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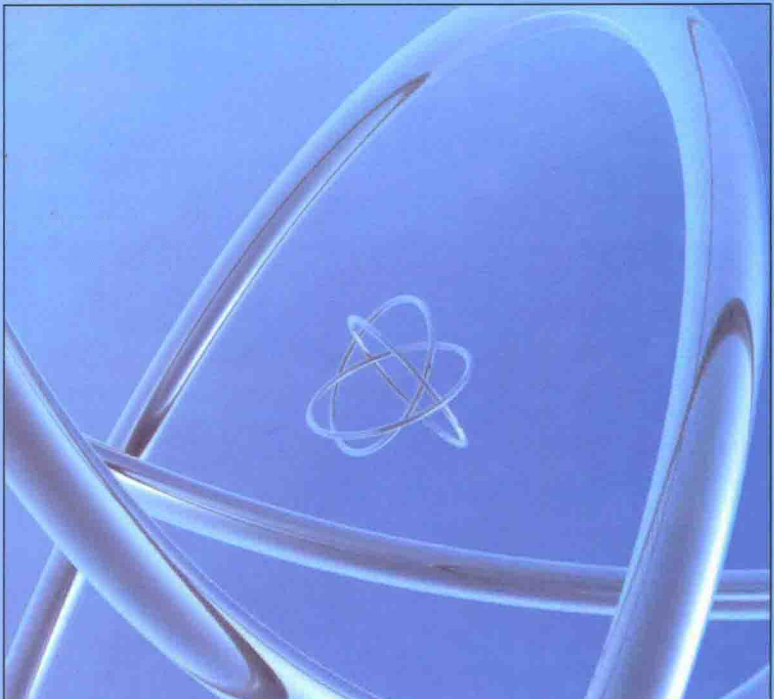
Carlos A. Bertulani

Nuclear Physics in a Nutshell

核物理学



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Corrigendum

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Carlos Bertulani
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Selected portions of the text appearing on pages 81-84, 87-88, and 95-96 were excerpted from the following original source without proper citation:

Dobaczewski, Jacek. *Interactions, Symmetry Breaking, and Effective Fields from Quarks to Nuclei (A Primer in Nuclear Theory)*, Trends in Field Theory Research, Nova Science Publishers, 2005.

The text in question spans from page 81 (last paragraph) to the end of subsection 3.4.1 on page 84, including Figure 3.3 (redrawn); the first sentence of subsection 3.4.4 on page 87 to the last paragraph of this subsection on page 88; and subsection 3.5 on pages 95-96.

Contents

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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 ofhadrons 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.

1 Hadrons

1.1 Nucleons

The scattering experiments made by Rutherford in 1911 [Ru11] led him to propose an atomic model in which almost all the mass of the atom was contained in a small region around its center called the *nucleus*. The nucleus should contain all the positive charge of the atom, the rest of the atomic space being filled by the negative electron charges.

Rutherford could, in 1919 [Ru19], by means of the nuclear reaction

$$ {}^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{17}_{8}\mathrm{O} + \mathrm{p}, \tag{1.1}$$

detect the positive charge particles that compose the nucleus called *protons*. The proton, with symbol p, is the nucleus of the hydrogen atom; it has charge $+e$ of the same absolute value as that of the electron, and mass

$$m_p = 938.271998(38)\ \mathrm{MeV}/c^2, \tag{1.2}$$

where the values in parentheses are the errors in the last two digits.

From study of the hydrogen molecule one can infer that the protons in the molecule can be aligned in two different ways. The spins of the two protons can be parallel, as in *orthohydrogen*, or antiparallel, as in *parahydrogen*. Each proton has two possible orientations relative to the spin of the other proton, and like the electron the proton has spin $\frac{1}{2}$.

In orthohydrogen the wavefunction is symmetric with respect to the interchange of the spins of the two protons, since they have the same direction, and experiments show that the wavefunction is antisymmetric with respect to the interchange of the spatial coordinates of the protons. This justifies the wavefunction being antisymmetric with respect to the complete interchange of the protons. In parahydrogen the wavefunction is also antisymmetric with respect to the complete interchange of the two protons, being antisymmetric with respect to the interchange of the spins of the protons and symmetric with respect to the interchange of their spatial coordinates. This shows that the protons obey Fermi-Dirac statistics; they are *fermions* and the Pauli exclusion principle is applicable to them. At most one proton can exist in a given quantum state.

The *neutron*, with symbol n, has charge zero, spin $\frac{1}{2}$, and mass

$$m_n = 939.565330(38)\ \text{MeV}/c^2. \tag{1.3}$$

In 1930, Bothe and Becker [BB30] discovered that a very penetrating radiation was released when boron, beryllium, or lithium was bombarded with α-particles. At that time it was thought that this penetrating radiation was γ-rays (high-energy photons). In 1932, Curie and Joliot [CJ32] figured out that the radiation was able to pull out protons from a hydrogen-rich material. They suggested that this was due to Compton scattering, that is, the protons recoiled after scattering the γ-rays. This hypothesis, however, meant that the radiation consisted of extremely energetic γ-rays, and no explanation could be given for the origin of such high energies. Also in 1932, Chadwick [Ch32] showed, by means of an experiment conducted at the Cavendish laboratory in Cambridge, that the protons ejected from the hydrogen-rich material had collided with neutral particles with mass close to the mass of the proton. These were neutrons, the neutral particles that composed the penetrating radiation discovered by Bothe and Becker. The reaction that occurred when beryllium was bombarded with α-particles was

$${}^4_2\text{He} + {}^9_4\text{Be} \rightarrow {}^{12}_6\text{C} + {}^1_0\text{n}. \tag{1.4}$$

The existence of the neutron was also necessary to explain some features of the molecular spectrum showing that the wavefunctions of nitrogen molecules were symmetric with respect to interchange of the two ^{14}N nuclei. As a consequence, the ^{14}N nuclei were *bosons*. This could not be explained if the ^{14}N nucleus were composed only of protons and electrons, since 14 protons and 7 electrons are needed for that, which means an odd number of fermions. A system made up of an odd number of fermions is a fermion, since the interchange of two systems of this type can be made by the interchange of each of their fermions, and each change of two fermions changes the sign of the total wavefunction. In the same way, we can say that a system composed of an even number of fermions is a boson. This shows that if the ^{14}N nucleus is formed by 7 protons and 7 neutrons it is a boson, assuming that the neutron is a fermion. In this way, the study of the N_2 molecule led Heitler and Hertzberg [HH29] to conclude that atomic nuclei are composed of protons and neutrons and not of protons and electrons.

Several other studies established that neutrons obey the Pauli principle and thus are fermions, having spin $\frac{1}{2}$. We recall that particles with fractional spin $(2n+1)/2$ are fermions, and that particles with integer spin are bosons. Protons and neutrons have similar properties in several aspects, and it is convenient to utilize the generic name *nucleon* for both.

1.2 Nuclear Forces

The origin of the Coulomb force between charged particles is the exchange of photons between them. This is represented by the *Feynman diagram* (a) of figure 1.1. In this diagram

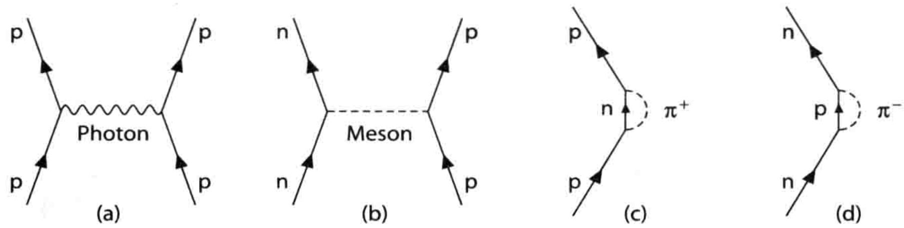

Figure 1.1 Diagrams that represent (a) the electromagnetic interaction, which occurs by exchange of photons, and (b) the nuclear interaction, due to meson exchange. (c and d) Virtual dissociation of the nucleons, giving rise to the anomalous magnetic moment.

lines oriented up represent the direction in which time increases. At some instant of time the particles exchange a photon, which gives rise to attraction or repulsion between them. The photon has zero mass and the Coulomb force is a long-range force.

The force that keeps the nucleus bound is the *nuclear force*. It acts between two nucleons of any type and, in contrast to the Coulomb force, it is of short range. In 1935 Yukawa [Yu35] suggested that the nuclear force has its origin in the exchange of particles with finite rest mass between the nucleons. These particles are called *mesons*, and this situation is described by the Feynman diagram of figure 1.1(b). In the emission of a meson with rest mass M, the total energy of the nucleon-nucleon system is not conserved by the amount $\Delta E = Mc^2$. From Heisenberg's uncertainty principle, $\Delta E\,\Delta t \simeq \hbar$, the exchanged meson can exist during a time Δt (in which violation of energy conservation is allowed), such that

$$\Delta t \simeq \frac{\hbar}{\Delta E} = \frac{\hbar}{Mc^2}. \tag{1.5}$$

During this time the exchanged meson can travel at most a distance

$$R = c\Delta t \simeq \frac{\hbar}{Mc}, \tag{1.6}$$

since the velocity of light c, is the maximum velocity. Then, if the nuclear force can be described by meson exchange, the mesons would exist "virtually" during a time permitted by the uncertainty principle. The nuclear force range would be approximately $\hbar/Mc$. Experimentally one finds that the nuclear force range is $R \simeq 10^{-13}$ cm. Thus, an estimate for the meson mass is

$$M \simeq \frac{\hbar}{Rc} \simeq 0.35 \times 10^{-24}\ \text{g} \simeq 200\ \text{MeV}, \tag{1.7}$$

where $1\ \text{MeV/c}^2 = 1.782 \times 10^{-27}$ g (for brevity, one normally omits c^2).

In 1936, Anderson and Neddermeyer [AN36] observed cosmic rays in a bubble chamber and found a particle with mass approximately equal to that predicted by Yukawa. These particles were investigated during the next ten years but, because their interaction with nucleons was extremely weak, they could not be the Yukawa meson. This puzzle was solved by Lattes, Muirhead, Powell, and Ochialini [La47]. They discovered that there are two types of mesons: the μ-mesons and the π-mesons. The π-meson interacts strongly with nucleons, but has a very short lifetime and decays into a μ-meson, the particle identified

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