
Hidden Worlds: The Search for Quarks in Ordinary Matter

BY MOST accounts, the quest to understand the basic structure of matter has been an old-fashioned success story of growth and expansion. Machines have become bigger; computers have gotten faster. Beams of light or particles have become brighter and more powerful. Interactions of elementary particles have become more fleeting, and have given rise to ever more energetic and more exotic by-products. The basic engine driving this growth, the particle accelerator, began as a tabletop instrument you could hold in your hand—and was no more powerful than a lightbulb. By the 1950s, accelerators had grown large enough to fill a small warehouse, and drew enough power to run a large printing press. Now they need farmland or rangeland to accommodate their dimensions, and enough power to run a medium-size city.

Higher energies enable experimenters to “see” finer and finer details, to probe and analyze matter at smaller and smaller scales. Today the world’s most powerful particle accelerators are operated at FermiLab, on the Illinois prairie about an hour’s drive southwest of Chicago, and at CERN (Council Européen pour la Recherche Nucléaire—The European Organization for Nuclear Research), the particle physics laboratory, in a rural suburb of Geneva just under the Swiss border with France. The FermiLab accelerator is a ring 4 miles around; inside the ring there is plenty

2 - CHAPTER 1

of room to pasture a herd of buffalo. At CERN, an even larger accelerator is under construction. When it comes into service in 2006, it will be 16 miles (27 kilometers) around.

At both these laboratories the combined accelerators and detectors are, in effect, magnificent microscopes that owe their magnifying powers to their ability to focus energy into electrons or protons that carry a trillion volts. With these energies both machines can resolve details in the structure of matter smaller than 10^{-18} meter across—a billionth of a billionth of a meter. And both machines are examples of science so big and so costly that they stretch the resources of individual sovereign states. CERN is funded by a European-wide consortium, and both laboratories are used by a collaboration of scientists from all over the world.

But the high price of the ability to probe such details is not measured only in dollars and cents. High energies can magnify, but they also carry great destructive power. It was often said in the early decades of high-energy physics that its basic investigative tactic was much like smashing two fine Swiss watches together in midair and then trying to understand how they worked by looking at the fragments. In fact, the true situation is even worse than that. Particles accelerated by today's state-of-the-art machines collide so violently that the collision fragments are often strikingly different from ordinary matter.

For many—even most—elementary particle physicists working today, that's just the point. The emphasis in the past few decades at such places as FermiLab and CERN has been to produce some of the most exotic particles predicted by theory, the “top” and the “bottom” mesons. On a different front, at Brookhaven National Laboratory on Long Island, a campaign is under way to create a “quark-gluon plasma,” a state of matter, as some physicists have described it, “not seen since the big bang.” Such phenomena can be studied only by accelerating, smashing, and, in effect, heating and squeezing ordinary matter to conditions beyond the edge of extreme: far beyond the temperatures and

THE SEARCH FOR QUARKS - 3

pressures prevailing even in the cores of the hottest stars, to regimes in which matter takes on strange and outlandish forms that do not exist at all in the universe as we now know it.

Yet in that rush to re-create such exotic conditions, and to study their implications for the birth, death, and ultimate structure of the universe, elementary particle physicists have almost forgotten the world in which we live. If the initial intellectual impulse was to probe the proton and the neutron in order to understand their role in ordinary matter, that impulse has virtually disappeared from the CERNs, FermiLabs, and Brookhavens of the world.

To my mind, that's a shame. I don't live at the dawn of time, and I don't live in a fantastically hot and energetic collision. I live in a world made up primarily of electrons, neutrons, and protons. And I want to know how they act and interact under "ordinary" conditions. I am a nuclear physicist, or to be more precise, a nucleon physicist. "Nucleon" is the generic term for neutron or proton, the particles that make up the atomic nucleus. My work and the work of my closest colleagues is dedicated to understanding the physics of ordinary nucleons, a layer in the onionlike organization of matter that gives rise to an incredibly rich set of phenomena. Those phenomena are quite literally destroyed among the debris of the highest-energy accelerators.

ORDINARY MATTER

Think about it this way: the universe that we understand is more than 99.95 percent neutrons and protons by mass. It is true that there are things we physicists don't understand, such as the stuff astronomers and cosmologists call dark matter. But the range of things we do understand in terms of electrons, neutrons, and protons is astonishing. Stars, those hot, glowing beacons in space, those light- and life-giving orbs suspended in the void, are made up of these three materials. Nebulae, the misty

4 - CHAPTER 1

veils of interstellar gas and dust that stretch like curtains across the galaxy, are made of the same stuff. Even the most exotic of stars, the so-called neutron stars, are made of the same three ingredients.

Closer to home, the wind, the rain, and the earth beneath our feet are made of these three building blocks. Even the substance of life itself—the blood coursing through our veins, the brain and nerve tissue that provide the scaffolding for our thoughts, the deoxyribonucleic acid (DNA) that carries the blueprints from which each of us is built—is made up entirely of electrons, neutrons, and protons. Books and tables, hands, hearts, and heads, are made of these three most basic substances.

At one time, not so many years ago, the study of such particles coincided with the frontiers of high-energy physics. One of the first laboratories I ever worked with was the National Instituut voor Kernfysica en Hoge Energie Fysica (NIKHEF) in Amsterdam, The Netherlands. Even if you don't speak Dutch, you can probably understand most of the name: read "hoge energie fysica" phonetically and you will hear "high-energy physics." Not so obvious is "kern-fysica," which corresponds to the English phrase "nuclear physics." Still, whether one uses the term "nuclear" or "kernel," the word is meant to emphasize the role of the nucleus at the very heart of the atom.

That's an important clue to understanding what stirs the soul of the nuclear and the high-energy physicist. When the word "nucleus" was coined in 1912, it was viewed as the "atom" had been before it: as the ultimate, indivisible, fundamental particle of matter. The nucleus stood at the core or kernel of the atom, the sun about which the planetary electrons orbited. Nuclear physics, therefore, was essentially a quest to discover and describe the most basic building blocks of the universe. When physicists discovered that the nucleus itself was divisible into nucleons and had structure, and that those nucleons also had internal structure, the "dream of a final theory" of ultimate particles had to be abandoned within the domain of nuclear physics. That dream

THE SEARCH FOR QUARKS - 5

was passed on to high-energy physics, a discipline that, by its very name, no longer defined itself by assumptions about where the ultimate particles would be found.

The NIKHEF accelerator could accelerate electrons to energies of 770 million electron volts (MeV). A 770 MeV electron beam can probe matter at a scale slightly smaller than a fermi, or 10^{-15} meter. That is just powerful enough to resolve structure in the atomic nucleus itself; you could say that NIKHEF marks the start of nucleon physics.

Another laboratory that I visited recently is called DESY (pronounced “daisy”), the Deutsches Elektronen-Synchrotron, in Hamburg, Germany. DESY’s beam energy is 30 billion electron volts (Giga electron volts [GeV]), 40 times more energetic than NIKHEF’s, which also makes its resolution 40 times finer. The trade-off is that DESY’s “field of view” is too small to be of much use for the study of nucleons. It could reasonably be argued that DESY marks the energetic upper limit of nucleon physics. The beam energy is so high that what you see are the “bare” constituents of nucleons. These constituents interact so violently that the nucleons themselves no longer maintain their identities, but become transformed instead into new and exotic particles. Indeed, most physicists at DESY identify themselves as high-energy physicists, not nuclear or nucleon physicists at all.

Beyond DESY, the high-energy frontier has moved even farther on, to CERN, to FermiLab, to Brookhaven, and elsewhere. NIKHEF and other accelerators of its class have long since been displaced as record holders for high energy, just as they had displaced their predecessors. But the continual historical advance of the high-energy frontier hardly means that the “captured” territories have been subdued, much less fully mapped or colonized. The physicists rushing ahead with plans for ever more powerful accelerators, for probing ever more deeply into the ultimate building blocks of matter, have seldom stopped to fully plumb the structures that they found along the way. Yet nucleons represent a level in the organization of matter having exceptional

6 - CHAPTER 1

stability, unique in the universe. Many physicists, and I am one of them, want to know as much as possible about electrons, neutrons, and protons.

WHAT MAKES A NUCLEON?

Just what do we physicists already know about these three particles? In the case of the electron, the summary can be quite brief. Electrons stand stark and innocent before us. What we see is essentially what we get: infinitesimally small particles, each with one unit of negative electric charge (-1), a spin of $\frac{1}{2}$, and a mass of 9×10^{-31} kilogram—some 2,000 times lighter than either the proton or the neutron.

And that is all. We can say no more about the physical properties of the electron because it appears that there is nothing more to say. I don't mean to be dismissive about the electron or its physics. Electrons are undoubtedly useful to twenty-first-century humankind, when we push or pull them through wires in the form of electricity. They are fundamental, of course, to the architecture of matter: the number of electrons and their orbital patterns in an atom or a molecule are what give rise to all of chemistry. Finally, the self-interaction of the electron is at the core of one of the greatest theoretical successes of the twentieth century: quantum electrodynamics, or QED. QED serves as a prototype on which theories of other particles (the quarks) are modeled. And QED has generated some of the most precise, experimentally confirmed predictions in all of physics.

But the electron itself appears to be truly elementary. Electrons seem to have persisted unchanged since the dawn of time, and they are likely to remain as they are, immortal, until the final sunset of the universe. There is no evidence that anything exists inside the electron; there are no "ultimate electrons" rattling around inside its shell. In all experiments ever performed it really and truly appears to be pointlike.

THE SEARCH FOR QUARKS - 7

Not so the nucleons: the proton and the neutron. A hundred thousand times smaller than the smallest atom, both the proton and the neutron are measured in fermis. Yet as small as that might be, there is a world hidden inside each one. At first glance that world appears to be exceedingly simple. Protons and neutrons are each made up of exactly three particles known as quarks. Whatever quarks really are, just think of them for the moment as three balls rattling around inside of the sphere we call a proton or a neutron. There are two common kinds of quark, known as the up quark and the down quark. The proton is made up of two up quarks and one down quark. The neutron reverses those numbers: it is made up of one up quark and two down quarks. The fact that the proton and the neutron each have three quarks gives rise to striking similarities in their masses, sizes, and interactions. But that single difference, an extra up quark in the proton, an extra down quark in the neutron, also accounts for their unique characteristics: their differing electric charge, their decay patterns, and the details of how they couple.

The genesis of such profound differences merely out of varying combinations of simple parts should not be too surprising. Science has vast experience at larger scales with objects whose distinctive properties arise out of the number, identity, and arrangement of their parts. The familiar shorthand for specifying molecules takes tacit advantage of the fact that it is often enough just to enumerate their elemental components: H_2O —water—is two parts hydrogen and one part oxygen. Of course there are cases in which one set of atomic ingredients (such as $C_6H_{12}O_6$) can give rise to two or more distinct but related molecules (in this case, glucose and fructose). Chemists call them isomers.

When we ratchet up the magnification and view the world on the atomic level, the very identity of an atom—the definition of its elemental type—depends solely on the number of protons in its nucleus (which is equal to the number of electrons orbiting that nucleus, in the electrically neutral atom). Helium is helium because it has two protons and two electrons. Carbon is carbon because it has six protons and six electrons. Quantum mechanics

8 - CHAPTER 1

dictates how those six electrons in the carbon atom arrange themselves physically, and that arrangement in turn ordains the chemistry of carbon: what it will bind to, with what strength, in what configurations. The concept of isomer has an analogue in atomic physics as well: a given element can come in several forms known as isotopes, chemically almost indistinguishable from one another, but different nonetheless in the number of neutrons that share real estate in the nucleus with the protons.

In sum, it seems entirely natural that the properties of the proton and the neutron themselves arise from the number and arrangement of the quarks that make them up. One of the chief burdens of this book is to show how their properties and configurations give rise to a “quark chemistry” of remarkable complexity—just as the configurations of atoms in molecules and the configurations of electrons in atoms give rise to ordinary chemistry. The concepts of isomer and isotope, for instance, have an analogue in the world of quarks, as we shall see with such particles as “ Δ s” and “Ropers.”

IN VITRO VERSUS IN VIVO

But before exploring those details, the very idea of quark chemistry can shed light, I think, on a curious question that afflicts nucleon physics with far more confusion than seems necessary. The question goes to the heart of the discipline: just what is nucleon physics? I once posed this question to a number of my colleagues during lunch at a conference at a laboratory that specializes in what I call nucleon physics, the Jefferson Lab, in Newport News, Virginia. And I was surprised to find that even my use of the phrase “nucleon physics” was controversial. Some people wanted to call it “intermediate-energy physics,” a name motivated partly by the kinds of accelerators the work relies on and partly by the recognition that the study of the quarks inside nucleons bridges the study of the role of nucleons in the atom (nuclear physics) and the study of high-energy physics proper.

Yet most of the physicists at our lunch saw what we nucleon physicists do as less of a branching away from nuclear physics than as an extension of it—and an obvious extension at that. Further muddying our discussion is the way physicists identify themselves: who is a nucleon physicist and who is a high-energy physicist? Two experimentalists working side by side on the same experiment might identify themselves as “nuclear” or “high-energy” physicists, not on the basis of the experiment at hand, but rather on the basis of their own experiences in graduate school. Physicists who had been part of a high-energy research group in graduate school might wear that tag for an entire career. Likewise, physicists whose advisors called them “nuclear” could carry that label into retirement.

Perhaps it is not surprising that the labeling of physicists is a social, hence largely accidental, phenomenon. But the labeling of the subdisciplines of physics need not be the product of historical accident as well. Part of the confusion about nucleon physics stems from the historical shift I noted earlier in the boundaries of high-energy physics. A 1 GeV electron accelerator in the 1960s clearly belonged to the high-energy community, whereas at present it is the province of the nuclear physicist. What that early convergence in labeling concealed was that the two fields have named themselves according to different criteria. Nuclear and nucleon physics are named after the subjects they study; high-energy physics is named after the machines and detectors it uses. If nucleon physics was once “high-energy” physics, but the high-energy frontier has now moved on, doesn’t it follow that nucleon physics has now become “intermediate-energy” physics?

The answer is no. But let me try to clarify the situation by moving from a chemical analogy to a biological one. In biology, laboratory workers often remove and purify a cell line to study the cells “in vitro,” that is, in a test tube. (“In vitro” literally means “in glass.”) In vitro studies can give “clean,” unambiguous results. Any variables—temperature, radiation, chemical concentrations—that might affect the results can be scrupulously controlled. But no biologist would jump to the conclusion that

10 - CHAPTER 1

some result observed in a test tube or petri dish implies that the same results would necessarily unfold “in vivo.” (“In vivo” means “in life,” that is, in the living organism.) The effect of a drug on cells in vitro, for instance, might be quite different from its effect on those same cells in their natural habitat, the body of the organism from which they come. The behavior of cells in vivo is often so complex and so different from their behavior in vitro that in vivo study is a complementary discipline in its own right.

Once I was at a computational workshop at FermiLab when I was asked what distinguished the studies of protons, neutrons, and their quark constituents that we pursue from the studies that high-energy physicists make of the same particles. My answer was “in vivo versus in vitro.” The proton and neutron physics we study is the study of quarks in vivo, in their natural home within the body of a nucleon. High-energy physics looks at quarks in a more rarefied, extra-nucleon environment. It turns out that nature forbids the observation of a single quark, but you can infer a great deal about the nature of quarks from the fragments they form. To pursue the Swiss watch analogy, nucleon physics studies the watch by listening to its ticks, and, without opening it, tries to infer what is going on inside.

So I propose the following working definition of the differences between nucleon and high-energy physics:

High-energy physics is the study of quarks, gluons, bosons, and other exotic, fundamental, and elementary particles of nature, whereas nuclear/nucleon physics is the study of these particles as they combine to form normal matter; as they combine within the hidden world buried inside protons and neutrons.

CONFINEMENT

No matter how you study quarks, one of their most distinctive properties makes investigating them a peculiar and difficult exercise: quarks are always hidden, buried deep within some larger

THE SEARCH FOR QUARKS - 11

particle. No one has ever been able to isolate a single quark. It is not just that we have not been clever enough to build a “proton smasher,” or some better machine or experiment. Rather, nature has contrived its laws in such a way that not only have we never seen an isolated quark—but we never will! That is the root of a great deal of frustration, and at the same time the source of the scientific challenge that we explore in this book.

So how do we proceed? Shouldn't this “non-observability” lead to a kind of intellectual crisis? Doesn't the forward movement of science have to be fueled by observation? Yet—it bears repeating—*we will never observe quarks*. I suspect that a staunch positivist would have a field day with the quark hypothesis. We cannot see them, or even detect them, yet we know a great deal about them. To overcome that limitation we will have to examine and rethink what is meant by good evidence. In fact, a special emphasis of this book is to consider how we know what we claim to know.

A lot of books about contemporary science report the end products of a generation of research. A book on quarks would give great prominence to the hard-won list of their six known “flavors.” But for me the road to these results is at least as interesting as the results themselves. The issue is one of personal taste and appreciation, but let me try to explain it this way: I admire the great beauty of a medieval cathedral such the Dom, in Graz, Austria, or York Minster, in northern England. But when I think about how these vaulting expressions of the human spirit were handcrafted in a preindustrial age, without girders of iron or steel, the cathedrals are transformed to my sensibilities from the merely beautiful to the truly magnificent.

So how can we know anything about something we cannot even see or sense? Briefly, the solution is to make theory and experiment work so closely together that they become interleaved. Given a theory of quarks, how might a proton be built out of them, and what, under various testable conditions, would we see? Then, when we do see something that roughly matches those expectations in our experiments, we promote and fine-tune the theories that predicted it. These general procedures

12 - CHAPTER 1

hold for any attempt to reconcile theory with experiment. Yet our experiments that look at the way quarks combine to build particles are not like the ones conducted at the high-energy laboratories such as the Stanford Linear Accelerator Center (SLAC) in California, or FermiLab, or CERN. Instead of hurling particles at each other with such fury and energy that they are destroyed, we tickle and excite the particles. In that way we study the quarks “in vivo.”

THE SECRET LIVES OF QUARKS

The laboratories that measure the shape and excitations of protons and neutrons “in vivo” are of modest proportions, compared with high-energy facilities. The energy of the electron beam at Jefferson Lab can reach roughly six billion electron volts. MIT-Bates Lab, north of Boston, has an accelerator capable of delivering particles whose energy reaches a billion electron volts, 1,000 times smaller than the “Tevatron” at FermiLab. But these laboratories do have unique features. They deliver high currents with high precision, and they can manipulate the alignment and orientation of the spins of the electrons, protons, and neutrons. By using these so-called polarization tools they can disentangle the nuclear effects from the quark effects, nudging out the secrets of the proton and the structure of the neutron.

“A riddle wrapped in a mystery inside of an enigma.” Winston Churchill’s words could apply to quarks as well they did to the old Soviet Union. What are these most lilliputian particles that lie forever hidden from our gaze? What are we trying to measure in our nucleon physics laboratories? One curious property of protons and neutrons is that they vibrate at certain fixed, resonant frequencies; they have a number of natural “harmonics.” We will talk about how to “ring” a proton—that is, hit it hard enough to make it resonate. That very concept brings us back to the interplay between theory and experiment, which is so important for unraveling the riddles of the quark. A good theory should explain

how hard we need to strike a proton to get it to ring. A good theory should be able to predict the magnitude, shape, and energy of a resonance. It should also explain why such resonances exist, and then go a bit further, and predict what no one has ever seen. At the same time, a good experiment should be able to distinguish among an entire spectrum of candidate theories, identifying the good ones and rejecting the ones that diverge from the data. On occasion an experiment should even show us something the theorists had never thought of modeling with their theories. Sometimes an observation is completely unexpected.

Resonances are just one test, only one of the kinds of clues we have to solve our mystery. We can also ask, What is the shape of a neutron or a proton? Are the quarks inside them rigidly fixed in space, or do they float about freely? Or perhaps the truth is something in between: do the up quarks tend to congregate in one region of the nucleon and the down quarks in another? How do these quarks orbit and swirl around each other?

Three quarks, sometimes exhibiting a resonance, sometimes performing a quantum mechanical dance—is that all there is inside a proton or a neutron? Yes and no. When we peek just beneath the surface of the proton, all we see is this simple choreography of three quarks. But on closer inspection something else is going on. There seem to be emissaries dashing back and forth between the stately quarks. The intermediate particles are called gluons. They make the quarks aware of one another, and, as their name implies, they bind the quarks together. These gluonic emissaries can add their own jigs to the dance, giving rise—perhaps—to a new resonance, a new harmonic “ring.”

After watching the ballroom floor for a while, we start to notice other dancers. Wasn't there another couple of quarks swirling around each other off in a corner, just for the briefest moment? They seemed to pop into existence and then vanished again. Yet somehow they did it without defying that cardinal rule: three quarks and three quarks only on the dance floor.

To understand how we can see this quantum choreography, this stately waltz, we need to discuss three major tools of the

14 - CHAPTER 1

trade. How can accelerators push electrons nearly to the speed of light? (Only then do they have enough energy to ring or tickle a nucleon.) Curiously enough, these fascinating machines are built essentially out of microwaves and magnets. How do we detect particles such as protons and neutrons, which are a quadrillionth of a meter across, or electrons, which are even smaller, with little more than charged wires and plastic that glows? And how can we find our way through a terabyte of data (a terabyte is a million megabytes), and then say that we “saw” the shape of a neutron, or “heard” the delta resonance, or “felt” the vibrations of the dancing gluons?

The evidence is indirect, and so we need to proceed deliberately, one step at a time. But the idea that within my lifetime a whole new world has been glimpsed inside of the proton and the neutron is intriguing and exciting, an intellectual adventure of the highest degree. “Three quarks for Muster Mark!” wrote James Joyce in *Finnegan’s Wake*, with seeming prescience. By the time he wrote that last novel, Joyce was nearly blind. Now we too will find out how much we can get to know without really being able to see.