
INTRODUCTION

Physics is the discipline of science that concerns itself with the study of the most general laws of matter and energy and the fundamental structure of matter. The branch of atomic physics aims primarily at the study of that structure at what is called the *atomic scale*—a term for sizes between those of molecules and the nuclei of atoms. Figure I.1 gives us a perspective on the dimensions of our universe from clusters of galaxies to the nucleus of the atom. While the concept of atoms has a history of more than 2000 years, atomic physics as we know it today is a discipline that began to form in the present century and parallels the development of modern physics.

As is well known, the word “atom” is derived from the ancient Greek with its original meaning being “the indivisible.” In the fourth century B.C., the ancient physicist Democritus advanced this concept and thought of atoms as the smallest unit of matter. In the same period, however, some scholars such as Aristotle, Anaxagoras, and others denied such an atomic view of matter and held that matter was continuous and so was divisible indefinitely. This point of view dominated through the Middle Ages. But, after the sixteenth century, the atomic picture of matter was revived with the new emphasis on experimentation and the development of new experimental techniques. Famous scholars such as Galileo Galilei, René Descartes, Robert Boyle, and Isaac Newton supported such a point of view. In the early 1800s John Dalton gave several rules that formed the basis of an atomic theory in which atoms were the smallest units of matter. Dalton’s atomic model included the following basic postulates: (1) All matter is composed of small particles, which are called atoms. (2) The atoms of each element are all alike in weight and in all other properties. (3) The atoms of different elements are of different weights, and their other properties also differ. (4) Atoms are indestructible and can neither be created, destroyed, nor divided. They preserve their identity during chemical reactions and only undergo rearrangement. (5) When two or more elements combine to form a compound, their atoms combine to form identical groups of atoms, which are called molecules.

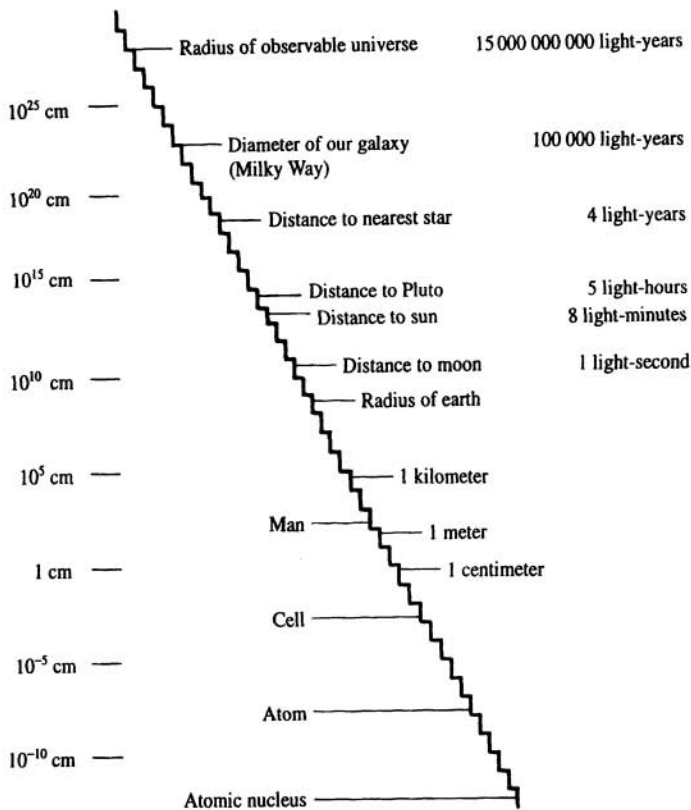


FIGURE I.1
Dimensions of objects in our universe.

It is not as generally well known in the West that the concept of atom goes back equally far in Eastern thought. In China, the two viewpoints mentioned above may be traced back at least to the Period of the Warring States (476–221 B.C.). The most famous school that denied the infinite divisibility of matter was founded by Mo-Di. In the book called *Mo-Jing*, there is the following sentence: “Point: The orderless and foremost of the body.” Basically, the so-called “point” is something that is indivisible (“orderless”) and primary (“foremost”) and from which bodies are composed. At the same time Huishi said: “A thing is so small that it has no interior, and this is called the smallest unity.” Here the “smallest unity” is without an inside, so it can not be divided further. It is the most elementary particle. In that period, a book *Zhong-Yung* (The Intermediate) of the Confucian School pointed out more definitely: “As to the small, no body can break it in the world.” A later authority on Confucian doctrine, Zhu-Xi of the Sung Dynasty (960–1279), explained: “No one can break it means interiorless. That is to say, suppose there is a smallest thing that one can break into two parts, then there may be some room for something else between those two parts.

Conversely, if it is interiorless, it can never be broken again.” When the scholar Yan-Fu of the Qing Dynasty (1616–1911) translated Mill’s *Logical System* into Chinese, he introduced the word “atom” into China for the first time. He translated “atom” as “Mo-Po” (the indivisible) and translated “atom theory” as “Mo-Po particle theory”.

However, another school of the Warring States period maintained the infinite divisibility of matter as represented by Gung-Sun-Lung, who wrote, “With a rod one foot long, you can never exhaust it by cutting off one half of it everyday.” In many ways the speculation of Gung-Sun-Lung two thousand years ago has been pushed continuously to smaller and smaller scales by modern science.

Toward the end of the last century, it began to be realized that atoms are only one of the levels in the structure of the matter. Many important discoveries led to our understanding of atoms as important units of matter and of smaller units and scales including the atomic nucleus, the nuclear constituents, the proton and neutron, and then their substructures of quarks and gluons.

- 1806 J. Proust of France discovered that molecules of chemical compounds obey the law of definite proportion.
- 1807 J. Dalton of England discovered the law of multiple proportions and suggested an atomic theory.
- 1808 J. Gay-Lussac of France discovered the law that in the chemical combination of gases, their volumes are in simple ratios to each other; hence he concluded that, in a gaseous state, the weight of an element in a given volume would be proportional to its atomic weight.
- 1811 A. Avogadro of Italy made his hypothesis: Under the same temperature and pressure, there are the same number of molecules in the same volumes of gases.
- 1826 R. Brown of England observed that some corpuscles suspended in liquid were in random fluctuating motion, the so-called Brownian motion.
- 1833 M. Faraday of England formulated the law of electrolysis, and reduced the chemical affinity to electric forces.
- 1869 Independently, D. Mendeleev of Russia and L. Meyer of Germany suggested a periodic law of the elements.
- 1895 W. Roentgen of Germany discovered x-rays.
- 1896, 1897 H. Becquerel followed by M. and P. Curie of France discovered radioactivity, and J. Thompson of England discovered the electron. These two discoveries gave the first evidence that atoms were not indestructible and indivisible as Dalton had proposed.
- 1900 M. Planck of Germany introduced the idea of the quantum which, with the previous three great discoveries lifted the curtain of modern physics.
- 1905 A. Einstein of Germany explained Brownian motion as the result of the bombardment of the suspended particles by the random

motion of the atoms and molecules which make up the liquid, as well as giving us the special theory of relativity and a quantum explanation of the photoelectric effect.

- 1908 J. Perrin of France carried out careful measurements to confirm Einstein's theory of Brownian motion and so firmly established the existence of atoms.
- 1911 E. Rutherford of England interpreted the work of his co-workers, Geiger and Marsden, to be evidence that atoms had tiny cores which contained essentially all the mass and all the positive charge of the atom and that the core was almost 100 000 times smaller than the atom itself.
- 1913 N. Bohr of Denmark proposed the first quantum theory of atomic structure to open the door to new chapters in atomic physics.
- 1919 E. Rutherford performed the first artificial transmutation of elements by nuclear reactions.
- 1923 A. H. Compton of the United States completed the particle (photon) nature of light with the discovery of the Compton effect.
- 1924 L. de Broglie of France proposed that particles of matter have waves associated with them, to complete the duality of particles and waves.
- 1925 E. Schrödinger of Austria and W. Heisenberg, Germany, developed the new quantum mechanics, and W. Pauli of Switzerland proposed the exclusion principle to give a basis for the Periodic Table of the Elements.
- 1928 P. Dirac of England predicted the existence of a new companion particle to the electron, the positron, based on his new relativistic quantum theory of the electron.
- 1930 W. Pauli suggested the existence of another new particle beyond the electron and proton, the neutrino.
- 1932 Two new particles were discovered, the positron by C. D. Anderson of the United States and the neutron by J. Chadwick of England.
- 1934 I. and F. Joliot-Curie of France discovered new radioactivities which are not present in nature, and E. Fermi of Italy proposed his theory of beta decay in which the electron and neutrino are created by the weak nuclear force.
- 1935 H. Yukawa of Japan proposed still another new particle, the meson, to explain the force that holds protons and neutrons together.
- 1936 The μ lepton was discovered by H. Neddermeyer, C. D. Anderson and co-workers of the United States, but it was not until 1947 that C. Powell and co-workers of England discovered the meson which has properties similar to those proposed by Yukawa.
- 1939 O. Hahn and F. Strassmann of Germany discovered the fission of uranium induced by neutron absorption.

- 1940 G. Seaborg, E. McMillan and co-workers in the United States discovered the first new elements beyond uranium, then the heaviest known element and the heaviest to be found in nature.
- 1949, 1953 The first detailed predictive models of the structure of nuclei were proposed, the shell model by M. G. Mayer of the United States and J. H. D. Jensen and co-workers in Germany, and the collective model by A. Bohr of Denmark and B. R. Mottelson of the United States.
- 1955 O. Chamberlain, E. Segre, and co-workers in the United States discovered the antiproton. This fueled efforts to build larger and larger particle accelerators and opened the gates to the discovery of multitudes of new particles.
- 1964 M. Gell-Mann and G. Zweig in the United States proposed a new substructure of several quarks held together by gluons to explain the multitude of heavy particles being observed, including the proton and neutron.
- 1974 B. Richter and co-workers and S. Ting and co-workers in the United States separately discovered the J/Ψ particle to establish the fourth quark, called the charmed quark. Now, to explain the known heavy particles, one needs six quarks and six antiquarks, each with three colors or types—36 quarks held together by 8 colored gluons in the current Standard Model!
- 1983 C. Rubbia, an Italian physicist at Harvard-CERN, and S. van der Meer, a Dutch physicist and co-workers at CERN, discovered the massive W^\pm , Z^0 particles that mediate the weak nuclear force.

More precise experimental data from atoms led to the creation of the new quantum mechanics. Our understanding of the structure of atoms has continued to advance significantly in each decade right on through the present as new and more powerful experimental techniques have been developed and new, improved quantum mechanical theories have come forth. A renaissance is occurring in atomic physics today through the use of high-powered lasers and nuclear accelerators, including very energetic heavy-ion accelerators capable of accelerating atoms up through uranium to relativistic velocities. These are yielding exciting new insights into the structure of atoms. For example, with lasers atoms can be studied in previously inaccessible exotic conditions where the electrons are in orbits with radii up to 1000 times larger than those in normal atoms. Now scientists are very much interested in higher-energy beams of uranium up to several GeV (10^9 electron-volts) and higher-powered lasers to study in detail atoms up to uranium with only one or two electrons surrounding the nucleus. There previously unseen higher-order processes can occur to test and expand our theoretical insights and to probe possible previously unobserved fundamental properties of nature.

Nuclear physics concerns itself with the structure and behavior of the next layer of matter, which forms the tiny inner core of the atom. The atomic nucleus is about 100 000 times smaller than the atom but contains all the positive charge and

essentially all the mass of the atom. One of the long-sought goals of nuclear physics is to understand the strong nuclear force which holds protons and neutrons together in the nucleus. Much progress has been made in understanding this force through the study of the radioactive decays of nuclei and through the interactions of nuclei with probes ranging from photons, electrons, and mesons, through light ions (p , n and α) and more recently heavy ions all the way up to uranium at energies from ultracold neutrons ($\ll 1$ eV) to 2 TeV (10^{12} eV) carbon-12 projectiles. In the absence of being able to express the strong nuclear interaction in closed form, models of the nucleus have been developed. The tiny nucleus of the atom can exhibit many different shapes from spherical to various deformed shapes such as prolate and oblate spheroids and triaxial, and now two or more of these shapes are seen in the same nucleus for different energy levels—nuclear shape coexistence. Nuclear matter is being probed in exotic regions of high temperature, high angular momentum, and high density—hotter than the sun and at densities approaching those of neutron stars.

The structure of matter has been taken to an even deeper layer as we probe in high-energy particle physics the substructure of the neutron and the proton. Neutrons and protons are themselves composite particles composed of three types of quarks held together by gluons. The quark structure of matter is now described by the “standard” model of quantum chromodynamics, QCD, in which the quarks have the additional property of flavor or color in addition to mass and charge. These latter two fields of nuclear and particle physics will be sketched in broad outlines to complete our picture of the basic structure of matter.

Chapter 1 presents the basic principles of the special theory of relativity which are necessary for understanding atomic, nuclear, and particle physics.

In Chapter 2, the first models of atoms are introduced. Then it will be shown that these models and classical theories could not account for even the experimental data at the turn of the century. Chapter 3 deals with Niels Bohr’s seminal work that originated from his endeavors to avoid the classical difficulties—the introduction of quantum behavior into the atomic region for the first time. He postulated the concept of stationary quantum states to explain the experimental data. To this point only the gross structure of the atom, where the electrons and the nucleus are point charges, was considered. In Chapter 4, starting from experimental facts, the necessity of the concept of “electron spin” is introduced. That concept was essential in understanding the finer structure of atoms and the spectra of light they emitted. The word “spin” was not unfamiliar in classical physics, but this concept represents a totally new form of motion in the microworld that has no classical counterpart at all. At the end of this chapter, we show how our understanding of the hydrogen atom has been deepened step by step. In Chapter 5, we generalize the properties of one-electron systems like hydrogen to many-electron ones and explain the periodic properties of the elements from our modern understanding of atomic structure. Here, one of the important concepts is the exclusion principle introduced by Pauli. In Chapter 6, the production and properties of x-rays that were discovered in 1895 are considered. Various experimental facts are presented to show that x-rays display both wave aspects and corpuscular

aspects. The contents of the first chapters will describe various difficulties that classical physics met in the atomic realm. Chapters 7 and 8 complete the necessity of the creation of quantum mechanics. There we try to disclose the essence of quantum mechanics from physical concepts but leave many details to a course on quantum mechanics.

Our understanding of the other constituent of the atom, the atomic nucleus, is introduced in Chapter 9. The basic features of the nucleus are presented there. Radioactivity is presented in Chapter 10. The nuclear force and nuclear models are discussed in Chapter 11. In Chapter 12, reactions between nuclei are considered along with their role in nuclear energy production. The hyperfine interactions between the atomic electrons and the nucleus that arise from the nuclear magnetic and quadrupole moments and electron motion and their fields are treated in Chapter 13. This field has developed into an interdisciplinary science between atomic and nuclear physics with many broad applications. The further substructure of the neutrons and protons in the nucleus and our present understanding of the basic constituents of matter at the next lowest level, as probed in the field of high energy physics, are described in Chapter 14.

Finally, some concrete examples of the practical applications of atomic and nuclear physics are given in Appendix I. These include the techniques of ion-beam analysis, emphasizing the applications of Rutherford scattering (Chapter 2), x-rays (Chapter 6) and nuclear reaction methods (Chapter 12) in material analysis.

Today studies of the structure of the atom, the structure of the nucleus, and the substructure of the nucleon and basic constituents of matter are exciting and expanding frontiers in science. The text seeks to interweave some of the new directions and research opportunities with the basic insights needed to go farther in these fields. Major, new facilities recently completed and under development including, for example, more powerful lasers, giant superconducting accelerators, large detector arrays, and more advanced super computers will continue to open up new research and new insights into our basic understanding of the workings of matter at each of these three levels. As well, they will make possible new opportunities in many other areas of basic and applied research along with new solutions to important societal problems.

In the early decades of the twentieth century when many of the basic discoveries which transformed our understandings of the laws of physics were taking place, international conferences would include the leading physicists in all areas of physics, as illustrated in Fig. I.2. Most of the founders of twentieth-century physics are seen in Fig. I.2, and their monumental works are the subject of much of this book. Today the number of physicists has grown tremendously and, unfortunately, their work has become so specialized that separate conferences are held to consider each of the subspecialties of physics. However, there is held in Lindau, Germany, a regular series of more popular conferences which bring together Nobel Laureates in all areas of physics. Reminiscent of the earlier conferences, as see in Fig. I.2, numbers of the new leaders along with some of the early ones are seen in Fig. I.3 at the 1983 Lindau Conference.

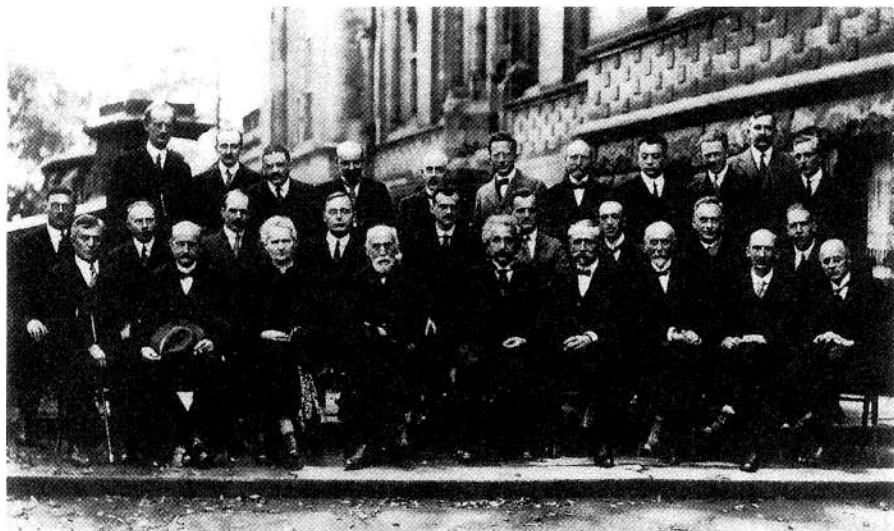


FIGURE I.2

Participants in the 1927 Solvay Conference. From left to right, bottom row: E. Langemeir, M. Planck, M. Curie, H. A. Lorentz, A. Einstein, P. Langevin, Ch. E. Guye, C. T. R. Wilson, O. W. Richardson. Second Row: P. Debye, M. Knudsen, W. L. Bragg, H. A. Kramers, P. A. M. Dirac, A. H. Compton, L. V. de Broglie, M. Born, N. Bohr. Back Row: A. Piccard, E. Henriot, P. Ehrenfest, Ed. Herzen, Th. DeDonder, E. Schrödinger, E. Verschaffelt, W. Pauli, W. Heisenberg, R. H. Fowler, L. Brillouin.

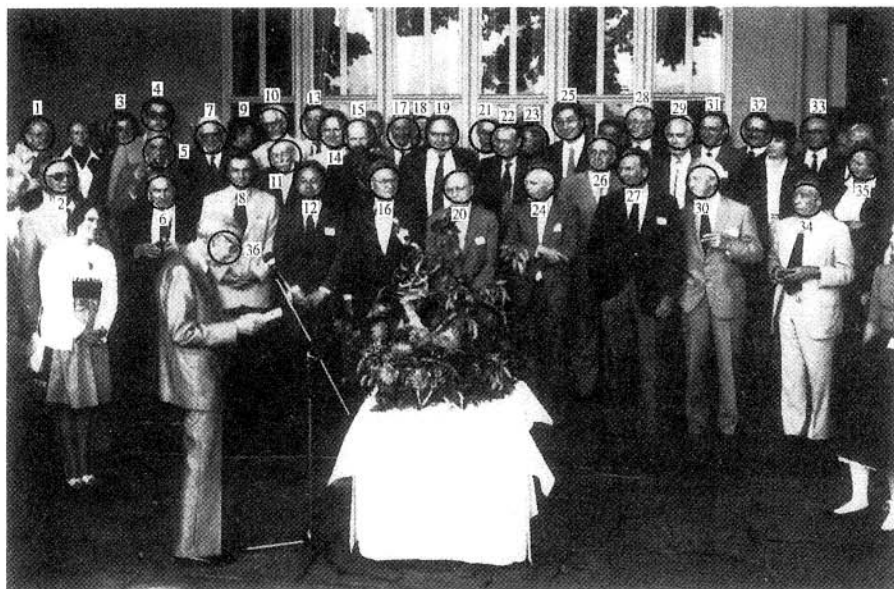


FIGURE I.3

Participants in the 1983 Lindau Conference from left to right: (1) T. C. Koopmanns, (2) Graf L. Bernadotte, (5) F. Bloch, (6) R. Hofstadter, (7) A. Butenandt, (8) I. Giaever, (10) J. Meade, (11) P. Dirac, (12) L. Esaki, (13) A. Penzias, (14) V. Fitch, (15) R. Wilson, (16) P. Samuelson, (17) K. Siegbahn, (19) A. Schawlow, (20) E. Wigner, (21) Walter Brattain, (22) N. Bloembergen, (24) R. Mössbauer, (25) S. Ting, (26) E. O. Fischer, (27) F. von Hayek, (28) J. R. Schrieffer, (29) W. Lamb, (30) H. Alven, (34) J. Schwinger, (35) A. Kastler