementary particles. It will unlock secrets of the universe we never dreamed possible. In short it will give us the master plan—the blueprint—of the universe.

Excitement is running high in the world of high-energy physics as we close in on this goal. Particle physicists are working around the clock, stretching their imaginations to the limit in an effort to make things fit, setting up ever more complex experiments in hopes of finding the last vital pieces of the puzzle.

At one time it was thought that the atom was the ultimate building block of matter. But as small as atoms are, there are particles that are a million trillion times smaller. If you could construct a microscope powerful enough, you would see that the atom is mostly empty space, made up of a tiny nucleus consisting of protons and neutrons, surrounded by a cloud of electrons. The protons and neutrons are small, but the electrons are far smaller. As strange as it seems, they may take up no space whatsoever.

The secrets that physicists are after involve not the atom, but its building blocks—the electron, proton, and neutron. At one time it was thought that all three of these particles were elementary in the sense that they are "ultimate" building blocks, but we now know this is not the case. Inside the protons and neutrons are even smaller particles called quarks. Evidence for these quarks was found at Stanford University's large accelerator near Palo Alto, California, in 1969. Realizing that protons were much larger than electrons, and might have hidden structure, scientists decided to bombard them with electrons. In a sense it was a rerun of a famous experiment performed in 1911 by Ernest Rutherford in which alpha particles (helium nuclei) were projected at gold atoms. To Rutherford's surprise some of the alpha particles were deflected through large angles. This was inconsistent with the accepted atomic model of the time, and Rutherford soon realized a new model was needed in which the electrons orbited a tiny, but heavy nucleus. In the Stanford experiment similar unexpected deflections occurred; this meant there had to be small pointlike particles inside the proton.

But Murray Gell-Mann of Caltech, and independently George Zweig at CERN, had already suggested that protons were composed of more elementary particles. In fact it was Gell-Mann who gave them the whimsical name "quarks," from a line in *Finnegans Wake*, "Three quarks for Muster Mark!" Consistent with the quote there were three kinds of quarks in each proton and neutron. Coincidentally, there were also three kinds of quarks in Gell-Mann's scheme; he called them up (u), down (d), and strange (s). But soon, as other discoveries were made, it was found that three was not enough. First, with the unexpected discovery of a particle we now call J/psi came a fourth quark, which was named charm. Then came two others, called bottom and top, for a total of six.

How many quarks are there? We do not know for sure, but it appears that this may be the end of the line. Inconsistencies develop in cosmology—the study of the structure of the universe—if there are many more. Does this mean, then, that the universe is built entirely of quarks? No; if we look back at the electron we see that it isn't composed of quarks, yet it is elementary. In fact, just as there is a quark family, so too there is an electron family, or as it is usually called, a lepton family. And just as there are six members of the quark family, so too there are six members of the lepton family. Besides the electron there is a particle that is similar to it except that it is heavier; we call it the muon. The third member is also like the electron, but it is heavier yet; it is called the tau. Corresponding to each of these particles is an elusive particle that may have no mass; it is called the neutrino.

For a while the quark model seemed to solve the problem of the ultimate structure of matter, but eventually difficulties developed and a new concept called color had to be introduced to overcome them. Color, as we refer to it here, though, has nothing to do with the usual meaning of the word. Certainly quarks wouldn't be red or blue if we could see them. It is a property of quarks, similar to electric charge, that enables them to join together to form particles such as the proton.

In short, then, it appears as if our world is made up of twelve different types of particles, six of which can be colored. But, strangely, even this isn't the end of the story. Back in 1928 the English physicist Paul Dirac predicted that to every type of particle in the universe there was an antiparticle, and when an antiparticle and a particle met, they annihilated one another in a burst of energy. Shortly thereafter, the positron, a particle similar to the electron except that it had a positive charge (the electron has a negative charge) was discovered, verifying his prediction. This means that in addition to the families of quarks and leptons there are also families of antiquarks and antileptons.

But these particles have to be held together if we are to have nuclei, atoms, and large objects such as stars. And indeed the forces that hold them together have been known for some time. The best known is gravity, the force that holds you to the earth.

But there's also a force that holds atoms together, called the electromagnetic force, and within atoms we have neutrons and protons held tightly together in the nucleus by a force called the strong nuclear force. The last of the four forces, one we'll talk about in more detail later, is called the weak nuclear force.

An important breakthrough in our understanding of these forces came in the late 1960s. It was found that the electromagnetic and weak nuclear force could be described by the same theory, and furthermore, that they could be mixed together. Although it was not a true unification, it showed us that fields could be joined, and it soon led to an attempt to understand the other fields in terms of unification. Unification, as we will see throughout this book, is one of the great quests of physics. The participants in the quest are theorists and experimentalists. The theorists devise theories and make predictions; the experimentalists build equipment and carry out experiments to see if the predictions are correct. If not, the theory is discarded and a new one is found to replace it.

Dramatic developments have capped our search for unification. Physicists have found that the macrocosm—the universe—and the world of elementary particles are intimately related. The elementary particles and forces of nature as we understand them today, were "fused" during the first fraction of a second after the big bang explosion that created the universe.

The big bang was like a giant "atom smasher," or particle accelerator, as it is referred to by scientists. But the energies and speeds generated by it were far greater than anything we can create here on earth. It is because of this link that physicists are trying to build larger and larger accelerators; they hope to probe ever closer to the first moment of creation. Much of our knowledge of elementary particles has, in fact, been made possible by the use of accelerators.

Although you may not realize it, you have a small accelerator in your home—your TV set. In a TV set a beam of electrons is accelerated toward the screen using high voltages. Magnets direct the beam, sweeping it back and forth across the screen, creating a picture. High voltages and magnets are also important in the giant accelerators scientists use. The first accelerators were built in the early 1930s by John Cockcroft and Ernest Walton in England, and by Ernest Lawrence in the United States. While Cockcroft and Walton's accelerator worked on the same principle your TV does, Lawrence's instrument was quite different. His first instrument looked like a pillbox, about 4 inches across. Charged particles spiraling around inside this box were given a boost each time they passed a certain point.

One of the first goals was to produce a machine that would give charged particles an energy of one million electron volts (an electron volt is roughly the energy gained by an electron as it flows from the positive to negative terminal of a flashlight battery). Lawrence and Livingston were the first to achieve the goal, beating out Cockcroft and Walton, but in their race for higher energy they lost an even more important race. Cockcroft and Walton had considerably less energy available but they used their instrument where it counted—for experimentation. And lo and behold in one of their first experiments they observed nuclear disintegration. They lost the race for a million electron volts, but they won where it really counted—in the physics.

But in the long run it was the cyclotron, the accelerator created by Lawrence, that was to become the important probe of nature. Lawrence and Livingston continued building larger and larger accelerators, and soon others were also building them. About twenty were completed before World War II.

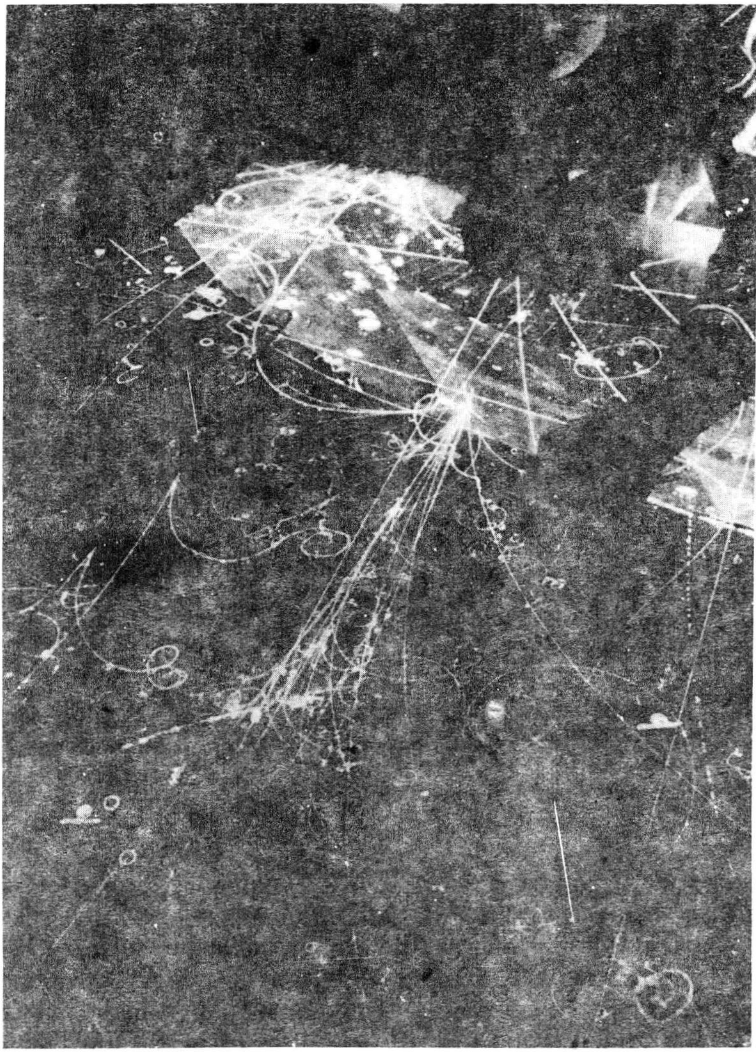
The war halted cyclotron production but it brought an important new concept: that of a "scientific team." Teams of scientists were set up at Chicago, Los Alamos, and Oak Ridge, and after the war confidence was so high, with the success of the atomic bomb, that it was believed such teams could do almost anything. National laboratories were soon set up. Lawrence Laboratory in California easily had the lead in cyclotron development, but an eastern equivalent—Brookhaven National Laboratory—was soon built.

And with these new labs and their accelerators came an influx of discoveries. At first everyone was excited as new particle after new particle was discovered. But eventually there were so many different types of particles physicists were overwhelmed. Willis Lamb, in his Nobel address, said, "The finder of a new particle used to be awarded a Nobel prize, but such a discovery now ought to be punished by a $10,000 fine." Most of the new particles were considerably heavier than the electron and proton, and all were extremely short-lived. We now know that these particles are not truly elementary particles, but are composed of quarks.

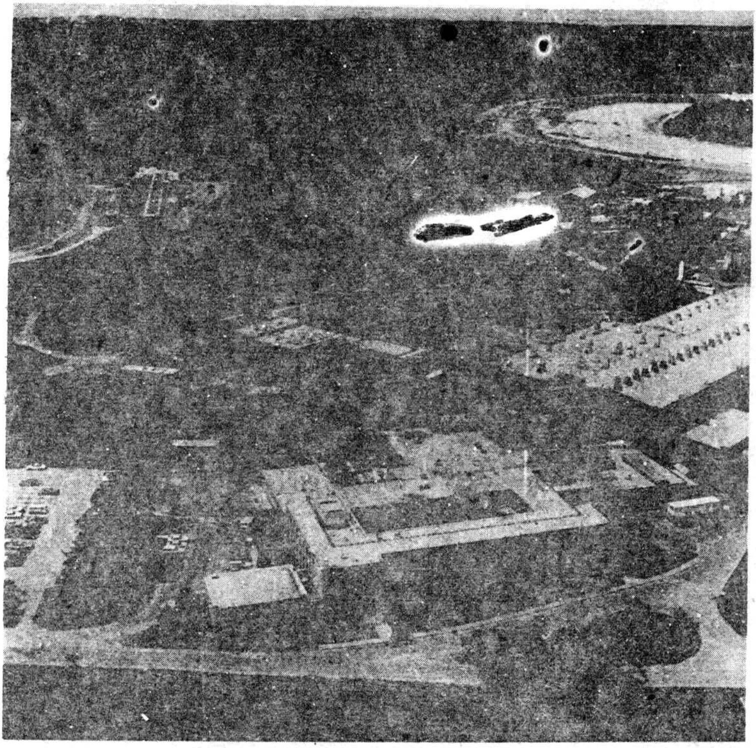
In the race to build large accelerators Europe was determined not to be left behind. In 1952 several European nations banded together and created CERN near Geneva, on the Switzerland–France border. Although they were years behind the United States when they began, they soon caught up. By 1962 Europe matched the United States in scientific manpower but by the late 1970s it had nearly 3000 particle physicists—twice the number the United States had. And its persistence eventually paid off. The quest for the elusive particles called W and Z that occur in the radioactive decay of atoms was a goal both groups were striving for in the early 1980s. They were found at CERN in 1983.

The Russians were also soon in the race. A facility similar to CERN for socialist countries was set up shortly after the war at Dubna, near Moscow. By 1954 they had completed a large synchrocyclotron (modified cyclotron). Americans were amazed at the progress the Russians had made—the synchrocyclotron was nearly twice the size of the Berkeley machine.

Following Brookhaven other facilities soon sprang up around the United States. A huge, two-mile accelerator, designed to accelerate electrons in a straight line, was built at Stanford University (called SLAC), and later a similar accelerator



Measuring particle tracks at Fermilab. (Courtesy Fermilab.)



Aerial view of the Alternating Gradients Synchrotron (AGS) at Brookhaven. (Courtesy Brookhaven National Laboratory.)

was built at Los Alamos. Then in 1967 America capped off its efforts with Fermilab at Batavia, Illinois.

The innocence of small-time physics was now long-gone. Where scientific experiments could once be done with small machines that stood on a desk, accelerators now snaked through underground tunnels several miles long. And where there were once three or four people working on a project there were now hundreds. The list of names on some scientific papers was almost as long as the paper itself.