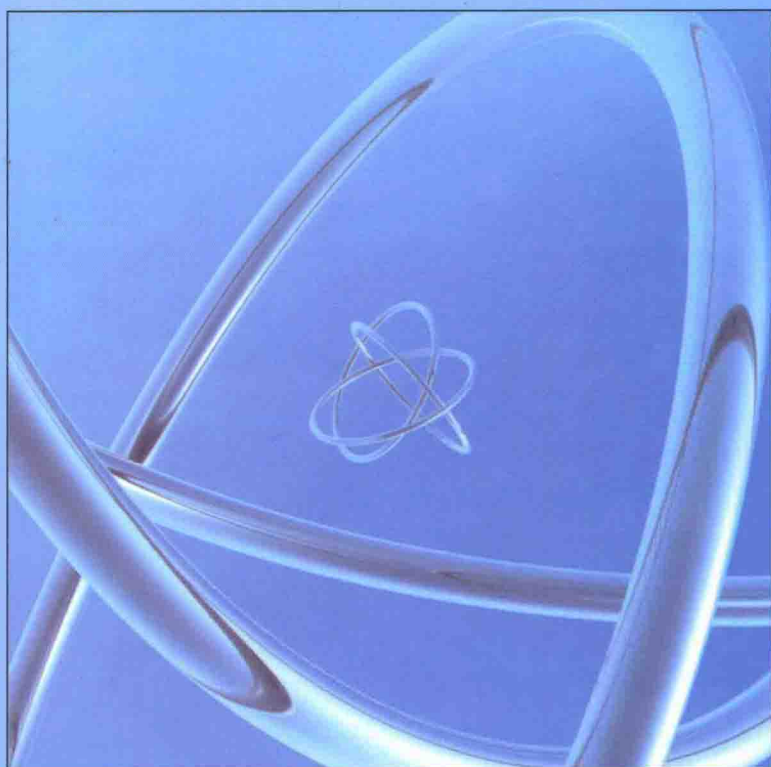


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Carlos A. Bertulani

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

Introduction	1
0.1 What is Nuclear Physics?	1
0.2 This Book	3

1 Hadrons	4
1.1 Nucleons	4
1.2 Nuclear Forces	5
1.3 Pions	7
1.4 Antiparticles	8
1.5 Inversion and Parity	8
1.6 Isospin and Baryonic Number	10
1.7 Isospin Invariance	13
1.8 Magnetic Moment of the Nucleons	14
1.9 Strangeness and Hypercharge	15
1.10 Quantum Chromodynamics	21
1.11 Exercises	29

2 The Two-Nucleon System	31
2.1 Introduction	31
2.2 Electrostatic Multipoles	32
2.3 Magnetic Moment with Spin-orbit Coupling	34
2.4 Experimental Data for the Deuteron	36
2.5 A Square-well Model for the Deuteron	38
2.6 The Deuteron Wavefunction	41
2.6.1 <i>Angular momentum coupling</i>	41
2.6.2 <i>Two particles of spin $\frac{1}{2}$</i>	42
2.6.3 <i>Total wavefunction</i>	43

2.7	Particles in the Continuum: Scattering	46
2.8	Partial Wave Expansion	49
2.9	Low Energy Scattering	53
2.10	Effective Range Theory	59
2.11	Proton-Proton Scattering	61
2.12	Neutron-Neutron Scattering	64
2.13	High Energy Scattering	65
2.14	Laboratory and Center of Mass Systems	65
2.15	Exercises	68
3	The Nucleon-Nucleon Interaction	71
3.1	Introduction	71
3.2	Phenomenological Potentials	72
3.3	Local Potentials	72
3.3.1	<i>Nonlocal potential</i>	78
3.4	Meson Exchange Potentials	80
3.4.1	<i>Yukawa and Van der Waals potentials</i>	80
3.4.2	<i>Field theory picture</i>	84
3.4.3	<i>Short range part of the NN interaction</i>	86
3.4.4	<i>Chiral symmetry</i>	87
3.4.5	<i>Generalized boson exchange</i>	89
3.4.6	<i>Beyond boson exchange</i>	91
3.5	Effective Field Theories	94
3.6	Exercises	96
4	General Properties of Nuclei	98
4.1	Introduction	98
4.2	Nuclear Radii	98
4.3	Binding Energies	101
4.4	Total Angular Momentum of the Nucleus	104
4.5	Multipole Moments	104
4.6	Magnetic Dipole Moment	106
4.7	Electric Quadrupole Moment	109
4.8	Excited States of Nuclei	111
4.9	Nuclear Stability	114
4.10	Exercises	116
5	Nuclear Models	119
5.1	Introduction	119
5.2	The Liquid Drop Model	119
5.3	The Fermi Gas Model	124
5.4	The Shell Model	128
5.5	Residual Interaction	142

5.6 Nuclear Vibrations	144
5.7 Nuclear Deformation	149
5.8 The Nilsson Model	150
5.9 The Rotational Model	153
5.10 Microscopic Theories	160
5.10.1 <i>Hartree-Fock theory</i>	160
5.10.2 <i>The Skyrme interaction</i>	162
5.10.3 <i>Relativistic mean field theory</i>	164
5.11 Exercises	166

6 Radioactivity	170
6.1 Introduction	170
6.2 Multiple Decays—Decay Chain	171
6.3 Preparation of a Radioactive Sample	173
6.4 Secular Equilibrium	174
6.5 Natural Radioactive Series	174
6.6 Radiation Units	176
6.7 Radioactive Dating	177
6.8 Properties of Unstable States—Level Width	179
6.9 Transition Probability—Golden Rule	181
6.10 Exercises	183

7 Alpha-Decay	185
7.1 Introduction	185
7.2 Theory of α -Decay	185
7.3 Angular Momentum and Parity in α -Decay	191
7.4 Exercises	194

8 Beta-Decay	195
8.1 Introduction	195
8.2 Energy Released in β -Decay	196
8.3 Fermi Theory	197
8.4 The Decay Constant—The $\log ft$ Value	202
8.5 Gamow-Teller Transitions	204
8.6 Selection Rules	206
8.7 Parity Nonconservation in β -Decay	206
8.7.1 <i>Double β-Decay</i>	211
8.8 Electron Capture	213
8.9 Exercises	215

9 Gamma-Decay	218
9.1 Introduction	218

9.2 Quantization of Electromagnetic Fields	218
9.2.1 <i>Fields and gauge invariance</i>	218
9.2.2 <i>Normal modes</i>	220
9.2.3 <i>Photons</i>	221
9.3 Interaction of Radiation with Matter	224
9.3.1 <i>Radiation probability</i>	227
9.3.2 <i>Long wavelength approximation</i>	228
9.4 Quantum and Classical Transition Rates	235
9.5 Selection Rules	240
9.6 Estimate of the Disintegration Constants	241
9.7 Isomeric States	243
9.8 Internal Conversion	244
9.9 Resonant Absorption—The Mössbauer Effect	249
9.10 Exercises	255

10 Nuclear Reactions—I	258
10.1 Introduction	258
10.2 Conservation Laws	260
10.3 Kinematics of Nuclear Reactions	261
10.4 Scattering and Reaction Cross Sections	265
10.5 Resonances	270
10.6 Compound Nucleus	273
10.7 Mean Free Path of a Nucleon in Nuclei	276
10.8 Empirical Optical Potential	277
10.9 Compound Nucleus Formation	282
10.10 Compound Nucleus Decay	290
10.11 Exercises	294

11 Nuclear Reactions—II	298
11.1 Direct Reactions	298
11.1.1 <i>Theory of direct reactions</i>	301
11.2 Validation of the Shell Model	303
11.3 Photonuclear Reactions	306
11.3.1 <i>Cross sections</i>	307
11.3.2 <i>Sum rules</i>	308
11.3.3 <i>Giant resonances</i>	312
11.4 Coulomb Excitation	315
11.5 Fission	319
11.6 Mass Distribution of Fission Fragments	321
11.7 Neutrons Emitted in Fission	324
11.8 Cross Sections for Fission	325
11.9 Energy Distribution in Fission	327

11.10 Isomeric Fission	328
11.11 Exercises	331

12 Nuclear Astrophysics	334
12.1 Introduction	334
12.2 Astronomical Observations	335
12.2.1 <i>The Milky Way</i>	335
12.2.2 <i>Dark matter</i>	336
12.2.3 <i>Luminosity and Hubble's law</i>	337
12.3 The Big Bang	338
12.4 Stellar Evolution	341
12.4.1 <i>Stars burn slowly</i>	341
12.4.2 <i>Gamow peak and astrophysical S-factor</i>	342
12.5 The Sun	347
12.5.1 <i>Deuterium formation</i>	348
12.5.2 <i>Deuterium burning</i>	350
12.5.3 <i>^3He burning</i>	351
12.5.4 <i>Reactions involving ^7Be</i>	352
12.6 The CNO Cycle	354
12.6.1 <i>Hot CNO and rp process</i>	355
12.7 Helium Burning	357
12.8 Red Giants	360
12.9 Advanced Burning Stages	362
12.9.1 <i>Carbon burning</i>	362
12.9.2 <i>Neon burning</i>	364
12.9.3 <i>Oxygen burning</i>	365
12.9.4 <i>Silicon burning</i>	365
12.10 Synthesis of Heaviest Elements	367
12.11 White Dwarfs and Neutron Stars	368
12.12 Supernova Explosions	370
12.13 Nuclear Reaction Models	375
12.13.1 <i>Microscopic models</i>	375
12.13.2 <i>Potential and DWBA models</i>	376
12.13.3 <i>Parameter fit</i>	377
12.13.4 <i>Statistical models</i>	377
12.14 Exercises	379

13 Rare Nuclear Isotopes	385
13.1 Introduction	385
13.2 Light Exotic Nuclei	388
13.2.1 <i>Halo nuclei</i>	390
13.2.2 <i>Borromean nuclei</i>	393

13.3 Superheavy Elements	395
13.4 Exercises	400

Appendix A Angular Momentum	401
A.1 Orbital Momentum	401
A.2 Spherical Functions	402
A.3 Generation of Rotations	402
A.4 Orbital Rotations	403
A.5 Spin	404
A.6 Ladder Operators	406
A.7 Angular Momentum Multiplets	409
A.8 Multiplets as Irreducible Representations	412
A.9 SU(2) Group and Spin $\frac{1}{2}$	413
A.10 Properties of Spherical Harmonics	414
A.10.1 <i>Explicit derivation</i>	414
A.10.2 <i>Legendre polynomials</i>	415
A.10.3 <i>Completeness</i>	416
A.10.4 <i>Spherical functions as matrix elements of finite rotations</i>	417
A.10.5 <i>Addition theorem</i>	417

Appendix B Angular Momentum Coupling	419
B.1 Tensor Operators	419
B.1.1 <i>Transformation of operators</i>	419
B.1.2 <i>Scalars and vectors</i>	420
B.1.3 <i>Tensors of rank 2</i>	421
B.1.4 <i>Introduction to selection rules</i>	422
B.2 Angular Momentum Coupling	423
B.2.1 <i>Two subsystems</i>	423
B.2.2 <i>Decomposition of reducible representations</i>	424
B.2.3 <i>Tensor operators and selection rules revisited</i>	426
B.2.4 <i>Vector coupling of angular momenta</i>	427
B.2.5 <i>Wigner-Eckart theorem</i>	428
B.2.6 <i>Vector Model</i>	429

Appendix C Symmetries	432
C.1 Time Reversal	432
C.2 Spin Transformation and Kramer's Theorem	433
C.3 Time-conjugate Orbits	435
C.4 Two-component Neutrino and Fundamental Symmetries	436
C.5 Charge Conjugation	437
C.6 Electric Dipole Moment	438
C.7 <i>CPT</i> -Invariance	439

Appendix D Relativistic Quantum Mechanics	440
D.1 Lagrangians	440
D.1.1 Covariance	441
D.2 Electromagnetic Field	442
D.3 Relativistic Equations	444
D.3.1 Particle at rest	446
D.3.2 Covariant form: γ matrices	446
D.4 Probability and Current	448
D.5 Wavefunction Transformation	448
D.5.1 Bilinear Covariants	450
D.5.2 Parity	451
D.6 Plane Waves	451
D.6.1 Summary of plane wave spinor properties	453
D.6.2 Projection operators	454
D.7 Plane Wave Expansion	454
D.8 Electromagnetic Interaction	455
D.9 Pauli Equation	455
D.9.1 Spin-orbit and Darwin terms	457
 Appendix E Useful Constants and Conversion Factors	 459
E.1 Constants	459
E.2 Masses	460
E.3 Conversion Factors	460
 <i>References</i>	 461
<i>Index</i>	469

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

2 | Introduction

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.

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



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

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

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

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

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



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 ${}^{14}\text{N}$ nuclei. As a consequence, the ${}^{14}\text{N}$ nuclei were *bosons*. This could not be explained if the ${}^{14}\text{N}$ 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 ${}^{14}\text{N}$ 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

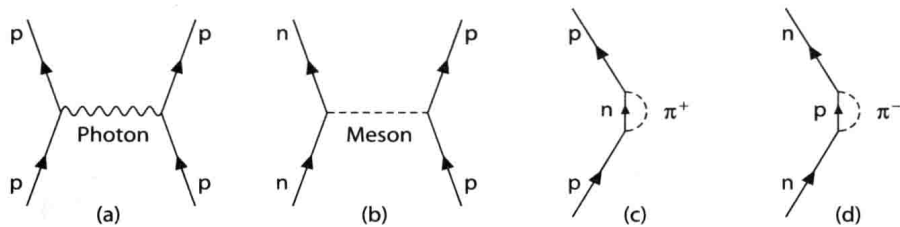


Figure 1.1 Diagrams that represent (a) the electromagnetic interaction, which occurs by exchange of photons, and (b) the nuclear interaction, due to meson exchange. (c and d) Virtual dissociation of the nucleons, giving rise to the anomalous magnetic moment.

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

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

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

$$R = c\Delta t \simeq \frac{\hbar}{Mc}, \quad (1.6)$$

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

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

where $1 \text{ MeV}/c^2 = 1.782 \times 10^{-27} \text{ g}$ (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