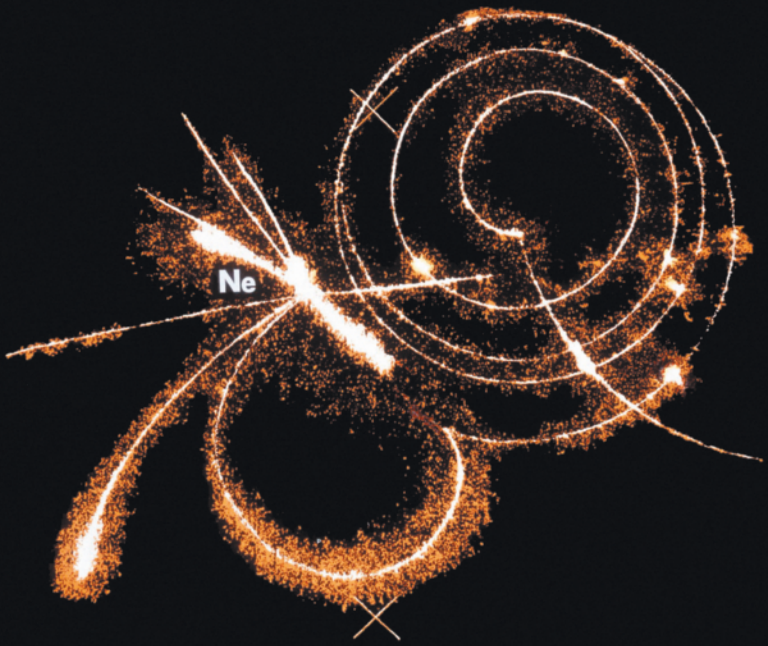
Beatriz Gato-Rivera

ANTIMATTER

What It Is and Why It's Important in Physics and Everyday Life



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To the memory of Carl Anderson and Dmitri Skobeltzyn,
and to my husband, Bert Schellekens, for his constant support

Preface

This book is a substantially extended and updated version of the Spanish book *Antimateria*, published in October 2018 by the Editorial CSIC/Los Libros de la Catarata. That book was, in turn, a natural extension of several outreach talks I gave in the CSIC (Spanish National Research Council), in Madrid, on the subject of antimatter, from 2015 until 2017.

The present English version contains additional chapters due to the extensive enlargement of the existing material that led to its rearrangement. One chapter is however written completely anew. It describes the main features of antimatter, dark matter and dark energy, contrasting them with each other, in order to provide a global view of the 'exotic side' of the Universe. I decided to add that chapter to shed some light on these topics since they seem to create some confusion. In fact, antimatter is often confused with dark matter, which, in turn, is also confused with dark energy.

Madrid, Spain
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Beatriz Gato-Rivera

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I am also really grateful to many colleagues for sharing with me very useful information. From cosmologists Emilio Elizalde (ICE-CSIC, Barcelona) and Pilar Ruiz Lapuente (IFF-CSIC, Madrid), I have learned very interesting facts about the early history of Cosmology and the acceleration of the Universe, respectively. From cosmic-ray experts, Manuel Aguilar (CIEMAT, Madrid) and Fernando Arqueros (UCM, Madrid), I got updates and advice about the AMS experiment, on board the International Space Station, and about the Pierre Auger Observatory, respectively. Stefan Ulmer (RIKEN, Ulmer Fundamental Symmetries Laboratory, Japan) provided the last updates on the antimatter experiments conducted at CERN. I have also benefit very much from scientific discussions with particle physicists Sergio Pastor Carpi and Juan José Hernández (IFIC-CSIC, Valencia) who in addition helped me finding data and references on various issues. I wish to thank Alexander Dolgov (Novosibirsk State University and University of Ferrara), for detailed information on the current state of the research about antimatter structures in the Universe, and Horst Breuker (CERN) for a guided visit to CERN's Antimatter Factory in September 2018. I also acknowledge Jan Willem van Holten and Robert Fleischer (Nikhef, Amsterdam) for some useful information about cosmic rays and B meson systems, respectively, and Pierre Sikivie (University of Florida) for some remarks on axion detection.

I really appreciate the help and kindness of Angela Lahee and Christian Caron, from Springer, who from the very beginning supported this project. I also would like to thank the Spanish 'Editorial CSIC' and 'Los Libros de la Catarata' for allowing me to use the Spanish book *Antimateria* as basis to elaborate the present book, which is a very much extended and updated version of the former. In this respect, I am also indebted to Alberto Casas (IFT-CSIC, Madrid) and Fernando Barbero (IEM-CSIC, Madrid) for their many comments to the manuscript of that book.

Finally, I am very grateful to the National Institute of Subatomic Physics (Nikhef, Amsterdam), in The Netherlands, where part of this book was written, for hospitality.

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About the Author

Beatriz Gato Rivera also known as B. Gato, is a Staff Scientist at the 'Instituto de Física Fundamental' (IFF, Madrid, Spain) of the CSIC (Spanish National Research Council). After finishing her Ph.D. on the topic of Supergravity, she spent three years at the Massachusetts Institute of Technology (MIT, Cambridge, USA) and another three years at CERN (Switzerland), working on String Theory. She has been the Principal Investigator of four research projects. In addition, at the IFF she was the head of the department of 'Particle Physics and Cosmology' for four years, and coordinator of the 'Mathematical Physics' group from 2008 until 2019. Her scientific interests are centered on Mathematical Physics, Particle Physics, Gravitation, and Foundations of Quantum Mechanics. In the last ten years, she has also been involved in outreach activities, especially public talks, and in 2018 she published the book *Antimateria* in the CSIC's collection '¿Que sabemos de?'. This was the basis for the much extended and updated English version now available as the present volume *Antimatter*.

1

Introduction

1.1 Preliminaries

Antimatter is one of the most fascinating aspects of Particle Physics. When one reads or hears the word antimatter, whether in the media, in the cinema, or in a novel, the first thing that comes to mind is: but what are they talking about? In fact, its very name bears some scent of science fiction in it, of something out of this world. This impression is misleading, however, since we actually live surrounded by antimatter and by the products of its annihilation against matter. For one thing, we are immersed in a constant shower of thousands of particles, from matter as well as antimatter, reaching incessantly the surface of the Earth in all directions. They come from the upper layers of the atmosphere, where they are produced by the impact of the cosmic rays against the atomic nuclei of the molecules present there. Some of these particles can even penetrate our homes and buildings traversing everything they encounter in their path, including ourselves.

Stars themselves are an important source of antimatter since it is produced copiously in the plasma of their nuclear furnaces in the form of antielectrons, the so-called positrons. These annihilate rapidly with the electrons in the plasma providing part of the light and heat emitted by the stars. In the case of the Sun, about 10% of the visible light that shines on us these days originated from the electron-positron annihilations that took place within it several hundred thousand years ago. Besides that, some natural radioactive substances, such as Potassium-40, also emit positrons. This makes it possible for a banana to release 15 positrons every 24 h, approximately, from the radioactive nuclei of those atoms. Finally, it should be noted that antimatter is

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widely used in our society; in medicine as well as in cutting-edge technology, where it has many applications. As a matter of fact, positrons are the essential ingredient of PET imaging techniques carried out in hospitals all over the world.

The purpose of this book is to explain what antimatter is and many other issues related to it. We will see that it is the reverse of the ordinary matter, but to fully understand this idea one must descend into the realm of elementary particles; where for every kind of existing particle there is another one with opposite properties. Indeed, it is only a matter of convention which ones we call matter particles and which antimatter particles, or antiparticles for short. For this reason, in Chap. 2, after introducing atoms and antiatoms and the subject of matter-antimatter annihilation, we provide an introduction to Particle Physics. We start with the description of the subatomic particles and antiparticles, and the forces between them, with a detailed description of their main properties. Then we review the basic concepts on which the Standard Model is built, as well as some aspects beyond this model.

Chapter 3 explains what dark matter and dark energy are, comparing and contrasting them with antimatter, providing a fairly good introduction to these two subjects. It also describes in some detail the discovery of the expansion of the Universe and the further discovery of its acceleration. This chapter is not only useful on its own but is also included because many people confuse antimatter with the *invisible* components of the Universe (dubbed “dark” for historical reasons).

Chapter 4 reviews the major landmarks on the discovery of antimatter particles, from elementary particles all the way until antiatoms. In particular, the discovery of the first one, the positron, that changed physics forever, is described in very much detail. These findings took place first in cosmic rays and subsequently in particle accelerators, where they were artificially produced. The last section discusses primordial versus secondary antimatter, which is a crucial distinction since the former could have given rise to antimatter structures in the Universe, such as antistars, if it were to exist. Chapters 5 and 6 provide quite complete introductions to the subjects of cosmic rays and particle accelerators, which are the main sources of antimatter accessible to us, apart from some natural radioactive substances.

Chapter 7 deals with the by now famous problem of the matter-antimatter asymmetry in the Universe: *Why is there so much matter compared to antimatter in the Universe?* which is one of the most surprising enigmas in Astrophysics, Particle Physics and Cosmology. We discuss its main aspects in Astrophysics as well as in the Standard Model of Particle Physics, where use is made of the so-called Sakharov conditions as the guiding principle to shed light on the problem of the primordial baryogenesis (the creation of protons and neutrons). The chapter includes a brief account of the possibility of baryogenesis via a special type of neutrinos—leptogenesis—and also discusses some research on primordial antimatter; in particular, the possibility that it had given rise to large structures like antistars and antigalaxies. Finally, it also addresses the enigma of the Italian physicist Ettore Majorana and his fermions.

Chapter 8 describes mainly the experiments performed at the CERN Antimatter Factory to create and analyze antihydrogen atoms with the purpose of comparing their properties with those of the ordinary hydrogen. Chapter 9 addresses the medical and technological applications of antimatter: its use in hospitals to perform the Positron Emission Tomography, known as PET scanner, as well as its utilization for a multitude of research issues in Materials Science and Technology. It also clarifies why it is not feasible to use matter-antimatter annihilation as energy supply to cover the daily needs in our homes and factories, despite the fact that it represents the most energetic process that exists (a thousand times more efficient than nuclear energy).

Appendix A introduces Atomic Spectroscopy, which is an essential tool for both, the study of stars and galaxies in the Universe and the study of atoms and antiatoms in the laboratories. Appendix B debunks a myth about the Russian physicist Dmitri Skobeltzyn and the discovery of the positron, which began in middle 1950s in Cambridge (UK) and spread especially among British scientists.

Finally, the Epilogue discusses some prospects for next years with respect to antimatter research, and also contains a short science-fiction tale in order to illustrate the deep similarities between matter and antimatter.

We welcome all readers to embark on this adventure, this journey to the world of antimatter. But before we begin, we shall introduce some terms and concepts that are repeated throughout the text. We explain first the meaning of the *speed limit c* and what *ions, plasmas* and *isotopes* are. Then we introduce the *Kelvin temperature scale* and describe the *powers of 10*. Finally, we present the *units of mass, energy, time and distance* that are used in Particle Physics, also known as High Energy Physics.

1.2 Some Basic Concepts

1.2.1 The Speed Limit c

The speed limit *c* is the maximum speed with which a body can move towards or away from another one; its value is 299,792 km/s. In addition, massless particles must travel at this speed through the vacuum, where they do not meet other particles to interact with. This amazing result is deduced from the Theory of Special Relativity, which Albert Einstein formulated in 1905, and implies that it is not possible to accelerate subatomic particles, no matter how much energy is provided, to get them to surpass this maximum speed *c*. A word of caution should be added, however. Due to the expansion of the Universe, very distant galaxies are typically moving away from our Milky Way and from each other at velocities greater than *c*, dubbed superluminal velocities. The reason is that space itself grows very fast carrying the galaxies along, and this does not conflict with Special Relativity.

For historical reasons, *c* is known as the speed of light since it coincides with the speed of electromagnetic waves when they propagate through the vacuum. The reason for this is that electromagnetic waves can be interpreted in terms of massless particles—photons—traveling through space. By contrast, when photons, or equivalently electromagnetic waves, propagate through material media, their speed can be much lower, and even zero inside the opaque media that absorb them; this depends on the characteristics of the material and also on the frequency of the waves. For example, ordinary walls are opaque for the electromagnetic frequencies of visible light, but not for the frequencies corresponding to radio, TV, cell phones, etc. which is why these waves pass through the walls without much difficulty.

1.2.2 Ions and Plasmas

Atoms are composed of a central nucleus, consisting of protons and neutrons, and an outer shell formed by electrons, in equal numbers as protons. In normal conditions atoms are electrically neutral; that is, they have no electric charge because the positive charges of the protons (+1 per proton) are compensated by the negative charges of the electrons (-1 per electron). However, for different reasons atoms can gain or lose electrons. For example, a very energetic particle coming from outside Earth can collide with an atom's electron and pull it out of its orbit around the nucleus, which happens very often in our atmosphere. In these circumstances, the atoms cease to be electrically neutral and are called ionized atoms, or ions. If the ion has excess electrons, it is a negative ion, and otherwise it is a positive ion.

But it can also happen, due to high temperatures or strong electromagnetic fields, that stripping away electrons orbiting the atomic nuclei does not bring them very far apart. Then the ions and the unbound electrons behave like an electrically neutral gas called plasma with (almost) balanced positive and negative electric charges. Plasma is one of the four fundamental states of matter, the other three being solid, liquid and gas, and represents probably the most abundant form of ordinary matter in the Universe. Examples of partially ionized plasmas are lightning and neon adverts, whereas the interior of stars and their coronas consist essentially of fully ionized plasmas.

1.2.3 Isotopes

The atoms of each element in the Periodic Table are characterized by having a fixed number of protons in the nucleus. This is the so-called atomic number, on which the classification of the elements is based. However, the number of neutrons of a given element is variable and characterizes the different isotopes of it. For example, hydrogen is the simplest and lightest element, since it has a single proton in the nucleus, but it can have zero, one or two neutrons when it forms in nature. Therefore, there exist three natural isotopes of hydrogen, although only two are stable, and there are some other isotopes that have been synthesized in laboratories. The most abundant, the ordinary hydrogen ^1H, has no neutron in the nucleus; the second isotope, deuterium—denoted as ^2H or D—has one neutron; and the third isotope, tritium ^3H, has two neutrons, is radioactive and has a half-life of 12.3 years (the time it takes for half of any quantity to decay). The left superscript on the element′s symbol indicates the atomic mass number of the isotope, which is the number of protons plus the number of neutrons. The next element, helium, has two protons in the nucleus. It has several isotopes, but only two of them are stable: ^3He and ^4He, which is the ordinary helium, much more abundant than the first.

1.2.4 Kelvin Temperature Scale

The Kelvin temperature scale, used mainly by scientists, was proposed in 1848 by the British physicist William Thomson, best known as Lord Kelvin. It is an absolute temperature scale since it has an absolute zero below which temperatures do not exist. The reason is that temperature is a measure of energy, and zero Kelvin, 0 K, is the temperature at which atoms and molecules are at their lowest possible energy, the so-called zero-point energy. This lowest energy is non-zero, however, because of quantum fluctuations. The steps in the Kelvin scale - the Kelvin degrees (K) – are of the same size as those of the Celsius scale - the Celsius degrees (°C)–and the correspondence between the two scales is: 0 °C = 273.15 K and 0 K = −273.15 °C, where 0 °C is defined as the freezing temperature of water (and 100 °C as its boiling temperature) at sea-level atmospheric pressure. Although the Celsius scale is used in most of the world, in the USA one uses the Fahrenheit scale, with 180 degrees (denoted °F) between the freezing point of the water (32 °F) and the boiling point (212 °F). In this scale, the absolute zero of temperature corresponds to: 0 K = −459.67 °F.

1.2.5 Powers of 10

The powers of 10, which we write as 10^N, have a very simple meaning. If the power N is a positive number, it indicates the number of zeros to be added after the 1. For example, one thousand is expressed as $10^3 = 1000$; one million as 10^6; one billion as 10^9 and one trillion as 10^{12}. Conversely, if the power is negative, we can write 10^{-N} with N positive, and then the N zeroes go before the 1, which occupies the N-th decimal position. Thus, one thousandth is expressed as $10^{-3} = 0.001$; one millionth (also called micro) as 10^{-6}; one billionth as 10^{-9} and one trillionth as 10^{-12}.

1.2.6 Units of Mass and Energy

The units of mass and energy used in Particle Physics are the same as they are related through the Einstein's mass-energy conversion formula $E = mc^2$. These units are based on the electronvolt, eV, which is the energy that an electron acquires when it is exposed to an electric potential of one volt. The multiples of the eV most commonly used are:

$$1 \text{ keV} = 10^3 \text{ eV}, \;\; 1 \text{ MeV} = 10^6 \text{ eV}, \;\; 1 \text{ GeV} = 10^9 \text{ eV},$$

where k stands for kilo, M for Mega, and G for Giga. The electron mass is 511 keV/c^2, that is 0.511 MeV/c^2. This means that the mass of one electron can be transformed into photons with a total energy of 511 keV in suitable processes, such as annihilation with one antielectron. The proton mass is 938 MeV/c^2, hence 1836 times bigger than the electron mass. In kilograms, 1 MeV/c^2 is equivalent to 1.78×10^{-30} kg.

1.2.7 Times and Distances

Unlike the energies, in Particle Physics distances and times are very small in the processes and reactions among the particles. Thus, for distances and times one uses submultiples of the meter and the second, respectively, mainly:

the microsecond, $1\,\mu\text{s} = 10^{-6}$ s	the micrometer, $1\,\mu\text{m} = 10^{-6}$ m
the nanosecond, $1\,\text{ns} = 10^{-9}$ s	the nanometer, $1\,\text{nm} = 10^{-9}$ m
the picosecond, $1\,\text{ps} = 10^{-12}$ s	the picometer, $1\,\text{pm} = 10^{-12}$ m
the femtosecond, $1\,\text{fs} = 10^{-15}$ s	the femtometer, $1\,\text{fm} = 10^{-15}$ m

2

Antimatter Versus Matter

Antimatter can be considered as the reverse of matter. In a broad sense, it is analogous to its mirror image. As we all know from our own experience, when we look at ourselves in a mirror, the face we see is not exactly ours but has the right and left sides interchanged. Similarly, antimatter particles have opposite properties with respect to matter particles. This refers to all properties that admit opposite values, such as electric charge; but there also exist properties that do not admit opposite values, like the mass, and these are identical for the particles and their antiparticles. For example, as we will see later, quarks and their antiquarks have the same mass, the same spin and the same mean lifetime, but opposite values of the strong charge, the electric charge, the weak charge and the baryon number. Analogously, the electron and its antiparticle, the positron, have the same mass, the same spin and the same mean lifetime, but opposite values of the electric charge, the weak charge and the lepton number. Curiously, the positron is the only antiparticle bearing its own name; the other antiparticles are named like the ordinary particles but with the prefix *anti*. Indeed, all elementary particles have antiparticle partners, although a few of them are actually their own antiparticles, as in the case of the photon—the particle of light—and the Higgs boson.

In this chapter we will explain in some detail what matter particles and antimatter particles are, which are their properties and which forces and interactions they experience. We will also present the Standard Model of Particle Physics, and discuss briefly some proposals "Beyond the Standard Model" to address some problems that remain to be solved. To start, we will have a first encounter with atoms and antiatoms, as well as with the very remarkable issue of the matter–antimatter annihilation.

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2.1 Atoms and Antiatoms

As the Greek philosopher Leucippus (5th Cent. B.C.)[1] and his pupil Democritus (460 B.C.–370 B.C.) already anticipated, the entire material world in which we are immersed, and which forms our bodies, is made up of atoms. These bind together to form molecules, crystals, and other structures that build all the solids, liquids and gases that we perceive. However, unlike the atomic model of Leucippus and Democritus, in which these corpuscles were elementary, immutable, and indivisible, real atoms have a structure. They consist of a nucleus and a shell, and can be broken down and divided into their constituent subatomic particles: the nucleons—*protons* and *neutrons*—in the atomic nuclei and the *electrons* in the shells, orbiting the nuclei due to the electrical attraction between their negative charges and the positive charges of the protons.

Moreover, it turns out that protons and neutrons are not elementary either, but are composed of particles that are believed to be elementary: the *quarks*. These are bound together through the strong interactions, as we will discuss later. There are six types of quarks although only two of them are constituents of protons and neutrons. The latter are called quarks u and d, from up and down. The proton p is composed of two quarks u and one quark d, while the neutron n is constituted by one quark u and two quarks d:

$$p = (u, u, d), \quad n = (u, d, d). \tag{2.1}$$

The electron e^- also seems to be elementary. This actually means that Particle Physics experiments are not able to detect any structure, at present, neither in the quarks nor in the electrons. But if such structures existed and were detected in future experiments, these particles would no longer be considered elementary.

The antimatter atoms, on the other hand, are formed with the antiparticles of the particles that make up matter; i.e. with *antiprotons*, *antineutrons* and *positrons*. The electric charge of the atomic antinuclei is negative because the antiprotons have the opposite electric charge to that of protons; and orbiting the antinuclei one finds the positrons e^+ with a positive electric charge opposite to that of electrons. The antiprotons $\overline{p}$ and antineutrons $\overline{n}$ are composed of the antiquarks $\overline{u}$ and $\overline{d}$, in a similar way as the composition of protons and neutrons:

$$\overline{p} = (\overline{u}, \overline{u}, \overline{d}), \quad \overline{n} = \left(\overline{u}, \overline{d}, \overline{d}\right), \tag{2.2}$$

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[1] The dates of Leucippus's birth and death are not recorded. Aristotle and Theophrastos explicitly credited him as the originator of atomism.

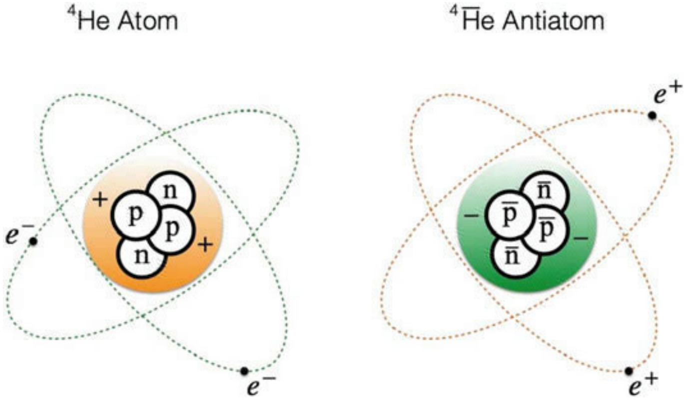

Fig. 2.1 Sketch of a Helium-4 atom and an Antihelium-4 antiatom. The nucleus of the atom, composed by two protons and two neutrons, has positive electric charge while the nucleus of the antiatom, composed by two antiprotons and two antineutrons, is negatively charged. These nuclei are named alpha particles and antialpha particles, respectively

where the bar over the symbol of the particles indicates that they are antiparticles.

In Fig. 2.1 we see a sketch of the helium atom ^{4}He, its most abundant isotope, and of its antimatter counterpart, the antihelium atom $^4\overline{\text{He}}$. They are not to scale since the distance between the atomic shells and the nuclei is actually about 100,000 times the size of the latter. The nucleus of the ^{4}He atom, composed by two protons and two neutrons, results to be a very stable—hard to break—configuration. It is called *alpha* particle, denoted as α, because the rays with the same name, discovered at the end of the nineteenth century in natural radioactivity, consist precisely of these particles when they are emitted by very massive unstable nuclei. Similarly, the nucleus of the $^4\overline{\text{He}}$ antiatom, formed by two antiprotons and two antineutrons, which is just as stable, is called *antialfa* particle and is denoted as $\overline{\alpha}$. Now, unlike α particles, which are very abundant in the Universe since its very beginning, $\overline{\alpha}$ antiparticles have never been detected in nature so far, although their discovery in the cosmic rays could be approaching, as will be discussed in Chaps. 5 and 7.

2.2 Matter-Antimatter Annihilation

Perhaps the most distinctive feature of antimatter is that when it comes into contact with matter they annihilate each other producing a large amount of radiation. Indeed, if a sufficient amount of antimatter could be stored, even

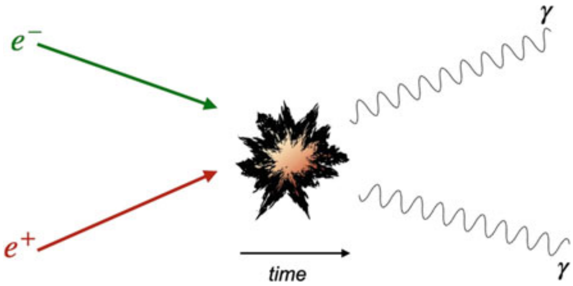

Fig. 2.2 Electron–positron annihilation producing two photons. The masses of the electron e^- and positron e^+ (511 keV/c^2) are totally transformed into the energies of the photons γ (511 keV), according to the mass-energy equivalence $E = m\,c^2$. This process can also occur in the opposite direction, and then it is called $e^+ e^-$ pair production

quite small compared to the amount of fuel present in nuclear weapons, a bomb could be built with an energy about a thousand times higher than that provided by the nuclear fusion of an equivalent mass. Suffice it to say that a single gram of antimatter would produce, upon contact with matter, a deflagration equivalent to more than twice the atomic bomb that struck Hiroshima in 1945. Fortunately, this enterprise is not easy, as we will see in Chap. 9.

When matter is annihilated with antimatter, each individual matter particle is annihilated with its corresponding antimatter particle—its antiparticle—resulting mainly in photons, denoted as γ, which are the smallest packages or quanta that constitute the electromagnetic radiation. Therefore, when an atom makes contact with an antiatom, each electron e^- is annihilated with a positron e^+, each quark u is annihilated with an antiquark $\overline{u}$ and each quark d is annihilated with an antiquark $\overline{d}$. As a result, the quarks of protons and neutrons are annihilated against the antiquarks of both antiprotons and antineutrons.[2]

In Fig. 2.2 one can see an illustration of an electron–positron annihilation resulting in two photons. As the photons γ are massless, the masses of the electron e^- and the positron e^+ (511 keV/c^2 each) disappear altogether, being transformed into the energies of the photons (511 keV each), as follows from Einstein's formula of mass-energy conversion: $E = m\,c^2$, where c is the speed limit. This is a fairly good description when the encounters between

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[2] Although the simplest annihilations of protons with antiprotons and neutrons with antineutrons giving just photons do exist, they are not the most likely annihilation processes because nucleons are very complicated systems. The dominant processes for nucleon-antinucleon interactions - $\overline{p}\,p$, $\overline{p}\,n$, $\overline{n}\,p$ and $\overline{n}\,n$ - occur through pion production, as will be explained in Sect. 2.4.3.

matter and antimatter particles take place at small speeds, that is at low energies. But reality becomes more complex when the particles collide at high energies moving near the speed limit[3] c. This is so because the energy of the collision is invested in creating also massive particles, in addition to photons, making use of the mass-energy conversion, as is usually the case in collisions where new particles are produced which are different from the original ones.

2.3 Other Elementary Particles

So far we have mentioned only the elementary particles that compose the atoms: the quarks u and d in the nuclei and the electrons e^- in the atomic shells. However, there exist many other elementary particles that are considered matter although they are not part of the composition of atoms. This circumstance created some sort of philosophical turmoil when Carl Anderson discovered in 1936 the first of these particles, the *muon* μ^-, in the cosmic rays, a particle 207 times more massive than the electron but otherwise identical to it. The problem is that no meaning was seen in its very existence, to the extent that the phrase *Who ordered the muon?* became very popular among physicists.

Apart from the muon μ^-, the other particles to which we refer are: the *tau* particle or *tauon* τ^-, which also has identical properties as electrons and muons but with a larger mass; three types of *neutrinos*: ν_e, ν_μ and ν_τ, mysterious particles in more than one sense, without electric charge and with hardly any mass; and the quarks of type c (*charm*), s (*strange*), t (*top*) and b (*bottom*). Moreover, one has to add to this list the antiparticles of all these particles. For example, the leptons μ^+ and τ^+, also called *positive muon* and *positive tauon*, are the antiparticles of the leptons μ^- and τ^-, where the term *lepton* denotes the matter particles without strong charge (only quarks have it).

Nevertheless, it turns out that, with the exception of neutrinos, these other particles of matter and antimatter decay rapidly. Indeed, the most long-lived ones, the muons, only exist for 2.2×10^{-6} s, so just a few millionths of a second. They do this spontaneously with the assistance of the weak interactions, which is why these particles are said to be unstable. Their fleeting existence arises when they are created by particles colliding with each other.

There are also elementary particles that are not considered matter or antimatter and are responsible for the interactions, i.e. the forces, between the particles. These interactions come in four types: *electromagnetic*, *strong*, *weak*

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[3] See the tutorial in the Introduction for more details about the maximum speed c, customarily called "the speed of light".

and *gravitational*. In Sect. 2.5.4 we will explain in detail the properties of these force-carrying particles, but we already anticipate that electromagnetic interactions consist of an exchange of photons between particles that have electric charge; strong interactions are due to the exchange of *gluons* between particles that have strong charge (also called *color*); and weak interactions, which are responsible for most particle decays, result from the exchange of the *bosons* W^+, W^- and Z^0, which are highly unstable themselves. Curiously, the bosons W^+ and W^- are antiparticles of one another whereas the photons and the bosons Z^0 are antiparticles of themselves. As for gravitation, in Particle Physics it is supposed to be mediated by the exchange of the hypothetical *gravitons*, but the experimental verification of their existence is totally out of reach. Finally, we have the Higgs boson H, which is its own antiparticle and is the mediator of an extremely weak force of extremely short range, which is why it is not counted among the forces.

2.4 Properties of Elementary Particles

We have seen that the only difference between matter and antimatter atoms resides in the elementary particles that compose them, which are known as antiparticles in the case of antimatter. The main properties of elementary particles are spin, helicity, mass, electric charge, strong charge, weak charge, baryon number and lepton number. Two of these properties, the spin and the mass, do not admit opposite values and hence are identical for each particle and its antiparticle, but the other properties can take opposite values and are the ones that differentiate particles from their antiparticles, as we pointed out at the beginning of this chapter. In the following paragraphs we will review these properties, except for the baryon and lepton numbers, which are also called baryonic and leptonic charges,[4] and will be introduced in Chap. 7.

2.4.1 Spin and Helicity

Spin is a quantum property similar to an intrinsic angular momentum corresponding to an internal rotation. As it is usual with quantum properties, we lack intuition for the spin, i.e. it is not a rotation like those we observe in our daily life described by Classical Physics. It can take integer values (in appropriate units), such as 0,1,2, in which case the particles are called *bosons*; or

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[4] The terms baryonic and leptonic "charges" were, and still are, widely used by particle physicists and cosmologists from the previous Soviet Union.

it can take half-integer values, such as 1/2 or 3/2, in which case the particles are called *fermions*. Examples of the latter are all matter and antimatter elementary particles, with spin ½, whereas all the elementary particles which mediate the interactions are spin 1 bosons.

The *helicity* is the sense of the spin with respect to the direction of motion of the particle, so it can be right-handed (clockwise) or left-handed (anticlockwise), taking opposite directions for particles and antiparticles. This property may seem irrelevant to the readers, who may wonder: *what difference it makes if a particle is rotating in one direction or the other?* However, as we will see later, this property is crucial since weak interactions manifest themselves differently depending on the helicity of the particles.

The bosonic or fermionic character of elementary particles is a crucial aspect that has many implications and determines their collective behavior. It also determines the collective behavior of composite particles and atoms because individual spins are combined in such way that an odd number of fermions gives rise to a fermion and an even number to a boson. As a consequence, some atoms are bosons, like ^{4}He, whereas some others are fermions, like ^{3}He. Identical fermions, whether particles or atoms, never share their quantum state, a result known as the *Pauli Exclusion Principle*. As a result, if in a given physical system two seemingly identical fermions have the same energy then they should differ in at least one property. Identical bosons, on the contrary, have the tendency to cluster together and share their quantum state. For this reason, only bosons can form the so-called Bose–Einstein condensates (Fig. 2.3), with a large number of them in the same lowest energy state, or ground state. It should be noted, however, that these condensates are

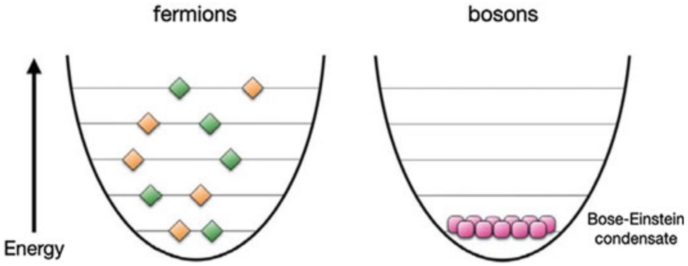

Fig. 2.3 Bosons and fermions have completely different collective behavior. Identical bosons cluster together sharing their quantum state, which is why they can form Bose–Einstein condensates, with a large number of them occupying the state with lowest energy. Identical fermions, on the contrary, never share their quantum state. So, if two seemingly identical fermions have the same energy, then they should differ in at least one property, represented here by the two different colors

only possible provided the temperature is extremely low, near the absolute zero (0 K) to prevent thermal fluctuations to interfere with the process.

To appreciate the importance of the fermionic or bosonic character of the particles, let us note that the stability of atoms, and their own existence as we know them, depend entirely on the fermionic nature of the electrons, with spin ½, which prevents them from descending all simultaneously to the ground state. The reason is that in the Universe it rules, so to speak, the law of minimum effort or minimum energy. Accordingly, if the electrons were bosons, then all of them, distributed in layers and orbitals with increasing energy levels around the nuclei, would fall to the bottom layer, to the ground state orbital. There they would cluster together sharing the same quantum state, so that the other orbitals would disappear de facto and with them the present electronic structure of atoms. But it is this electronic structure what determines the practical totality of the physico-chemical properties of atoms, including the formation of molecules, crystals and other structures, as well as all chemical reactions. In essence, if the electrons were bosons, the material Universe would be very different from the one we know: far more boring, with hardly any diversity and, almost certainly, incapable of harboring life.

2.4.2 Electric Charge and Electromagnetic Interactions

The *electric charge* is carried by all particles that experience electromagnetic forces. These are all the matter particles and their antiparticles, with the exception of neutrinos, as well as the bosons W^+ and W^-. The electric charge can be positive or negative, although the assignment of which charges are called positive and which negative is pure convention, since the charge of the electron could have been called positive and the charge of the proton negative. The relevant fact is that electromagnetic forces, which consist of an exchange of photons, can be attractive or repulsive: electric charges with the same sign—like charges—repel each other, while electric charges with opposite signs attract one another. Consequently, by having opposite electric charges, particles and their antiparticles profess a fatal attraction that often costs them their very existence.

To help intuition it is very useful to use the concept of field, introduced by Michael Faraday in the mid-nineteenth century, according to which electric charges create an electrostatic field around them. The properties of this field can be deduced from Coulomb's Law (1785) that describes the electrostatic force between two charges. This field develops a magnetic component, surprisingly, if the charges are moving with respect to the measuring device;

that is, with respect to the observer.[5] Particles without electric charge—neutral particles—not only do not create their own electromagnetic fields but, in addition, they are not sensitive to the electromagnetic fields in which they are immersed. And conversely, neutral particles are invisible to the electric and magnetic fields around them because these fields cannot detect them.

2.4.3 Strong Charge and Strong Interactions

The *strong charge* or *color* is a property of quarks, antiquarks, and gluons, exclusively, as these are the only particles sensitive to the strong forces. These are also known as "strong nuclear forces" because their range of action is very short and are confined within the atomic nuclei. This charge gives rise to purely attractive forces consisting of an exchange of eight types of gluons (the name gluon comes from glue due to their ability to strongly tie the quarks together). Unlike the electric charge, the strong charge comes in three different kinds, which are called colors in analogy with the three primary[6] colors: red, green and blue. Antiquarks have anticolors, which are antired, antigreen and antiblue. Interestingly, also gluons, which are the mediators of these interactions, are equipped with strong charge. This consists of a color-anticolor pair, for example blue-antigreen.

The main function performed by the strong forces is to bind quarks (and antiquarks) together, forming composite particles called *hadrons* ("dense" in Greek). Protons and neutrons are the most relevant hadrons and also receive the additional name of *baryons,* meaning that they are formed by three quarks. Interestingly, it was found that each of these three quarks has to come in a different color for the total to be neutral, what provides an analogy with the fact that the three primary colors combined together result in white. There are also hadrons formed, curiously, by one quark and one antiquark, with opposite colors so that the total strong charge is again neutral. They are named *mesons* and their mean lifetime is very short (2.6×10^{-8} s the longest). There is a whole variety of these mesons and they are classified into groups, or systems, whose members can be electrically charged or neutral. The most relevant mesons for Particle Physics are: *pions* π, which are composed of a quark and an antiquark of the same species that form protons and antiprotons, *kaons* K, and the B and B_S mesons. Quarks can also come in groups of four,

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[5] In Physics, observers denote detectors in general, whether they are instruments, human beings, animals or even just atoms.

[6] In Physics, the three primary colors are red, green and blue. In Fine Arts, the green is replaced by yellow as primary color. Anyway, the three "colors" of the strong interactions are just labels that bear no relation with the colors of the electromagnetic spectrum that we observe.