1

THE EPIC QUEST

Curious individuals have speculated about nature and humankind's place in it for all of recorded history. The interests of the ancient Greeks included the structure of matter on the smallest scale and that of the Universe on the largest (see, for example, Weinberg 2015). Some of their ideas were surprisingly similar to our modern understanding. Leucippus and his student Democritus proposed in the fifth century BCE an atomic theory in which matter ultimately consists of indivisible atoms that come in various sizes and shapes, accounting for the myriad materials and their properties that we observe. Aristarchus of Samos later proposed a heliocentric cosmology in which the planets rotated around the Sun and the distant stars were similar in character to the Sun. The technology did not exist to test either of these ideas until millennia later, and in fact there were alternative ideas that were more widely believed. Nevertheless, they illustrate the ingenuity and the craving for understanding of the human mind.

The atomic theory was not completely established until the nineteenth and early twentieth centuries, and the understanding of the structure of the atom and of the quantum-mechanical rules that govern its behavior were not fully worked out until some decades later. These ideas, combined with the parallel understanding of electricity and magnetism and of the kinetic theory, form the physical basis for chemistry, electronics, macroscopic matter in all its forms, and even biology.

By the late 1920s, it was known that the atom consists of a cloud of one or more electrons held in place by electrical forces as they orbit a tiny but very massive nucleus. Furthermore, the dynamics are governed not by the venerable classical mechanics of Isaac Newton, but by the weird quantum mechanics according to which electrons seem to be both particles and waves simultaneously. However, this understanding raised many more questions, such as the details of atomic transitions from one level to another. Similarly, what was the nature of the nucleus? Could the different nuclei somehow be composed of protons and electrons? What were the rules that govern the radioactive decays of nuclei that had been observed in the late nineteenth century? How could quantum mechanics, which governs the very small, be combined with Albert Einstein's relativity, which modifies the notions of space and time for rapidly moving observers or in the presence of matter?

Theoretical and experimental developments in the decades surrounding World War II answered some of these questions while raising others. Quantum theory and special relativity were elegantly combined in the Dirac theory and in the quantization of the electromagnetic field. The former predicted the existence of antimatter, which was subsequently observed. The neutron was discovered, and the basic structure of the nucleus as consisting of protons and neutrons held together by a complicated new *strong interaction* were gradually understood. Similarly, the properties of the *weak interaction*, which is responsible for one form of radioactivity (β *decay*) were gradually worked out, and the apparent non-conservation of energy in β decay was finally understood to result from the non-observation of an almost ghostly *neutrino*. The interactions of high-energy particles from cosmic rays or that were artificially accelerated in cyclotrons and subsequent particle accelerators led to the discovery of additional fundamental particles and of systematic properties of their interactions.

These advances led to the new fields of nuclear physics and then of *elementary particle* (or *high-energy*) physics, which sought to systematically understand the properties of the smallest constituents of nature and their interactions. For some 20 years, there was both confusion and painfully slow progress, involving mathematical difficulties in the theories and a proliferation of particles. Finally, however, what we now call the *standard model* (SM) of the elementary particles and their interactions was completed by the early 1970s. In the next 40 years or so, essentially all of the predictions and ingredients of the SM were experimentally verified, often in great detail, the most recent being the discovery of the *Higgs boson* in 2012. The standard model is a mathematically consistent theory that accounts for essentially all aspects of ordinary matter down to a distance scale of $\mathcal{O}(10^{-16}\text{ cm})$.

Despite these successes, the standard model is incomplete: It is very complicated and apparently arbitrary.

The strong, weak, and electromagnetic interactions are very different. Although all are based on the elegant concept of *gauge invariance*, they are not truly unified with each other. A quantum-mechanical description of gravity is not included, although classical general relativity can be grafted on. Furthermore, the SM involves numerous fundamental parameters whose values are not explained. Some of these appear to be fine-tuned to incredibly small (but nonzero) values. There is no explanation of why the electric charges of all particles are integer multiples of $e/3$, where $-e$ is the charge of the electron, nor is there an explanation of the observed excess of matter over antimatter. The neutrinos, initially thought to be massless, are now observed to have nonzero masses much smaller than those of the other fundamental particles. The origin and even nature of these oddball masses are yet to be determined. Finally, the astronomers have determined that the ordinary matter that we are made of and that is described by the SM is only a small fraction of the matter and energy in the Universe. The natures of the dark matter and dark energy are unknown. There is almost certainly a more fundamental desciption of nature that incorporates and extends the SM, generally referred to as *new physics* or *beyond the standard model* (BSM).

There are many ideas for "bottom-up" extensions, with such names as *supersymmetry*, *compositeness*, or *extra space dimensions*, which address some of these issues and which might be manifested in future accelerator and other experiments. "Top-down" ideas, such as *grand unification* or the even more ambitious *superstring* theories could possibly lead to an ultimate unification of the microscopic forces, perhaps including quantum gravity and tackling the origin of space and time. These mainly manifest themselves at incredibly short distance scales that are nearly impossible to directly probe experimentally (with *proton decay* a notable exception), but they might be tested indirectly by their predictions for the low-energy parameters or for new particles or interactions.

There have also been enormous advances since the time of the ancients in our understanding of nature on large scales, including the motions of the Solar System, the composition and energetics of the Sun and stars, of our Galaxy, and of the vast collections of galaxies extending across the fourteen billion light-year radius of the observable Universe.[1] Furthermore, the Universe is expanding and cooling, and can be traced backward to a *big bang* some 14 billion years ago, when it was incredibly hot and dense. Although astronomy and cosmology are not the main thrusts of this volume, they cannot be entirely ignored. The visible parts of stars, galaxies, and other astronomical objects are composed of the same atoms, molecules, nuclei, and elementary particles that we observe in the laboratory, and their dynamics are driven by these particles and their interactions. Even the dark matter is likely due to some still-unobserved elementary particle, while the dark energy may be associated with the ground state (vacuum) energy of some of the fundamental particles. There is even the intriguing suggestion from superstring theory that our observable Universe might

[1] The Universe could be much larger, but we can observe only as far as light has traveled since the big bang.

be but a tiny bubble in a vast *multiverse* of regions, each with different laws of physics! The physics of very small distances and astrophysics/cosmology have become inextricably linked.

The atomic theory and the standard model complete two important chapters in the epic quest begun by the ancient Greeks and others to understand the nature in which we live. Parallel chapters in astronomy include the undertanding of the Solar System, the discovery of galaxies, and the expanding Universe/big bang. Although there have been an enormous range of practical applications (especially of atomic physics) and spinoff technologies,[2] the most important aspect for many is simply curiosity about how nature works at her most fundamental level. The combination of new experimental and observational tools, as well as promising theoretical ideas, gives us the chance of even more exciting chapters yet to come on the very small, the very large, and their relation.

[2]Particle physics has contributed to many important spinoff technologies, including medical diagnostics and therapies, cryogenics, magnet technology, complex electronics, large-scale distributed computing, and the World Wide Web. Mathematical techniques have found application in other branches of physics. Finally, large experiments and labs have been a remarkable model for international cooperation.