1
Introduction

1.1
Low-Energy Nuclear Physics for Applications

During the past century the development of the physical sciences has been nothing short of astounding. We now take the existence of nuclear atoms and the molecules formed from them as the self-evident constituents of matter, without much consideration for the enormous energy, talent and genius that was needed to elucidate them and to define their fundamental properties. It is commonplace for high school students to see "pictures" of individual atoms on surfaces as revealed by atomic force microscopes. Three-dimensional structures of many of the fundamental molecules that define the function of our cells and tissues can be found in elementary texts on molecular biology. The understanding of atoms and molecules and their interactions has led to practical advances in almost every sphere of human endeavor. Fundamental studies in the physical sciences are continuing to provide the basis for practical applications at an ever-increasing rate.

The discovery of radioactivity during the latter part of the 19th century and the experimental and theoretical studies that took place early in the 20th century, led to our understanding of the nuclear atom and engendered intense interest in the nucleus itself. Advances came swiftly. The discovery of the neutron led to an understanding of the proton and neutron as the main "constituents" of the nucleus. The understanding that the radioactive decay process known as β^- decay led to an increase in the atomic number of an atom by one and the ability to create small neutron sources led to the search for elements beyond uranium and to the phenomenon of nuclear fission. Within a matter of a few years, nuclear weapons and the harnessing of fission for the production of electricity were both in development.

Today, applications of this type of physics, referred to as low-energy nuclear physics, are found almost everywhere. A sizeable fraction of the electric power generated in the industrialized nations is derived from nuclear fission reactors. Nuclear reactions are used to modify semiconductors to produce desirable properties and are used to study the properties of the surfaces of many of these materials. Radioactive decay is applied to determine the age of once-living objects, as well as the age of various minerals in the earth's crust. Indeed, radioactive decay is one of the fundamental means by which we know the age of the earth itself.

Nuclear Physics for Applications. Stanley G. Prussin

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The radiations emitted in radioactive decay are one of the means by which we gain an understanding of the physics of nuclei and they also represent the basis of important practical applications. Three-dimensional images of organs within the human body are often based on the measurements of γ-rays emitted following radioactive decay of atoms that have been introduced in forms that concentrate on specific tissues.

The title of this book, Nuclear Physics for Applications: A Simple Approach, is meant to indicate that the subjects treated are those that are most closely connected to current and likely applications of low-energy nuclear physics. In the present context, the reference to low energy is meant to indicate that we are concerned only with nuclear particles, nuclei and their reactions under conditions that do not require us to delve into the structure of the particles themselves or to consider the creation and characteristics of nuclear particles that are more massive than the neutron or proton. The material presented is neither exhaustive nor is it limited to a statement of facts and formulas for use in applications. Rather, it is a textbook on low-energy nuclear physics that attempts to provide a sound theoretical basis for understanding the fundamentals of nuclear structure, radioactive decay and nuclear reactions. In so doing, it introduces and applies the simplest models that make sense and that are often the basis of the much more sophisticated models that provide quantitative predictions. We chose this approach because a purely empirical and phenomenological presentation does not provide the student with the means for correlating different data, nor does it provide the student with a reasonable basis for advanced study. We will demand that the student pay attention to some of the underlying physics that can be presented only with use of a significant amount of mathematics. But the mathematics is, for the most part, familiar, having been encountered in previous mathematics and physics courses, and can be made reasonably understandable by explicit reference to the physical significance of the expressions that are developed.

In this chapter, we will introduce some of the fundamental concepts, notations and nomenclature that will be used throughout the text. We will also introduce the reader to some of the sources of information on low-energy nuclear physics and the interaction of radiation with matter that are useful for both fundamental and applied purposes.

At the very start, it is appropriate to issue a word of warning concerning nomenclature. Over the years a number of terms have been introduced to increase the precision of what we say and write, and we will try to stress the correct usage of such terms. But, as is often the case in older texts and even in some current literature, we may lapse into “common” usage from time to time. We will try to point out where common usage can be particularly confusing to the novice.

1.2 Some General Observations and Notations

At the present time, we have evidence for the existence of some 117 chemical elements. Of these, 86 exist on earth in more than trace abundance. The chemical elements are defined by the number of protons, Z, in their nuclei and their chemistry is defined by the behavior of their electron distributions. All elements have *isotopes* that contain different numbers of neutrons, N. Isotopes are generally indicated by their atomic number Z and mass number A, where A = N + Z. The standard symbol for an isotope is ${}^{A}_{Z}El_{N}$, where El represents the symbol for the chemical element (e.g., H, Cl, U, etc.) This designation is clearly redundant and the atomic and neutron numbers are often omitted. In many cases, it is common to refer to neutrons and protons collectively as *nucleons* and we will follow this practice when appropriate. Further, the term *nuclide* is used when referring to an arbitrary nucleus of given Z and N.

As far as we know, the heaviest known elements do not possess any isotopes with sufficiently long half-lives that they could have existed on earth for a time comparable to its age of about 4.5 billion years. Curiously, this is also true of the elements technetium (Tc; Z = 43) and promethium (Pm; Z = 61). Technetium was first discovered with certainty through reactions of neutrons and *deuterons* (nuclei of the hydrogen isotope ${}^{2}_{1}H_{1}$) with isotopes of the element molybdenum (Z = 42) [1] and promethium was first identified as a product of the nuclear fission of uranium and the reaction of neutrons with the element neodymium [2].

As indicated above, the chemical properties of the elements are defined primarily by the properties of their electron distributions. Under normal conditions, the mass of an atom has little effect on its chemistry. With the exception of the isotopes of the lightest elements, and conditions in which a process is employed specifically to make use of the very small mass dependence of chemical properties, all isotopes of an element have essentially the same chemistry.

The same is definitely not true for the nuclear properties of different isotopes of an element. The nuclear properties are sensitively dependent on the number of neutrons and protons they contain and their reactions with other nuclei, their nuclear chemistry[1)], is also sometimes exquisitely sensitive to these. It is quite common to find an isotope with certain properties more closely related to those of adjacent elements than to isotopes of the same element. For example, for some specific values of the neutron number N, the low-energy nuclear properties of isotopes of different elements can be remarkably similar. This is particularly true for the properties of isotopes with N = 51 and N = 83, respectively, which possess an even atomic number. Nuclei with the same number of neutrons but different number of protons are called *isotones*.

Remarkably, it is also found that the low-energy nuclear properties of isotopes with Z = 51 or Z = 83 are also similar if the neutron number is even, but these

1) Nuclear chemistry deals with changes in or transformations of the atomic nucleus. In many parts of the world, such topics are normally included in the definition of nuclear physics.

properties are quite distinct from those of the N = 51 and N = 83 isotones. Indeed, if one produces a *chart of the nuclides* by plotting the atomic number Z versus the neutron number N, and records the low-energy properties of nuclides at each point, the similarities between the properties of certain isotopes and isotones become evident. A study of the properties of *isobars* – nuclei with the same mass number A but different N and Z – shows that even here some remarkably similar properties exist with respect to their low-energy behavior.

All of these characteristics are a reflection of the structure of the nuclei themselves. Just as for atoms, the quantized structure of atomic nuclei leads to regularities in properties that are akin to the periodic structure demonstrated in the Mendelev periodic table of the elements. These regularities point to a type of shell structure that has a profound influence on the properties of nuclei and their reactions. Unlike the shell structure in atoms, however, shell structure in nuclei is complicated by the presence of two different nuclear constituents, the neutrons and protons, and the reference to nuclei of Z or N = 51 or 83 is suggestive that shell structure must exist separately for neutrons and protons. This idea is not altogether so strange if one considers the fundamental notion of the Pauli exclusion principle that defines the number of *identical* particles that can be placed into a given quantum state.

1.3 Overview of Radioactive Decay Processes and Nuclear Reactions

Three principal modes of radioactive decay have been observed among the nuclei found in nature and those produced in nuclear reactions, and the general characteristics of these will now be discussed. In the following and throughout the text, the symbol ${}^{A}_{Z}N$ will be used to denote the nucleus of an atom, and the symbols ${}^{A}_{Z}M$ or $M(Z, A)$ will be used to denote a neutral atom. Since it is possible to form nuclei or atoms in excited states, these symbols will further be restricted to imply that the nucleus or atom is in its lowest state of excitation, the so-called *ground state*. Should it be necessary to consider an arbitrary excited state, an asterisk will be appended as a superscript.

1.3.1 Alpha Decay

Radioactive decay by the emission of α-particles, nuclei of ${}^{4}_{2}He$, alpha decayis a principal decay mode among the heaviest elements found in nature. Alpha decay is generally symbolized as

$$ {}^{A}_{Z}N \rightarrow {}^{A-4}_{Z-2}N + {}^{4}_{2}N \quad (1.1) $$

or, more simply,

$$^{A}_{Z}N \rightarrow {}^{A-4}_{Z-2}N + \alpha \tag{1.2}$$

The nucleus produced as a result of the decay contains 4 fewer nucleons, 2 protons and 2 neutrons. As in all radioactive decay processes, the total of all particles in the nucleus, the sum of the neutrons and protons, is conserved. In addition, the total electrical charge is conserved.

A particularly important example of α-decay is that of the most abundant isotope of uranium in nature

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + \alpha \tag{1.3}$$

$^{238}_{92}U$ has a *half-life*, the time required for half of the nuclei to undergo decay, of 4.468×10^9 y and those nuclei still present on earth have existed since the time that the elements were created. $^{234}_{90}Th$, on the other hand, has a half-life of only 24.1 d and it would not exist on earth at all if it were not constantly being produced by the α decay of $^{238}_{92}U$. As will be seen in Chapter IX, the decay of $^{238}_{92}U$ gives rise to a series of radioactive nuclei that accounts for a large fraction of the total radioactivity that occurs naturally on earth.

1.3.2
Beta Decay

The term β decay actually refers to three processes that all derive from the same underlying physics. Taken together, they represent the most common radioactive decay mode among all of the known nuclei.

The first mode recognized experimentally was that of β^- decay. This is the process in which a neutron in the nucleus is converted into a proton in the nucleus with the simultaneous emission of an electron – the β^- particle. Under most circumstances, with common radiation detectors, this is exactly what is observed. However, when β^- decay was first studied, it produced profound consternation because it did not appear to satisfy the conservation laws of energy, momentum, and angular momentum. Today we know that an additional, very weakly interacting particle is also emitted. It is known as the *antineutrino* and is symbolized as $\bar{\nu}$. Accounting for the antineutrino, β^- decay is correctly symbolized as

$$^{A}_{Z}N \rightarrow {}_{Z+1}^{A}N + \beta^- + \bar{\nu} \tag{1.4}$$

This expression also demonstrates another conservation law that is evident in nature, the conservation of light particles. The particles of small mass, including the electron and antineutrino, belong to a family known as the *leptons*. Observation has shown that there is a conservation law applicable to particles within families; the creation or *annihilation* (destruction) of a particle must be accompanied by the annihilation or creation of an antiparticle[2)]. The creation of the electron, a particle, is accompanied by the creation of the antineutrino, an antiparticle, belonging to the same family.

One very common nuclide that decays by β^- decay is ${}^3_1H_2$ or *tritium*. Tritium is frequently incorporated into different biologically-active molecules and thereby serves as a radioactive "tag" to aid in unraveling a wide range of problems in molecular and cell biology. Tritium is also likely to be one of the main "ingredients" in the first nuclear fusion systems designed to produce electric power.

A second common nucleus that decays in this way is ${}^{14}_6C_8$ with a half-life of 5730 y. It is constantly being produced by the interaction of cosmic rays in the atmosphere. Because it behaves chemically as "normal" carbon, it becomes incorporated into all living matter and it is one of the isotopes that confers natural radioactivity to the human body. ${}^{14}_6C_8$ has provided the basis for one of the more accurate means of determining the age, since death, of a previously living organism, because, after death, no additional ${}^{14}_6C_8$ is taken up by the organism. Thus, if we know the fraction of carbon in living matter that is ${}^{14}_6C_8$, the time since death can be determined by measurement of the fraction of the original ${}^{14}_6C_8$ that remains at the time of dating.

Finally, and perhaps the most important β^- decay with respect to understanding the underlying physics of the process itself, is the decay of the free neutron. Free neutrons can be produced by a wide variety of reactions and they are produced in abundance in nuclear fission reactors. The free neutron decays with a half-life of 10.37 min.

A second mode of β decay involves the emission by nuclei of *positrons*, symbolized by β^+. The positron is the antiparticle to the electron. It has exactly the same mass and magnitude of electric charge as an electron but the charge is of opposite sign. In β^+ decay, the overall effect is the transformation of a proton in the nucleus into a neutron in the nucleus with the emission of a positron and a *neutrino*, ν. The decay can then be written as

$$ {}^A_ZN \rightarrow {}_{Z-1}^{A}N + \beta^+ + \nu \tag{1.5} $$

In some respects, this is quite strange. Free protons appear "stable". They do not undergo radioactive decay by any known mechanism; the protons present in the nuclei of atoms found in nature have existed since the creation of the elements themselves. And yet protons incorporated into certain nuclides seem to be able to transform by the process of positron emission. The explanation for this seeming contradiction is that it is the *nucleus as a whole* that gives rise to the decay. This is true for all radioactive transformations.

While not generally found in nature, positron emitters are easily produced by a variety of nuclear reactions. One of the positron emitters that is finding increasing use in medical technology is the nuclide ${}^{18}_9F_9$. It has a half-life of 1.83 h and is very easily detected. Because of its small size and the strong bonds it makes with carbon

2) The concept of the conservation of leptons is under very active study today. Although not of practical importance to the studies presented here, the violation of the law of conservation of leptons would have great implications concerning our understanding of matter itself.

atoms, it can be substituted readily for a hydrogen atom in a large biologically-active molecule without changing the chemistry of the molecule to a great extent. Currently, ${}^{18}_{9}F_9$ is commonly incorporated into a molecule with very similar properties to glucose. So similar that the molecule acts just like glucose in the body and thus is used as a metabolic tracer in nuclear medicine procedures. It is the most widely used isotope in the powerful diagnostic imaging procedure known as *positron emission tomography* (PET) imaging.

The third mode of β decay is called *electron capture* and it can only take place when a nucleus has at least one atomic, or orbital, electron. In this decay, an orbital electron is captured by the nucleus and a proton is converted into a neutron. Because the electron is annihilated, a neutrino is created and emitted. The decay can be written as

$$ {}^{A}_{Z}N + e^{-} \rightarrow {}_{Z-1}^{\ \ A}N + \nu \tag{1.6}$$

Electron capture decay can be a difficult process to observe because the only radiation that must be emitted is the neutrino, which, under most conditions, has a negligible probability of detection. However, because an orbital electron has been removed from an atom's electron distribution, the remaining electrons will quickly re-arrange with a high probability that an x-ray will be emitted in the process. This can be detected with relative ease. An example is the electron capture decay of ${}^{55}_{26}Fe$, which is accompanied by the emission of an x-ray that is characteristic of the element manganese (Mn). Following Eq. (1.6), the decay can be written as ${}^{55}_{26}Fe + e^{-} \rightarrow {}^{55}_{25}Mn + \nu$.

1.3.3 Spontaneous Fission

Spontaneous nuclear fission is only found among the heaviest elements. It is very similar to, but not the same as, the fission process that takes place in nuclear power reactors. In spontaneous fission, a nuclide undergoes decay by and of itself. In power reactors, the fission is "induced" by the interaction of a neutron with a uranium or plutonium nucleus. Fission is an extremely complicated process that is still the subject of active research.

The most common mode of spontaneous fission can be represented symbolically as

$$ {}^{A}_{Z}N \rightarrow {}^{A_L}_{Z_L}N^{*} + {}^{A_H}_{Z_H}N^{*} \tag{1.7}$$

where $A = A_L + A_H$ and $Z = Z_L + Z_H$. The nucleus undergoing spontaneous fission splits to produce two nuclei, the so-called *fission fragments*, that contain all of the neutrons and protons present initially. The subscripts L (light) and H (heavy) are meant to indicate that the mass numbers of the two fragments are generally not the same. The asterisks on ${}^{A_L}_{Z_L}N^{*}$ and ${}^{A_H}_{Z_H}N^{*}$ indicate that these nuclides are generally created in some excited state and not in their ground state. However, the excited states decay rather quickly by the emission of electromagnetic radiation – *γ-rays* – and neutrons, and the *net* process can then be written as

$$ {}^{A}_{Z}N \rightarrow {}^{A_L}_{Z_L}N + {}^{A_H}_{Z_H}N + (A - A_L - A_H){}^{1}_{0}n + \gamma \text{ rays} \qquad (1.8)$$

where, in this case, $A - A_L - A_H$ is the number of neutrons that are emitted in the decay of the excited fragments[3]. Again, $Z = Z_L + Z_H$. The nuclei produced *after* the emission of neutrons and γ-rays, the so-called *prompt* neutrons and γ-rays, are generally referred to as *fission products*.

The spontaneous fission of a single nuclide is found to take place in literally hundreds of ways. For example, the mass numbers of the products of spontaneous fission of ${}^{252}_{98}Cf$ range from as low as 66 to as high as 172 and isotopes of over one-half of the elements found in nature are produced. On the average, 2–4 neutrons are emitted following fission of the most common isotopes. The half-life for spontaneous fission, the half-life that a nuclide would possess if it decayed only by this mode, is found to vary over an enormous range. For example, the isotope ${}^{239}_{94}Pu$, one of the isotopes responsible for power production in nuclear fission reactors, has a spontaneous fission half-life of about 5.5×10^{13} y. But the spontaneous fission half-lives of ${}^{241}_{95}Am$, ${}^{252}_{98}Cf$, and ${}^{259}_{102}No$ are 1.1×10^{12} y, 85.4 y and 4.5 h, respectively. Spontaneous fission is one of the decay modes that will limit the heaviest elements we can hope to create and study in the laboratory.

1.3.4
Gamma Decay

Gamma (γ) decay, or γ-ray emission, is the process in which an excited state of a nucleus transforms into a lower-energy state with the difference in energy appearing as electromagnetic radiation, the γ-ray. This is entirely analogous to the emission of x-rays when an excited electronic state of an atom decays to a lower-energy state. γ-rays are frequently emitted following α and β decay and indicate that, just as the fission fragments are generally produced in excited states, both α and β decay often lead to excited states of their product nuclei as well. In many cases, emission of a number of γ-rays of different discrete energies is observed in radioactive decay, indicating that a number of different excited nuclear states must be produced.

While most excited states of nuclei have very short half-lives – so short that for normal applications they can be considered to decay "instantly" – some have lifetimes so long that they appear as independent radioactive species, just as is found for the decay of some excited states of atoms and molecules. We call such states *metastable states* or *nuclear isomers* and will designate them by appending the mass number with the letter m. Thus ${}^{99m}Tc$ denotes a metastable state of the nuclide ${}^{99}Tc$. While ${}^{99}Tc$ has a half-life of 2.11×10^{5} y, ${}^{99m}Tc$ has a half-life of 6.01 h.

3) In the literature on nuclear engineering, the symbol $\bar{\nu}$ is commonly used to denote the number of neutrons emitted in fission, averaged over all fission modes. This should not be confused with the integral number of fission neutrons emitted in a specific fission of the type indicated by Eq. (1.8).

Although α decay, β decay, spontaneous fission and γ decay are usually presented on an equal footing to the principal forms of radioactive decay, a clear distinction between γ decay and the other three modes should be made. Unlike the others, γ decay does not produce a *transformation* of the nucleus to some other nuclide.

1.3.5 Nuclear Reactions

The term "nuclear reaction" is quite generic. It is used to refer to the interaction of nuclei with nuclei, individual nucleons with nuclei, nucleons with one another and even the interactions of photons and electrons with nuclei. Nuclear reactions are the fundamental means by which we probe the nature of the nuclear force, the structure of complex nuclei, and the means by which we produce radioactive nuclei for study or applications.

We will restrict our attention to low-energy nuclear reactions and, for the moment, will consider only *binary* nuclear reactions. These can be symbolized by the expression

$$^{A_1}_{Z_1}N + ^{A_2}_{Z_2}N \rightarrow ^{A_3}_{Z_3}N + ^{A_4}_{Z_4}N \tag{1.9}$$

where, as a result of conservation, $A_1 + A_2 = A_3 + A_4$ and $Z_1 + Z_2 = Z_3 + Z_4$. The reaction products may, as in the case of the fission fragments, be produced in various states of excitation and these generally decay by emission of γ-rays. If decay takes place by emission of neutrons, protons, α particles, etc., the latter are included in the reaction itself.

As an example, the reaction that is the principal source of the $^{14}_{6}C_8$ found in the environment is

$$^{14}_{7}N + n \rightarrow ^{14}_{6}C + p \tag{1.10}$$

The neutrons are produced primarily by the interaction of cosmic ray protons with the oxygen and nitrogen of the atmosphere. Production of $^{18}_{9}F_9$ for use in positron emission tomography and other applications is readily achieved with the reaction

$$^{18}_{8}O + p \rightarrow ^{18}_{9}F_9 + n \tag{1.11}$$

Nuclear reactions such as those in Eqs (1.10) and (1.11) are frequently written in the short-hand notation $^{14}_{7}N(n, p)^{14}_{6}C$ and $^{18}_{8}O(p, n)^{18}_{9}F_9$, respectively. This notation arose in the description of a typical reaction for which the heavier of the reaction partners was usually contained in a stationary *target* in the laboratory and was bombarded by the light reaction partner produced from a particle accelerator or nuclear reactor. In this case, the light particle is generally referred to as the *projectile*. The short-hand notation then symbolizes target (projectile, light product) heavy product. In keeping with this, the principal reactions leading to energy production in nuclear fission reactors are symbolized as ${}^{235}_{92}\mathrm{U}(n, f)$ and ${}^{239}_{94}\mathrm{Pu}(n, f)$, where f refers to fission and the fission products go unnamed.

The nuclear atom was defined experimentally by Ernest Rutherford through the study of the scattering of α particles by a gold foil. Most of the scattering events were consistent with the interaction of an α particle of charge $Z = 2^{+}$ with a gold nucleus of charge $Z = 79^{+}$. Such interactions were simply described as the elastic scattering of two point charges in their mutual Coulomb field. These reactions would generally be symbolized as ${}^{A}_{Z}\mathrm{N}(\alpha, \alpha){}^{A}_{Z}\mathrm{N}$, or simply described as the elastic scattering of α particles on ${}^{A}_{Z}\mathrm{N}$.

1.4
The Model-based Character of this Text

Essentially all students who might use this text have been exposed to the beauty and precision of classical mechanics and electricity and magnetism. The study of these topics is so beautiful because they are based on very well-defined and very well-tested physical laws. Newton's Laws, the conservation of energy and momentum and the various laws met with in electricity and magnetism, allow one to specify a problem precisely, solve it with the appropriate physics and then be sure that if an experiment were performed as accurately as possible, the experimental result would agree with theory within very small uncertainties. Unfortunately, and with the exception of those problems that involve only the application of conservation laws, the same cannot be said for most problems in low-energy nuclear physics. We simply do not have an expression for the interaction of two nuclear particles that describes the physics with the same sense of exactness as the gravitational interaction, the Coulomb interaction, etc. We do not have a law for the nuclear interaction. It is simply too complex. To make matters worse, we usually deal with nuclei containing many particles. And as you know, only two-body problems and a few other special cases can be solved exactly. This means that, for most of interesting problems we will treat, some sort of approximation method must be applied.

It is for these reasons that the majority of problems in low-energy nuclear physics are attacked by use of different models, each chosen to best describe the problem under consideration in a tractable manner and which, to a reasonable degree, will reflect reality to a good approximation. Some of these models are indeed very complex and are capable of providing near-quantitative agreement with experiment. Some of them are rather crude but still permit semi-quantitative agreement with experiment and a simple means for correlating a large body of data.

In this text, we will make extensive use of the simplest models that make sense and that serve as an introduction to the main ideas on which much more accurate models are based. While certainly not providing the satisfaction of an exact description, these models do have a bit of beauty attached to them. They do permit some very nice insights into an extremely complicated and very important part of the physical world around us.

1.5 Sources of Nuclear Data

There are a number of sites on the worldwide web that are particularly good sources for nuclear data and links to other useful sites. The National Nuclear Data Center at the Brookhaven National Laboratory (http://www.nndc.bnl.gov) is an excellent source of evaluated data on nuclear structure and the properties of nuclear reactions, especially neutron reactions. One can also access authoritative files of experimental and evaluated atomic masses. Some unevaluated experimental data are also accessible as well as a computer index of experimental neutron data. In addition, evaluated cross sections for the interaction of electromagnetic radiation with matter are available. Quite recently, the website has made available means by which log ft values for β transitions and internal conversion coefficients can be calculated directly.

A second site of great utility is the Nuclear Data Dissemination Home Page, sponsored jointly by the Isotopes Project of the Ernest Orlando Lawrence Berkeley National Laboratory and the Lund Nuclear Data WWW Service of LUNDS Universitet, Sweden (http://ie.lbl.gov/toi.html). From this page one can obtain direct links to the Table of Radioactive Isotopes and on-line programs that permit the examination of evaluated data on the properties of levels in essentially every nuclide that is known. In addition, it is possible to obtain drawings of level schemes of nuclei as well as the decay schemes of radioactive nuclei.

Much of the information available on the Nuclear Data Dissemination Home page is contained in the publication *Table of Isotopes* by Richard B. Firestone, edited by Coral M. Baglin and S.Y. Frank Chu, CD-Rom editor, Wiley-Interscience, New York. The publication is available in both a two-volume set or on a CD-ROM. The appendices in this reference provide numerous useful parameters in graphical form, that are handy for quick calculations.

Finally, we should add that the National Institute of Science and Technology (http://physics.nist.gov/) provides authoritative information in many areas that are important to low-energy nuclear physics and provides up-to-date information on physical constants, units and their uncertainties.

The information available from the references above and the literature in general fall into two broad classes: *experimental* data and *evaluated* data. Experimental data represent the results of individual measurements of various properties along with estimates of the uncertainties in the measurements. Evaluated data most often represent the best estimates of individual parameters or entire data sets after very careful, and often very complex, analysis of all data that exist in the literature. Both types of compilations are very useful. But, as with all experimentally-derived information, it is incumbent upon the user to ensure that data are used correctly in the context of a specific application. For general purposes, data in evaluated files can be taken as the "best" information available in the judgement of acknowledged experts. This is especially true when a number of investigators have made measurements and there is good reason to believe in the quality of the data. However, in some demanding cases or when dealing with nuclear properties that have not been well-studied experimentally, it is necessary that the user investigate the raw data and examine the publications that describe the measurements in question and their uncertainties.

One of the very unfortunate properties of many authoritative data files is that they do not present well-defined errors on the individual parameters contained in them, primarily because they are intended to be used as complete data sets. The novice and many experienced users tend to take the parameters in such compilations as fact and do not question their reliability or real accuracy. In addition, some sets of evaluated data contain estimates of parameters that are obtained by extrapolation, interpolation or model calculations. This is a real danger and something of which the user must be wary.

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