1

BASIC CONCEPTS

Whether we date the origin of nuclear physics from Becquerel's discovery of radioactivity in 1896 or Rutherford's hypothesis of the existence of the nucleus in 1911, it is clear that experimental and theoretical studies in nuclear physics have played a prominent role in the development of twentieth century physics. As a result of these studies, a chronology of which is given on the inside of the front cover of this book, we have today a reasonably good understanding of the properties of nuclei and of the structure that is responsible for those properties. Furthermore, techniques of nuclear physics have important applications in other areas, including atomic and solid-state physics. Laboratory experiments in nuclear physics have been applied to the understanding of an incredible variety of problems, from the interactions of quarks (the most fundamental particles of which matter is composed), to the processes that occurred during the early evolution of the universe just after the Big Bang. Today physicians use techniques learned from nuclear physics experiments to perform diagnosis and therapy in areas deep inside the body without recourse to surgery; but other techniques learned from nuclear physics experiments are used to build fearsome weapons of mass destruction, whose proliferation is a constant threat to our future. No other field of science comes readily to mind in which theory encompasses so broad a spectrum, from the most microscopic to the cosmic, nor is there another field in which direct applications of basic research contain the potential for the ultimate limits of good and evil.

Nuclear physics lacks a coherent theoretical formulation that would permit us to analyze and interpret all phenomena in a fundamental way; atomic physics has such a formulation in quantum electrodynamics, which permits calculations of some observable quantities to more than six significant figures. As a result, we must discuss nuclear physics in a phenomenological way, using a different formulation to describe each different type of phenomenon, such as α decay, β decay, direct reactions, or fission. Within each type, our ability to interpret experimental results and predict new results is relatively complete, yet the methods and formulation that apply to one phenomenon often are not applicable to another. In place of a single unifying theory there are islands of coherent knowledge in a sea of seemingly uncorrelated observations. Some of the most fundamental problems of nuclear physics, such as the exact nature of the forces that hold the nucleus together, are yet unsolved. In recent years, much progress has been made toward understanding the basic force between the quarks that are the ultimate constituents of matter, and indeed attempts have been made at applying this knowledge to nuclei, but these efforts have thus far not contributed to the clarification of nuclear properties.

We therefore adopt in this text the phenomenological approach, discussing each type of measurement, the theoretical formulation used in its analysis, and the insight into nuclear structure gained from its interpretation. We begin with a summary of the basic aspects of nuclear theory, and then turn to the experiments that contribute to our knowledge of structure, first radioactive decay and then nuclear reactions. Finally, we discuss special topics that contribute to microscopic nuclear structure, the relationship of nuclear physics to other disciplines, and applications to other areas of research and technology.

1.1 HISTORY AND OVERVIEW

The search for the fundamental nature of matter had its beginnings in the speculations of the early Greek philosophers; in particular, Democritus in the fourth century B.C. believed that each kind of material could be subdivided into smaller and smaller bits until one reached the very limit beyond which no further division was possible. This *atom* of material, invisible to the naked eye, was to Democritus the basic constituent particle of matter. For the next 2400 years, this idea remained only a speculation, until investigators in the early nineteenth century applied the methods of *experimental science* to this problem and from their studies obtained the evidence needed to raise the idea of atomism to the level of a full-fledged scientific theory. Today, with our tendency toward the specialization and compartmentalization of science, we would probably classify these early scientists (Dalton, Avogadro, Faraday) as chemists. Once the chemists had elucidated the kinds of atoms, the rules governing their combinations in matter, and their systematic classification (Mendeleev's periodic table), it was only natural that the next step would be a study of the fundamental properties of individual atoms of the various elements, an activity that we would today classify as atomic physics. These studies led to the discovery in 1896 by Becquerel of the radioactivity of certain species of atoms and to the further identification of radioactive substances by the Curies in 1898. Rutherford next took up the study of these radiations and their properties; once he had achieved an understanding of the nature of the radiations, he turned them around and used them as probes of the atoms themselves. In the process he proposed in 1911 the existence of the atomic nucleus, the confirmation of which (through the painstaking experiments of Geiger and Marsden) provided a new branch of science, nuclear physics, dedicated to studying matter at its most fundamental level. Investigations into the properties of the nucleus have continued from Rutherford's time to the present. In the 1940s and 1950s, it was discovered that there was yet another level of structure even more elementary and fundamental than the nucleus. Studies of the particles that contribute to the structure at this level are today carried out in the realm of elementary particle (or high energy) physics.

Thus nuclear physics can be regarded as the descendent of chemistry and atomic physics and in turn the progenitor of particle physics. Although nuclear physics no longer occupies center stage in the search for the ultimate components of matter, experiments with nuclei continue to contribute to the understanding of basic interactions. Investigation of nuclear properties and the laws governing the structure of nuclei is an active and productive area of physical research in its own right, and practical applications, such as smoke detectors, cardiac pacemakers, and medical imaging devices, have become common. Thus nuclear physics has in reality three aspects: probing the fundamental particles and their interactions, classifying and interpreting the properties of nuclei, and providing technological advances that benefit society.

1.2 SOME INTRODUCTORY TERMINOLOGY

A nuclear species is characterized by the total amount of positive charge in the nucleus and by its total number of mass units. The net nuclear charge is equal to $+Ze$, where Z is the *atomic number* and e is the magnitude of the electronic charge. The fundamental positively charged particle in the nucleus is the *proton*, which is the nucleus of the simplest atom, hydrogen. A nucleus of atomic number Z therefore contains Z protons, and an electrically neutral atom therefore must contain Z negatively charged electrons. Since the mass of the electrons is negligible compared with the proton mass ($m_p \simeq 2000 m_e$), the electron can often be ignored in discussions of the mass of an atom. The *mass number* of a nuclear species, indicated by the symbol A, is the integer nearest to the ratio between the nuclear mass and the fundamental mass unit, defined so that the proton has a mass of nearly one unit. (We will discuss mass units in more detail in Chapter 3.) For nearly all nuclei, A is greater than Z, in most cases by a factor of two or more. Thus there must be other massive components in the nucleus. Before 1932, it was believed that the nucleus contained A protons, in order to provide the proper mass, along with $A - Z$ *nuclear* electrons to give a net positive charge of Ze. However, the presence of electrons within the nucleus is unsatisfactory for several reasons:

1. The nuclear electrons would need to be bound to the protons by a very strong force, stronger even than the Coulomb force. Yet no evidence for this strong force exists between protons and *atomic* electrons.
2. If we were to confine electrons in a region of space as small as a nucleus ($\Delta x \sim 10^{-14}$ m), the uncertainty principle would require that these electrons have a momentum distribution with a range $\Delta p \sim \hbar/\Delta x = 20$ MeV$/c$. Electrons that are emitted from the nucleus in radioactive β decay have energies generally less than 1 MeV; never do we see decay electrons with 20 MeV energies. Thus the existence of 20 MeV electrons in the nucleus is not confirmed by observation.
3. The total intrinsic angular momentum (spin) of nuclei for which $A - Z$ is odd would disagree with observed values if A protons and $A - Z$ electrons were present in the nucleus. Consider the nucleus of deuterium ($A = 2$, $Z = 1$), which according to the proton-electron hypothesis would contain 2 protons and 1 electron. The proton and electron each have intrinsic angular momentum (spin) of $\frac{1}{2}$, and the quantum mechanical rules for adding spins of particles would require that these three spins of $\frac{1}{2}$ combine to a total of either $\frac{3}{2}$ or $\frac{1}{2}$. Yet the observed spin of the deuterium nucleus is 1.

4. Nuclei containing unpaired electrons would be expected to have magnetic dipole moments far greater than those observed. If a single electron were present in a deuterium nucleus, for example, we would expect the nucleus to have a magnetic dipole moment about the same size as that of an electron, but the observed magnetic moment of the deuterium nucleus is about $\frac{1}{2000}$ of the electron's magnetic moment.

Of course it is possible to invent all sorts of ad hoc reasons for the above arguments to be wrong, but the necessity for doing so was eliminated in 1932 when the *neutron* was discovered by Chadwick. The neutron is electrically neutral and has a mass about equal to the proton mass (actually about 0.1% larger). Thus a nucleus with Z protons and $A - Z$ neutrons has the proper total mass *and* charge, without the need to introduce nuclear electrons. When we wish to indicate a specific nuclear species, or *nuclide*, we generally use the form ${}^{A}_{Z}\mathrm{X}_{N}$, where X is the chemical symbol and N is the *neutron number*, $A - Z$. The symbols for some nuclides are ${}^{1}_{1}\mathrm{H}_{0}$, ${}^{238}_{92}\mathrm{U}_{146}$, ${}^{56}_{26}\mathrm{Fe}_{30}$. The chemical symbol and the atomic number Z are redundant—every H nucleus has $Z = 1$, every U nucleus has $Z = 92$, and so on. It is therefore not necessary to write Z. It is also not necessary to write N, since we can always find it from $A - Z$. Thus ${}^{238}\mathrm{U}$ is a perfectly valid way to indicate that particular nuclide; a glance at the periodic table tells us that U has $Z = 92$, and therefore ${}^{238}\mathrm{U}$ has $238 - 92 = 146$ neutrons. You may find the symbols for nuclides written sometimes with Z and N, and sometimes without them. When we are trying to balance Z and N in a decay or reaction process, it is convenient to have them written down; at other times it is cumbersome and unnecessary to write them.

Neutrons and protons are the two members of the family of *nucleons*. When we wish simply to discuss nuclear particles without reference to whether they are protons or neutrons, we use the term nucleons. Thus a nucleus of mass number A contains A nucleons.

When we analyze samples of many naturally occurring elements, we find that nuclides with a given atomic number can have several different mass numbers; that is, a nuclide with Z protons can have a variety of different neutron numbers. Nuclides with the same proton number but different neutron numbers are called *isotopes*; for example, the element chlorine has two isotopes that are stable against radioactive decay, ${}^{35}\mathrm{Cl}$ and ${}^{37}\mathrm{Cl}$. It also has many other unstable isotopes that are artificially produced in nuclear reactions; these are the radioactive isotopes (or *radioisotopes*) of Cl.

It is often convenient to refer to a sequence of nuclides with the same N but different Z; these are called *isotones*. The stable isotones with $N = 1$ are ${}^{2}\mathrm{H}$ and ${}^{3}\mathrm{He}$. Nuclides with the same mass number A are known as *isobars*; thus stable ${}^{3}\mathrm{He}$ and radioactive ${}^{3}\mathrm{H}$ are isobars.

1.3 NUCLEAR PROPERTIES

Once we have identified a nuclide, we can then set about to measure its properties, among which (to be discussed later in this text) are mass, radius, relative abundance (for stable nuclides), decay modes and half-lives (for radioactive nuclides), reaction modes and cross sections, spin, magnetic dipole and electric quadrupole moments, and excited states. Thus far we have identified

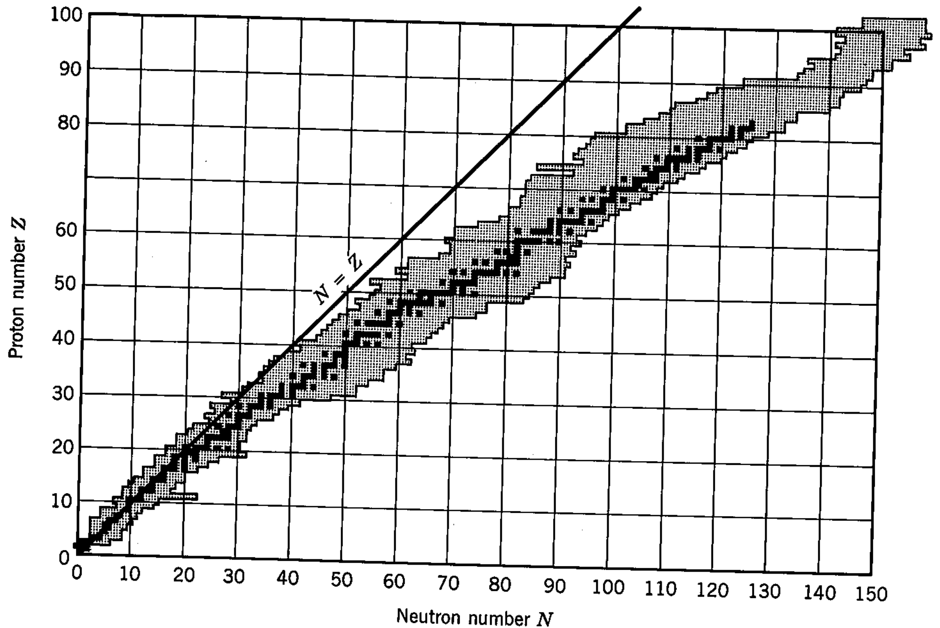

Figure 1.1 Stable nuclei are shown in dark shading and known radioactive nuclei are in light shading.

nuclides with 108 different atomic numbers (0 to 107); counting all the different isotopes, the total number of nuclides is well over 1000, and the number of carefully studied new nuclides is growing rapidly owing to new accelerators dedicated to studying the isotopes far from their stable isobars. Figure 1.1 shows a representation of the stable and known radioactive nuclides.

As one might expect, cataloging all of the measured properties of these many nuclides is a formidable task. An equally formidable task is the retrieval of that information: if we require the best current experimental value of the decay modes of an isotope or the spin and magnetic moment of another, where do we look?

Nuclear physicists generally publish the results of their investigations in journals that are read by other nuclear physicists; in this way, researchers from distant laboratories are aware of one another's activities and can exchange ideas. Some of the more common journals in which to find such communications are *Physical Review*, Section C (abbreviated *Phys. Rev. C*), *Physical Review Letters* (*Phys. Rev. Lett.*), *Physics Letters*, Section B (*Phys. Lett. B*), *Nuclear Physics*, Section A (*Nucl. Phys. A*), *Zeitschrift für Physik*, Section A (*Z. Phys. A*), and *Journal of Physics*, Section G (*J. Phys. G*). These journals are generally published monthly, and by reading them (or by scanning the table of contents), we can find out about the results of different researchers. Many college and university libraries subscribe to these journals, and the study of nuclear physics is often aided by browsing through a selection of current research papers.

Unfortunately, browsing through current journals usually does not help us to locate the specific nuclear physics information we are seeking, unless we happen to stumble across an article on that topic. For this reason, there are many sources of compiled nuclear physics information that summarize nuclear properties and give references to the literature where the original publication may be consulted. A one-volume summary of the properties of all known nuclides is the *Table of Isotopes*, edited by M. Lederer and V. Shirley (New York: Wiley, 1978). A copy of this indispensible work is owned by every nuclear physicist. A more current updating of nuclear data can be found in the *Nuclear Data Sheets*, which not only publish regular updated collections of information for each set of isobars, but also give an annual summary of all published papers in nuclear physics, classified by nuclide. This information is published in journal form and is also carried by many libraries. It is therefore a relatively easy process to check the recently published work concerning a certain nuclide.

Two other review works are the *Atomic Data and Nuclear Data Tables*, which regularly produces compilations of nuclear properties (for example, β or γ transition rates or fission energies), and the *Annual Review of Nuclear and Particle Science* (formerly called the *Annual Review of Nuclear Science*), which each year publishes a collection of review papers on current topics in nuclear and particle physics.

1.4 UNITS AND DIMENSIONS

In nuclear physics we encounter lengths of the order of 10^{-15} m, which is one femtometer (fm). This unit is colloquially known as one fermi, in honor of the pioneer Italian-American nuclear physicist, Enrico Fermi. Nuclear sizes range from about 1 fm for a single nucleon to about 7 fm for the heaviest nuclei.

The time scale of nuclear phenomena has an enormous range. Some nuclei, such as ^{5}He or ^{8}Be, break apart in times of the order of 10^{-20} s. Many nuclear reactions take place on this time scale, which is roughly the length of time that the reacting nuclei are within range of each other's nuclear force. Electromagnetic (γ) decays of nuclei occur generally within lifetimes of the order of 10^{-9} s (nanosecond, ns) to 10^{-12} s (picosecond, ps), but many decays occur with much shorter or longer lifetimes. α and β decays occur with even longer lifetimes, often minutes or hours, but sometimes thousands or even millions of years.

Nuclear energies are conveniently measured in millions of electron-volts (MeV), where 1 eV = 1.602×10^{-19} J is the energy gained by a single unit of electronic charge when accelerated through a potential difference of one volt. Typical β and γ decay energies are in the range of 1 MeV, and low-energy nuclear reactions take place with kinetic energies of order 10 MeV. Such energies are far smaller than the nuclear rest energies, and so we are justified in using nonrelativistic formulas for energy and momentum of the nucleons, but β-decay electrons must be treated relativistically.

Nuclear masses are measured in terms of the *unified atomic mass unit*, u, defined such that the mass of an *atom* of ^{12}C is exactly 12 u. Thus the nucleons have masses of approximately 1 u. In analyzing nuclear decays and reactions, we generally work with mass energies rather than with the masses themselves. The conversion factor is 1 u = 931.502 MeV, so the nucleons have mass energies of approximately 1000 MeV. The conversion of mass to energy is of course done using the fundamental result from special relativity, $E = mc^2$; thus we are free to work either with masses or energies at our convenience, and in these units $c^2 = 931.502$ MeV/u.

REFERENCES FOR ADDITIONAL READING

The following comprehensive nuclear physics texts provide explanations or formulations alternative to those of this book. Those at the introductory level are at about the same level as the present text; higher-level texts often form the basis for more advanced graduate courses in nuclear physics. No attempt has been made to produce a complete list of reference works; rather, these are the ones the author has found most useful in preparing this book.

These "classic" texts now mostly outdated but still containing much useful material are interesting for gaining historical perspective: R. D. Evans, *The Atomic Nucleus* (New York: McGraw-Hill, 1955) (For 20 years, since his graduate-student days, the most frequently used book on the author's shelves. Its binding has all but deteriorated, but its completeness and clarity remain.); David Halliday, *Introductory Nuclear Physics* (New York: Wiley, 1955); I. Kaplan, *Nuclear Physics* (Reading, MA: Addison-Wesley, 1955).

Introductory texts complementary to this text are: W. E. Burcham, *Nuclear Physics: An Introduction* (London: Longman, 1973); B. L. Cohen, *Concepts of Nuclear Physics* (New York: McGraw-Hill, 1971); Harald A. Enge, *Introduction to Nuclear Physics* (Reading, MA: Addison-Wesley, 1966); Robert A. Howard, *Nuclear Physics* (Belmont, CA: Wadsworth, 1963); Walter E. Meyerhof, *Elements of Nuclear Physics* (New York: McGraw-Hill, 1967); Haro Von Buttlar, *Nuclear Physics: An Introduction* (New York: Academic Press, 1968).

Intermediate texts, covering much the same material as the present one but distinguished primarily by a more rigorous use of quantum mechanics, are: M. G. Bowler, *Nuclear Physics* (Oxford: Pergamon, 1973); Emilio Segré, *Nuclei and Particles* (Reading, MA: W. A. Benjamin, 1977).

Advanced texts, primarily for graduate courses, but still containing much material of a more basic nature, are: Hans Frauenfelder and Ernest M. Henley, *Subatomic Physics* (Englewood Cliffs, NJ: Prentice-Hall, 1974); M. A. Preston, *Physics of the Nucleus* (Reading, MA: Addison-Wesley, 1962).

Advanced works, more monographs than texts in nature, are: John M. Blatt and Victor F. Weisskopf, *Theoretical Nuclear Physics* (New York: Wiley, 1952); A. Bohr and B. R. Mottelson, *Nuclear Structure* (New York: W. A. Benjamin, 1969); A. deShalit and H. Feshbach, *Theoretical Nuclear Physics* (New York: Wiley, 1974).

2

ELEMENTS OF QUANTUM MECHANICS

Nucleons in a nucleus do not behave like classical particles, colliding like billiard balls. Instead, the *wave behavior* of the nucleons determines the properties of the nucleus, and to analyze this behavior requires that we use the mathematical techniques of quantum mechanics.

From a variety of scattering experiments, we know that the nucleons in a nucleus are in motion with kinetic energies of the order of 10 MeV. This energy is small compared with the nucleon rest energy (about 1000 MeV), and so we can with confidence use *nonrelativistic* quantum mechanics.

To give a complete introduction to quantum mechanics would require a text larger than the present one. In this chapter, we summarize some of the important concepts that we will need later in this book. We assume a previous introduction to the concepts of modern physics and a familiarity with some of the early experiments that could not be understood using classical physics; these experiments include thermal (blackbody) radiation, Compton scattering, and the photoelectric effect. At the end of this chapter is a list of several introductory modern physics texts for review. Included in the list are more advanced quantum physics texts, which contain more complete and rigorous discussions of the topics summarized in this chapter.

2.1 QUANTUM BEHAVIOR

Quantum mechanics is a mathematical formulation that enables us to calculate the wave behavior of material particles. It is not at all *a priori* evident that such behavior should occur, but the suggestion follows by analogy with the quantum behavior of light. Before 1900, light was generally believed to be a wave phenomenon, but the work of Planck in 1900 (analyzing blackbody radiation) and Einstein in 1905 (analyzing the photoelectric effect) showed that it was also necessary to consider light as if its energy were delivered not smoothly and continuously as a wave but instead in concentrated bundles or "quanta," in effect "particles of light."

The analogy between matter and light was made in 1924 by de Broglie, drawing on the previous work of Einstein and Compton. If light, which we