Introduction

0.1 What is Nuclear Physics?

The most accepted theory for the origin of the universe assumes that it resulted from a great explosion, soon after which the primordial matter was extremely dense, compressed and hot. This matter was mainly composed of elementary particles, such as quarks and electrons. As it expanded and cooled down, the quarks united to form heavier particles, called hadrons, which contain 3 quarks (baryons) or 2 quarks (mesons). The protons and neutrons (which are baryons) formed nuclei, and the electrons were captured in orbits around the nuclei forming atoms.

The larger and heavier nuclei were created inside stars, which were formed by the collection of large amounts of the primordial matter. Some of those stars ejected parts of their mass to the interstellar space, leading to the formation of smaller stars, planets, nebulae, etc. The chemical substances were created by the union of atoms in molecules and, finally, by the grouping of several types of molecules in complex structures.

The evolution of the universe is the object of study of cosmology and astrophysics; nuclear astrophysics studies the synthesis of heavy nuclei starting from lighter ones, in temperature and pressure conditions existing in the stars. Nuclear physics studies the behavior of nuclei under normal conditions or in excited states, as well as the reactions among them. Chemistry studies the structure of the atomic molecules and the reactions among them. Finally, biology studies the formation and development of the great molecular agglomerates that compose living beings. In any of these sciences, the objective is to understand complex structures starting from simpler structures and from the interactions among them.

In nuclear physics the simpler structures are the nucleons, the generic name given to protons and neutrons. The nucleon-nucleon interaction, responsible for maintaining the nucleus bound, can be deduced from the analysis of scattering experiments, that is, from the collisions between nucleons. Knowledge about this interaction is in general quite good, which in principle should allow a description of the structure of an atomic nucleus with precision. But this is not exactly the case, and the reason is that in a many-particle system several structures appear, which most of the time do not depend on the interaction between them. For example, a molecule of benzene possesses a structure in the form of a hexagonal ring. We know that the interaction responsible for the formation of molecules is of a Coulombic nature. However, an attempt to describe the symmetry of a molecule solely as due to the properties of the Coulomb interaction will likely fail. Therefore, even if we knew exactly the form of the nucleon-nucleon interaction, that would be insufficient to describe the details of the structure of nuclei with precision. This is a general characteristic of a many-body system. In fact, it is not always clear that good knowledge of the nucleon-nucleon interaction is necessary to determine certain nuclear characteristics. Several interactions with different properties can lead to the same characteristics.

The known atomic nuclei possess at most about 280 nucleons. This number is not so large as to justify the description of the nucleus by macroscopic quantities such as pressure, temperature, elasticity coefficient, and so on, as we do with gases, liquids, and solids in thermodynamic balance. On the other hand, a nucleus with few nucleons is not so simple to describe either: the problem of three interacting particles already possesses a large enough degree of complexity not to allow an exact solution. This situation makes atomic nuclei ideal "laboratories" for the study of the effects of correlations that are developed in a many-body system.

Nuclear physics is intimately linked to other disciplines. In field theory, for example, both the weak interaction and the strong interaction were studied first in atomic nuclei. In fact, the atomic nucleus serves as a micro-laboratory for the study of these interactions in a many-body system. The most celebrated example in this sense is the experiments that demonstrated that the weak interaction is not symmetrical under space reflection.

Similarly, nuclear physics possesses a traditional connection with atomic physics. The interaction of nuclei with their atomic neighbors creates the hyperfine structures in the atomic spectrum. This is important not just in atomic physics, but also in solid state physics. In addition, radioactive nuclei are used as probes for the study of the electromagnetic fields in atomic bonds in crystals.

Nuclear physics is of essential importance for astrophysics. The "burning" of nuclei in the stars can only be studied through experiments of nuclear reactions accomplished in laboratories. This allows understanding of a star's temporal evolution, finally leading to the formation of neutron stars, good examples of the existence of macroscopic nuclear matter (this will be discussed in more detail in chapter 12). The burning of nuclei in stars leads to the creation of heavy elements in nature. In this way, the results of studies in nuclear physics are the basis of the "cosmic" chemistry, which studies the creation and distribution of the elements in the universe.

In a similar way, the methods of nuclear dating, as well as the micro-analytical methods (for example, activation induced by neutrons), are important applications in geology and archaeology.

Nowadays, in the medical as well as technological areas, one cannot neglect the use of nuclear methods. Examples of applications happen in the diagnosis and therapy in medicine, in the study of new materials, and elsewhere.

0.2 This Book

The general idea of the book is to present basic information on the atomic nucleus and the simple theories that try to explain it. Although there is reference to experiments or measurements when I find it necessary, there is no attempt to describe the equipment and methods of experimental nuclear physics in a systematic and consistent way. In the same way, practical applications of nuclear physics are mentioned sporadically, but there is no commitment to giving a general panorama of what exists in this area.

In the ordering of the subjects, I chose to begin with a study of the basic components of the nuclei, the protons and neutrons, and of other particles that compose the scenario of nuclear processes. Pions and quarks play an essential role here, and a summary of their properties is presented.

In chapter 1 the properties of hadrons are summarized. Chapters 2 and 3 treat the system of two nucleons, the deuteron and the nucleon-nucleon interaction, while in the next chapter the properties of nuclei with any number of nucleons is introduced. The nuclear models that have been developed in an effort to explain these properties are described in chapter 5.

Chapters 6 to 9 work with nuclear transformations, starting with a general study of radioactive properties followed by the description of alpha, beta, and gamma decay.

Chapters 10 and 11 embrace the second great block of study in nuclear physics, nuclear collisions, and chapter 12 treats the role of nuclear physics for stellar evolution in several contexts of astrophysics.

Chapter 13 discusses the rapidly growing field of rare nuclear isotopes, short-lived nuclei far from the valley of stability.

An adequate level for a complete understanding of this book corresponds to a student studying at the end of a first degree in physics, including, besides basic physics, a course in modern physics and a first course in quantum mechanics. Students of other exact sciences, and of technology in general, can profit in good part from the subjects presented in this book.