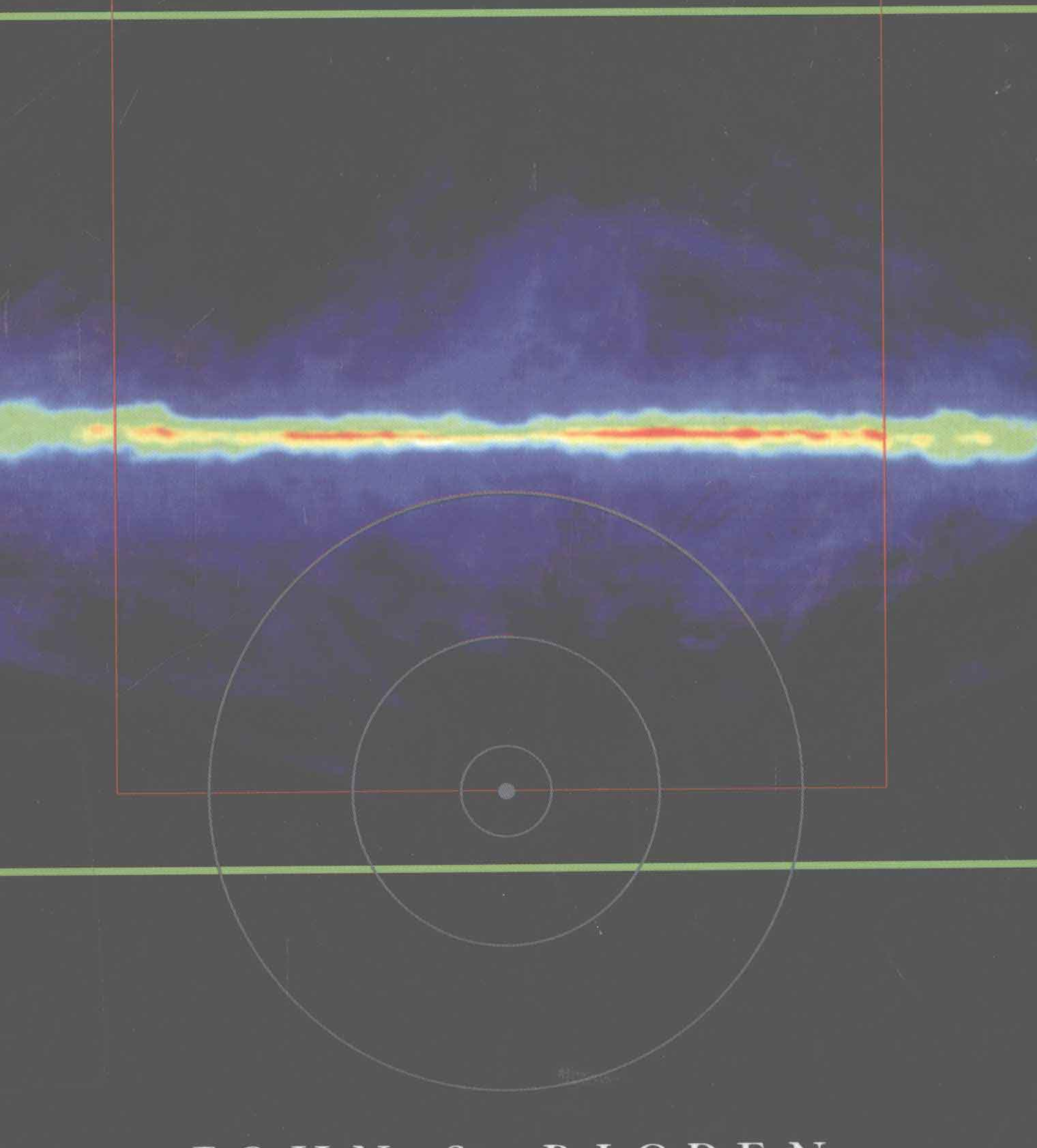
HYDROGEN

The Essential Element



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Prologue

Hydrogen is the most important constituent of the universe.

—Gerhard Herzberg

The heroine of this book is nature's simplest atom, the hydrogen atom. With one exception—the helium atom—hydrogen is the mother of all atoms and molecules. The hydrogen atom consists of a single electron and a single proton; the proton is the nucleus of the hydrogen atom and serves as the electron's anchor. The universe is teeming with hydrogen: every cubic centimeter of dark interstellar space, essentially void of any other known matter,[1] contains a few atoms of hydrogen. At the other extreme, every cubic centimeter of the planet Jupiter's interior contains in excess of 10 million billion billion (10^{25}) atoms of hydrogen. And every star, throughout its long life, illuminates its cosmic neighborhood with light that originates with the burning of the atom that dominates its material composition—hydrogen.

One must not dismiss this chemical element because of its simplicity. In fact, it is the simplicity of the hydrogen atom that has enabled scientists to unravel some of the mysteries of nature. This humble atom has consistently surprised the most distinguished (and confident) scientists and contributed to our understanding of the natural world.

This book, however, is more than a book about the hydrogen atom. It is a drama, written for the general reader, in which the intriguing hydrogen atom plays a starring role. Each chapter unfolds a particular episode in which hydrogen has led scientists to new scientific insights.

Collectively, the twenty-three chapters that follow reveal much about the conduct of science. On one level it is a focused story that chronicles the hold the simplest atom has had on the minds of the world's greatest scientists over the decades reaching back into the nineteenth century. Niels Bohr, Arnold Sommerfeld, Otto Stern, Werner Heisenberg, Wolfgang Pauli, Erwin Schrödinger, Paul Dirac, Harold Urey, I. I. Rabi, Norman Ramsey, Edward Purcell, Felix Bloch, Willis Lamb, Daniel Kleppner, and Theodor Hänsch all have advanced and refined knowledge of the physical world through their fascination with the hydrogen atom.

On another level, the story of hydrogen reveals how science is conducted. Physical theories are created to provide explanatory schemes whereby the observed world can be understood with quantitative precision. Those theories that capture the support of scientists are those that allow detailed predictions to be made and lead to new insights into the natural world. Good theories are simple theories that unite disparate realms of experience. Physical theories, however, must always yield to the demands of experimental data. Experimental facts are incontrovertible. If they are not accommodated by theory, the theory is held in question. Theories, good theories, are not quickly abandoned. Strenuous effort is exerted to refine a good theory so that experimental facts can be explained. In the final analysis, however, experimental results, once tested and retested, once verified by independent experimental methods, ultimately rule. Dirac's theory was elegant and beautiful, but in the face of data from Lamb and Rabi, it fell short. Their data then became the stimulus for the more powerful theory of quantum electrodynamics.

The experiments on the hydrogen atom chronicled in these chapters demonstrate the significance of precise measurements. Although all scientists seek to refine their experimental procedures to minimize the uncertainties in their measured results, uncertainties of several percent are typical. However, to expose shortcomings in theories and to test their limits, precise results are often necessary. The hydrogen atom has been the premier physical system for challenging theoretical constructs and precise measurements are the *sine qua non* when hydrogen is the subject of investigation. Furthermore, precise measurements can reveal unexpected results. In Rabi's series of experiments to measure the magnetic moments of the proton and deuteron, uncertainties were reduced from 26 percent to 0.7 percent. With the improved precision, evidence for a new property of the nucleus, the quadrupole moment, was found lurking in the data.

Through the example of hydrogen, we have also seen how basic science may lead to practical applications. Basic science typically operates far from the technological applications that predictably follow. The objective of basic science is to learn how the world works. Nonetheless, the knowledge gained through basic research and the methods developed to probe the natural world frequently hold within them the potential for very practical and welcome uses. The magnetic resonance method discovered by Rabi and his group of students led to nuclear magnetic resonance at the hands of Purcell and Bloch, which in turn led to the powerful medical diagnostic tool of magnetic resonance imaging. Ramsey's and Kleppner's hydrogen maser clock is an integral part of the technology of global positioning systems, which have manifold applications.

When nature's ways are understood, applications follow that can be used for good or bad, for peace or war. Consider the fusion of hydrogen. Einstein's relativity theory, basic physics at its best, showed how nuclear fusion could produce vast amounts of energy. Applications were soon understood. On the one hand, for example, it was understood that the fusion of hydrogen occurs in the Sun and its energy nurtures life on planet Earth. On the other hand, the fusion of hydrogen can occur in a bomb and its energy can inflict devastating destruction. The hydrogen bomb is an important part of the hydrogen story and it could have been the subject of a chapter in this book. I decided against it for two reasons. First, the prominent theme of the following chapters is how the hydrogen atom led to new basic scientific knowledge. The fusion bomb does not fit into that theme. Second, there is a vast literature on the hydrogen bomb and another chapter seemed hardly necessary.

Science is an international enterprise, which the examples in this book make clear. Although communities may differ enormously in their cultures, their religious convictions, their artistic expressions, and their political structures, in the arena of science, the world's diverse human groups are unified. There is no German science, no Asian science, no Hindu science. Bose was Indian, Einstein was German, but the two came together as scientists and predicted a new form of matter—the Bose-Einstein condensate, which was eventually verified by American scientists.

This book further illustrates how science itself has changed over the decades. The early chapters typically have one name associated with them. In earlier eras, science was such that an individual could work alone and make significant contributions. The experimental apparatus was relatively simple, could be constructed by one scientist, and put together on a laboratory table. As science progressed through the twentieth century, however, it became more specialized, and the experimental apparatus required became more complex. Many talents are now required to conduct an experiment and science has become a group activity. Many scientists have measured the Rydberg constant and could have been identified along with Hänsch. Four experimental physicists were identified with the discovery of the Bose-Einstein condensate, and no one was identified with the discovery of antihydrogen simply because many scientists at different laboratories were involved.

The hydrogen atom has intrigued physicists because its simplicity allows conceptual models to be created and then tested against experimental data. The inherent logic of a conceptual model is expressed mathematically and the simplicity of the hydrogen atom permits the resulting mathematical expressions to be solved exactly and compared directly with experimental data. This is physics at its best.

At various times in the history of physics, there has been a tendency for physicists to believe that the time to unravel the final mysteries of nature was at hand. In response to this malady, I once wrote a short piece entitled "H Stands for Hydrogen . . . and Humility."[2] (This piece, I am told, hung for a period on an office wall at CERN, the high energy physics laboratory in Geneva, Switzerland.) In the essay I raised a cautionary note about claims that we were nearing a "grand unified theory" that would explain all physical interactions or that we were nearing a complete understanding of such momentous questions as how the universe began. "The hydrogen atom," I wrote, "still beckons."

1

In the Beginning: Hydrogen and the Big Bang

If God did create the world by a word, the word would have been hydrogen.

—Harlow Shapley

The story of hydrogen begins before there was anyone to notice. Long before the Earth and its planetary siblings existed, before the Sun and the Milky Way existed, and even before chemical elements like oxygen, sodium, iron, and gold existed, the hydrogen atom was old, old news.

According to current wisdom, our universe began about 15 billion years ago at a point with infinite density and infinite temperature. That was the beginning of time; that was the origin of space. Since then, the original point has expanded in all directions to the dimensions of the current universe. As the universe expanded, the cosmic clock ticked and the temperature cooled: at 0.01 second after the big bang, the temperature was 100,000 million degrees K; 0.12 second, 30,000 million degrees K; 1.10 seconds, 10,000 million degrees K; 13.83 seconds, 3,000 million degrees K. By the time the universe was four minutes old, the basic ingredients required for all that was to follow were present and their basic modes of interaction were established. The stage was set for everything that followed.[1]

Hydrogen is the simplest of all atoms. In its dominant form, hydrogen consists of one electron and one proton; in its rare form, called deuterium, there are three particles: an electron, proton, and a neutron. By contrast, ordinary water, a simple molecule, consists of twenty-eight particles: ten electrons, ten protons, and eight neutrons. The water molecule is very complicated when compared to the hydrogen or deuterium atoms. Because of its simplicity, hydrogen dominates the 15 billion-year tale of our universe. Approximately 300,000 years after the origin of our universe, the temperature had cooled to approximately 3,000 degrees and the hydrogen and helium atoms took their characteristic forms. Even this early, a particular kind of universe was inevitable: a universe that would eventually become a hospitable haven for life.

When atoms first began to take form, the ingredients available were limited. There were photons (particles of light) and neutrinos, and elementary particles of matter—electrons and protons (the nucleus of the hydrogen atom is a proton). There were composites of elementary particles—deuterons, a proton plus a neutron (the deuteron is a special part of the story told in this book because it is the nucleus of the heavy hydrogen atom, deuterium), and alpha particles, two protons plus two neutrons (the nucleus of the helium atom is an alpha particle). By the time the universe was 300,000 years old, neutrinos were aloof from their surroundings and did not participate in the birth of atoms, and photons were not essential to the atom-forming process. So, to form the first atoms of our universe there were electrons, protons, deuterons, and alpha particles. In this mix, protons outnumbered alpha particles by about eleven to one. The deuteron was a mere sprinkling in the mix. Thus, when atoms formed, the ingredients present coupled with the particle recipes for hydrogen and helium resulted in an atomic mix of about 92 percent hydrogen, 8 percent helium, and a fraction of a percent deuterium. Today, 15 billion years after hydrogen and helium were first formed, these elements remain the most abundant throughout the cosmos: hydrogen makes up approximately 90 percent of the total, whereas helium comes in at about 9 percent.

Since the ingredients for hydrogen and helium atoms—elec-

Figure 1.1 A cosmic cloud of hydrogen, where stars are born, in the form of a pillar, as seen by the Hubble Space Telescope. The globules are forming stars. This picture of this cloud, in M16, was taken by John Hester and P. Scowen in 1995.

trons, protons, and neutrons—were present in the earliest seconds of the universe, why did it take 300,000 years before atoms appeared? Dropping temperatures over this span of years slowed the rapidly moving protons and electrons to speeds that allowed the electrical attraction between them to challenge their independent motions, bring them together, and form stable atoms. In fact, even the strongest force of nature, the nuclear force, was not strong enough to pull the frantic protons and neutrons together into nuclei during the earliest seconds of the universe. It was not until the universe was about fourteen seconds old and had expanded and cooled considerably that the first nuclei, alpha particles, formed. The early formation of alpha particles testifies to their stability. Deuterons, while simpler than alpha particles, are not as stable. Consequently, they did not form until the universe was almost four minutes old.

The primordial period of nuclear synthesis was all over by the time the universe was four minutes old. Nuclei heavier than that of helium—nuclei of beryllium, boron, and carbon, for example—did not form because these heavier nuclei could not compete with the inherent stability of the helium nucleus. Thus, all the free neutrons that were still available at the four-minute point took refuge in either the helium nucleus or the heavy hydrogen nucleus.

Essentially all the heavy hydrogen in the universe today originated during the first minutes of cosmic time. One thousand tons of heavy water, used to detect solar neutrinos, fill the tank at the Sudbury Neutrino Observatory in Sudbury, Ontario. This heavy water, each molecule of which consists of one oxygen atom, one hydrogen atom, and one deuterium atom, brings together deuterium that was formed when the universe was about four minutes old. When you hold a tube of heavy water in your hand, you hold primordial atoms, remnants from the first moments after the big bang.

Today, 473 million billion seconds after the big bang, the temperature of the universe has dropped to three degrees above absolute zero. Embedded in this frigid environment are galactic systems distributed across the far reaches of the observable universe. Each galaxy consists of stars and dust clouds. Each star, each dust cloud in each and every galaxy consists of about 90 percent hydrogen atoms and 9 percent helium atoms. Because of this composition, established approximately 15 billion years (or 473 million billion seconds) ago, the stars twinkle and the Sun shines.

The Sun is a typical star. The composition of the Sun (as well as other stars) reflects the cosmic abundance: about 90 percent of the atoms making up the Sun are hydrogen. And it is the fusion of hydrogen that fuels the Sun. Every second, 600 million tons of hydrogen are fused into helium in the core of the Sun, releasing prodigious energy that slowly makes its way from the core to the Sun's surface, heating it to a temperature of 5,800 K. The Earth, 92 million miles away, basks in this life-giving warmth.

Approximately 3.5 billion years ago, life emerged on at least one planet orbiting one star. There may be planets other than Earth that nurture life: we simply do not know. On planet Earth, hydrogen remained obscure for many centuries. Paracelsus (born Theophrastus Bombast von Hohenheim) noted during the early years of the sixteenth century that when acids attacked metals, flammable gas was a by-product. He had unknowingly observed hydrogen. Other chemists and physicists produced hydrogen and in 1671 Robert Boyle described its properties. As is frequently the case in science, the credit for discovering hydrogen rests on how "discovery" is defined. The credit for isolating and characterizing hydrogen goes to Henry Cavendish, who isolated hydrogen and determined its density in 1776. The French chemist Antoine-Laurent Lavoisier, whose head was severed by the guillotine on May 8, 1794, gave hydrogen its name.

The world as we know it is a consequence of the balance between the number of hydrogen nuclei and the number of helium nuclei, established in the early moments after the big bang. Perhaps it is preferable to say that the world is a consequence of the basic laws that *produced* this particular blend of hydrogen and helium. Did the laws of nature exist prior to the origin of the universe? Did the laws of nature take their present form at the instant of the big bang? One millionth of a second after the big bang? No one can say. Looking back, however, we can say the following: if the weak force had been just a little weaker, the free neutron would decay a little more slowly and, as a result, the universe would have started out as predominantly helium rather than hydrogen. A world without hydrogen is a world without water, a world without carbohydrates, a world without proteins—a world without life.

So take your pick. We can say that the world is the way it is because the laws of nature are the way they are. Or we can say that the world is the way it is because hydrogen is the way it is. Whichever you select, one or the other, is a matter of preference. Either way, the little hydrogen atom commands the stage on which the long and enchanting drama of our universe, the story of galaxies, stars, planets, and life, unfolds.