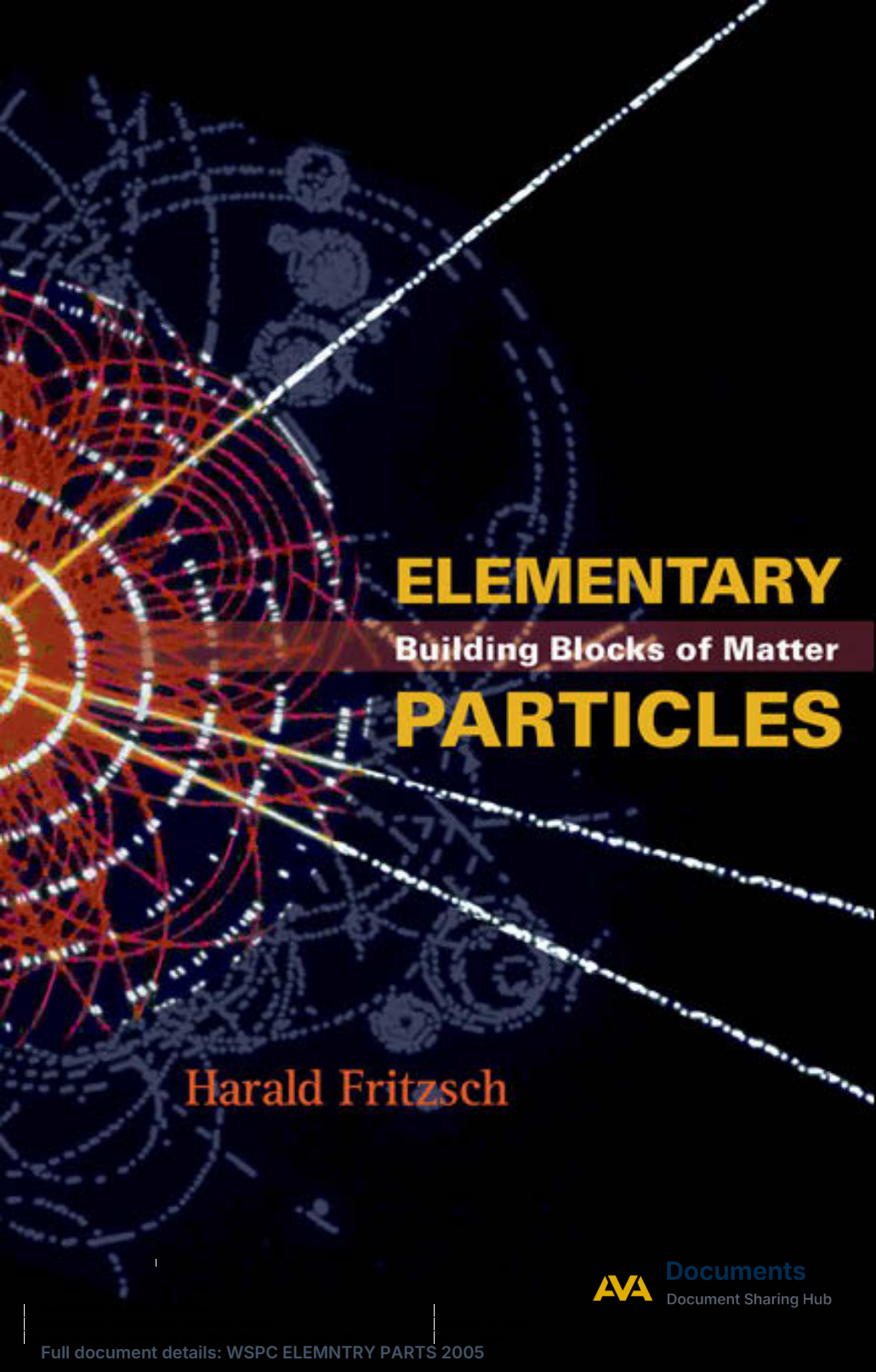


The background of the cover is a dark blue field filled with intricate, glowing particle tracks. These tracks are composed of numerous small dots and lines, forming complex, swirling patterns that resemble particle collision events or the structure of matter at a subatomic level. The tracks are primarily in shades of red, orange, and yellow, with some white and light blue lines interspersed. The overall effect is one of dynamic energy and scientific exploration.

ELEMENTARY

Building Blocks of Matter

PARTICLES

Harald Fritzsch

An abstract, grayscale visualization of a particle detector, likely a bubble chamber or cloud chamber, showing complex, overlapping circular and spiral patterns that resemble particle tracks or detector components.

ELEMENTARY PARTICLES

Building Blocks of Matter

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ELEMENTARY PARTICLES

Building Blocks of Matter

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Translated by

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Full document details: WSPC ELEMNTY PARTS 2005

Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

Library of Congress Cataloging-in-Publication Data

Fritzsche, Harald, 1943–

[Elementarteilchen. English]

Elementary particles : building blocks of matter / Harald Fritzsche.

p. cm.

ISBN 981-256-141-2 (alk. paper)

1. Particles (Nuclear physics)--Popular works. 2. Quantum chromodynamics--Popular works. 3. Quantum electrodynamics--Popular works. I. Title.

QC793.26 .F7513 2005

539.7'2--dc22

2005044181

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

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Chapter 1

Introduction

Philosophers in Antiquity were already tackling the question: what does matter surrounding us ultimately consists of? Will we hit a boundary when we take a piece of material, say, a piece of wood or a diamond, and break it down into smaller pieces? If so, what defines that boundary? Are there minuscule objects that can no longer be split up? Or is that boundary simply that a further division, for whatever reason, does not make sense any longer?

Let me give an analogy, starting from the question: what are the original elements of, say, the German library in the city of Leipzig or, for that matter, of any large library? To find out, we step into that library and find thousands of books. We open a book and discover the building blocks of that book – often more than a hundred thousand words. We recall that there are dictionaries that contain information about all of those words – tens of thousands of them. And each of these words is made up of letters. Our alphabet contains twenty-six different letters. All of the words in the books are made up of these twenty-six letters.

These days, books are often written on the computer. The word processor in the computer writes these letters in terms of sequences of the symbols zero and one – they are digitally produced just like the Morse code which allows the letters to be shown as a series of

points and lines:

a : -, b : -..., c : --., etc.

All words can be reduced to the level of sequences of “bits” – of the elementary building blocks of information, of 0’s and 1’s. That is where our search for basic elements ends. It makes no sense to try and dissect the symbols 0 and 1 onto an even smaller level. We have come to the end of the process of dissection. The basic elements of a library have thereby been found — 0 and 1. These are also the basic elements of information — we might say, these are the atoms of the science of informatics.

Now let’s replace the library by our material universe, the books by what the universe is made up of — objects living or dead that we see around us: trees, rocks, stars, planets, desks, diamonds, ants, dogs. . . .

Every attentive observer of natural phenomena is impressed of the enormous variety of phenomena and of material objects that are observed. Obviously, there is no random set of observed phenomena. Many of these phenomena are repetitive. A speck of salt here looks just like another one thirty miles away, they are as indistinguishable as two eggs. The leaves of a maple tree in Berlin or in Washington D.C. are indistinguishable. On one hand, there is an incalculable variety of phenomena and occurrences; on the other hand, there are also elements that we encounter again and again. This duality of great variety and of constancy prompted the Greek philosophers, thousands of years ago, to set up the hypothesis that the universe consists of elementary building blocks that can no longer be split up the “atoms” (derived from the Greek word “atomos” which means indivisible). Leukippos of Miletus and his student Democritus of Abdera in the 5th century B.C. came up with this hypothesis. Only few such atoms should be enough to produce this enormous variety of things in ever new combinations of atoms. “There is nothing” Democritus said, “except atoms and empty space”.

Another viewpoint was presented by Anaxagoras — who was born about 500 B.C. He assumed that there are infinitely many basic materials that, appropriately mixed, can make up the great variety of

materials that exist in the world. These materials were assumed to be indestructible and their variety was thought to be due to their motion during the mixing process. Empedocles, some ten years younger than Anaxagoras, felt the materials of our world are basically made up of these four elements: earth, water, air, and fire.

It is interesting that only in the framework of the notion of atoms, the concept of empty space became important. Up to that time it was believed that space was filled with matter, constructed by matter, and there was no thought of empty space. Only in the framework of atomic theory was there an important function for empty space: it became the framework of geometry; the atoms moved around in it.

Atoms move in space but have only geometric qualities. Democritus said: "Just as tragedy and comedy can be written down with the same letters, different phenomena can be realized in our world by the same atoms, provided they assume different positions and different movements. Some given matter may have the appearance of a given color; may appear to us as tasting sweet or bitter – but in reality there are only atoms and empty space".

Later on, Greek philosophy took on the elements of the theory of atoms and developed it. Plato discussed in his dialogue "Timaios" possible connections between the atoms and Pythagoras' model of harmonic numbers. He identified the atoms of the elements: earth, water, air and fire with the regular geometric patterns of dice, octahedrons, icosahedrons and tetrahedrons. As the atoms move, that motion has to be ascribed to the laws of nature: they are not moved by forces like love and hatred, but rather as a manifestation of the laws of nature.

What began about two and one-half thousand years ago in what was then Greece on the Western coast of Turkey, was nothing less than the start of a revolution that is still in progress. For many thousands of years before, people believed that whatever happens in our world is primarily due to supernatural origins. Magic and superstition ruled the world. This changed about two thousand years ago on the Ionic Coast. The time and the location of that emerging turning point were not coincidental. The city states on the Ionic Coast had developed democratic values. New ideas were accepted and

were easily spread, not least due to the transition from hieroglyphic writing to scripture based on an alphabet. Religion did not play a dominant role. This permitted the establishment of the idea that our world is recognizable, that the natural processes we observe can be analyzed and understood rationally. The notion of atoms was basic to this development. The red thread that can be followed from the Ionic Coast of Turkey through two-and-one-half millennia of our history to the point where it ends in our present scientifically and technically developed world; and that means, it defines man's knowledge of the building blocks of matter.

Many details of what was taught about atoms in antiquity were revealed to us by happenstance, as it turns out, in the year 1417 when a manuscript of the Roman poet and philosopher Lucretius was found. In well-measured hexameters, this work, called "De rerum natura" (about the nature of matter), Lucretius' described not only ideas originally developed by Leukippos and Democritus; but also developed them further. In the work by Lucretius, ancient atomism reached its highest point. His book was one of the first published after the invention of printing and was circulated throughout the Europe; ever since, it has influenced developing notions of Nature.

With astonishing clarity, Lucretius anticipated the basic elements of modern particle physics. In his manuscript: "De rerum natura" which we might well translate into "The world of atoms", he writes:

"There is no doubt an ultimate end to the body that our senses cannot see; it is not further divisible, minuscule in size, and has never existed all by itself, nor will it be able to do so in the future. It is, after all, part of this body, and resembles it. Since it cannot exist alone, it is rooted in the larger structure, and no power can pull it away. That means there are basic structure elements of the tightest simplicity; they are stuck, tiny as they are, tightly together with their likes – and form a large multiple space together. Not that they form a multiple whole; rather, the forces that hold them together are enriched by their eternal simplicity; nothing can pull them apart, nor can their basic nature be simplified and still hold on to their seed." (De rerum natura, book one).

It is interesting to follow Lucretius' argument for the indivisibility of atoms: *"If there is no such thing as a smallest unit, that would mean that even the tiniest body, or structure, consists of many limitless parts: halving half of it will become part of an unstoppable chain. Where then is the difference between the universe and the tiniest constituent? There is no difference. After all, even if the summation process goes on and on endlessly, the smallest part remains divisible interminably"* (*De rerum natura*, book one).

Lucretius' writings give us the best and the most detailed account of the atomic teaching in antiquity, which, however, was not able to resist the idealistic teaching of Plato and Aristotle. He brings in the interminable questions of an attempt to understand nature, trying to clear up unending questions about nature; moving away from its mythology without losing a deep respect towards its unshakable laws. Had Lucretius' notion of how to understand nature been accepted two thousand years ago, the course of world history would have looked quite different from what actually happened; certainly it would have avoided religious excesses, and religious wars in Europe and Asia. Unfortunately, reality was different. After the collapse of the Roman Empire, the Western world suffered more than a millennium of intellectual frustration while religious fanaticism and superstition dominated. It was not before the time of the Italian Renaissance that, in large parts of Europe, the intellectual clarity of the Greek way of thought reemerged from its thousand-year atrophy. At that time, scientific thinking made its breakthrough; Copernicus, Johannes Kepler, and Galileo Galilei carried it forward heroically.

In the 17th century, the concepts of philosophers in Antiquity were linked to those of the natural sciences of that time. Scientists of that period noticed that chemical elements such as hydrogen, oxygen, or copper are made up of identical atoms for each species. Isaac Newton (1643–1727), who first wrote down the laws of mechanics and thus became the founding father of theoretical physics, noticed and taught that the stability of materials, such as the cohesiveness of a metal, is based on forces acting between individual atoms.

In the second half of the 19th century, this concept of the atomic basis of material led to important progress in chemistry. The



chemists noticed that chemical reactions are not easily understood if we assume that materials in these processes consist of minuscule and not-further-divisible particles: the atoms. A chemical element like hydrogen then consists simply of nothing but one and the same species of atoms. It was possible to determine the size of the atoms by chemical methods; and that turned out to be 10^{-8} cm.

One billion hydrogen atoms might be lined up so as to form a chain 10-cm long. Today, we know one-hundred-and-ten different elements, and that means we know one-hundred-and-ten different kinds of atoms. The Greek philosophers would not be able to subscribe to this idea — they never thought of the possibility that there might be more than one-hundred different kinds of atoms. In the early 20th century, the realization that atoms are not elementary in the sense conceived by the ancient Greek atomists was not due to the chemists; it was the physicists who realized that atoms are not really elementary particles, but rather that they are made up of smaller constituents: of electrons that orbit around atomic nuclei, where the nuclei contain most of the mass of the atoms.

The great breakthrough of atomic physics came in the 1920s and 1930s: the new insight provided by quantum mechanics made it possible for physicists to understand, for the first time, the structure of atomic matter that is governed, both qualitatively and quantitatively, by a few basic principles. Most of the problems that physicists and chemists of the previous centuries had not been able to explain, were now open to elegant explanations.

Next, the physicists applied those very principles to atomic nuclei; they hoped to be able to find a deep understanding for nuclear phenomena as rapidly by following similar lines of thought. That hope turned out to be unrealistic. True enough, it was soon found that atomic nuclei are by no means elementary, but that they consist of smaller particles which we call protons and neutrons. This finding alone did not permit to draw conclusions about the detailed properties of atomic nuclei.

Things got worse: experiments that tried to find the inner structure of atomic nuclei by breaking them up, showed that new particles now emerged — the existence of particles had not been imagined

before. A whole range of new-fangled particles was found in a confusing variety, leading some physicists to despair of this confusing array; it made them compare sub-nuclear physics with botany. In the late 1940s, experiments produced many particles which are not actual building blocks of matter; rather, they are needed to hold the building blocks together and to see to the joint operation of the forces of nature.

The breakthrough came in the decades from 1960 to 1980; that is when it became possible to establish some order in the chaos of sub-nuclear phenomena. In the distant future, the 20th century will be remembered as the time in which most of the questions concerning sub-structure of matter were solved. We now know that stable matter consists of quarks – the elementary building blocks of atomic nuclei and of electrons. In the 1970s, all this was incorporated in a clear concept of the microstructure of matter. It was given the somewhat prosaic name the “Standard Model of Particle Physics”. This model is the subject of what we want to discuss in the following.

The Standard Model, it turns out, is much more than a theoretical model of elementary particles and their interactions. It lays claim to being a complete theory of all the phenomena that are observed in the realm of elementary particles. Today’s experts are able to define it in just a few lines of basic concepts; which constitute a kind of “world formula”. Such eminent theoretical physicists such as Albert Einstein and Werner Heisenberg had looked for it, but did not find it. Should we find that this theory – the Standard Model – is representative of the ultimate truth, then we will know that recent progress in physics has been able to define electrons and quarks as truly elementary constituents of nature. It would mean that the atoms of Democritus and Lucretius were truly found. To this day, however, this question has not been answered. The Standard Model contains elements that look unsatisfactory to many physicists. We therefore assume that the model provides no more than a very useful approximation of the true, ultimate theory. Today’s experimental physicists are very busy looking for new phenomena, phenomena that we call “beyond the Standard Model”.

The electrons and the quarks are not simply the building blocks

of matter which could be combined in any way we want. They are subject to forces, such as those of electromagnetism; and these forces in turn are mediated by minuscule particles. That is why, in particle physics, we should not speak of fundamental forces that act between the particles; we should speak of interactions. It turns out, as it were, that these interactions follow well-determined rules in the Standard Model, rules that are dictated by symmetry. A good part of this book will be discussion of these forces. A detailed understanding can be established only in mathematical terms.

The symmetries of nature are tightly connected with the interactions of elementary particles. In ancient times, Plato had already hinted at this connection. Werner Heisenberg, one of the founders of quantum mechanics and one of the most important physicists of the 20th century, put it this way: *“What is an elementary particle?” “Plato did not simply accept elementary particles as a given basis of matter, unchangeable and indivisible. There needs to be an explanation — the question after the existence of elementary particles winds up as a mathematical problem The ultimate basis of what we see is not just matter: it is the law of mathematics, its symmetry, its formulation”*.

Does that mean that, ultimately, ideas are more relevant than matter? Or, will the difference between matter and formalism vanish as we determine the ultimate boundaries of particle physics? To this day, this question has not been answered; we cannot even be certain whether the question is truly relevant. At the end of this book we will come back to this point.

Particle physics finds itself challenged by new questions at the beginning of this millennium, at the threshold of new discoveries. Physicists penetrated ever more deeply into the phenomena of basic matter in the 20th century; they opened up a world of new phenomena hitherto unknown, new horizons. The structure of microcosms became visible and turned out to be a complex world all by itself. Fortunately, it was possible to describe it in astonishingly simple mathematical terms. The questions to be answered became even more fundamental: whence does matter come our way? Whither does matter go in the distant future? Particle physics is and remains

a great adventure. Every time a new experiment is started, after years of complicated preparations by our experimental colleagues, we all head for a voyage into “terra incognita” (unknown territories).

The distance between the world of particle physicists and the general going-on of our society’s daily world is becoming dizzying. After all, why should we see it as our task to find new particles and new phenomena that appear irrelevant for our daily lives? The motivations are on the same level as those that make other scientists explore the universe, the ultimate depth of the ocean, any set of boundaries we have not penetrated yet. Similarly to every basic research activity, particle physics is part of our culture, setting itself the goal of understanding cosmic order. Basic research in physics is mostly concentrated on the particle front. Vast investments made by our society in the past have borne fruit in our understanding as our society became open and enlightened in most parts of the world. Particle physics mediated fascinating insights we gained into the structure of the microcosm. This very fact makes up part of the unquestionable conquests of humanity in the 20th century.

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Chapter 2

Electrons and Atomic Nuclei

The history of natural science probably never knew a time where important discoveries were as densely packed as in the last five years of the 19th century; all of these discoveries deal with phenomena that are part of today's particle physics. First, there was the 1895 discovery of a type of radiation which is now generally known, in English as X-rays, whereas the German-speaking world calls it Roentgen radiation after its discoverer Wilhelm Konrad Roentgen (1845–1923). In the following year, Henri Antoine Becquerel (1852–1908) hit on the phenomenon of natural radioactivity, which we will discuss later on. Let us just mention right here that this means the emission of particles by radioactive atoms, with energies a million times above those imparted to atoms in chemical reactions.

Physicists rather than their chemist colleagues noticed, at the beginning of the 20th century that atoms are not really elementary such as the ancient Greeks had believed, but rather that they, in turn, are built up out of smaller building blocks. This notion first appeared when the electron was discovered in 1897 — the first really elementary particle. A number of physicists were involved in this discovery: the Germans Emil Wiechert and Walter Kaufmann, and their British colleague Joseph John Thomson. Initially, the electrons were described as “electrical atoms” in January 1897, by Emil Wiechert in a presentation at Koenigsberg University in East Prussia. The birth date of the electron is frequently quoted in the English-speaking

world as April 30, 1897, when Thomson presented his experimental results with cathode rays at the Royal Institution in London.

Thomson was not the only scientist who, at that time, ran experiments on electrical discharge processes between two electrodes, an anode and a cathode, inside glass tubes that had been pumped empty of all air. Such discharges were frequently shown on public fairgrounds to the amazement of onlookers. Those lay people were just as astonished as the physicists at the many complex light phenomena in those tubes. Today's neon tubes are just one successful application. Once we diminish the gas pressure in the glass tube, those light phenomena inside the tube disappear. Then, on the glass surface opposite the cathode, which is connected to the negative voltage, we observe what we call fluorescence. This is a phenomenon due to radiation issued from the cathode, which was therefore originally called cathode rays; but it was not known what kind of radiation it was. It was noticed that it is useful for a number of informative experiments: it heats up materials it finds in its way; it blackens photographic plates. It also influences chemical reactions. And soon enough it was noticed that once those cathode rays hit materials in their path, they leave a negative electrical charge.

Thomson, Kaufmann, Wiechert, and many other physicists performed relevant experiments. Now knowing that these rays carry negative electric charges, Thomson speculated how he might identify them. He directed those rays through electric and magnetic fields and realized how those fields changed the path of his cathode rays. The degree to which their path was changed, he knew, depended on the electric charge and the mass of the “ray”. Thomson then noticed that he was observing a constant ratio of charges and masses, irrespective of the medium — air, hydrogen or carbon dioxide. He finally succeeded in measuring the energy, and thereby the mass of the particles: they were lighter by a factor of about 2000 than the hydrogen atoms (to be precise, by a factor of 1837). Thomson then declared he must have hit on a new state of matter — a state that must be part of the makeup of chemical elements. And it turned out that his hypothesis was correct: these particles which were later on called electrons are important ingredients of atoms. Their name is

due to the Greek word “elektron”, which described a silver-gold mix, or amber).

Walter Kaufmann in Berlin was another person to do experiments with cathode rays: he determined the ratio of the particles more precisely than Thomson. But, unfortunately, he was strongly influenced by the Vienna physicist and philosopher Ernst Mach. Mach refused to introduce hypothetical objects such as atoms or even smaller particles if they were not directly observable. That is why Kaufmann avoided talking about the discovery of new particles. Had he done so, we would have to recognize him, together with Thomson, as the discoverer of the electron. Let this example simply show that, in physics as in other natural sciences, it is not only important to discover a new phenomenon, but also to come to a correct interpretation. For the latter it is very important to advance the fitting theoretical framework.

So, what Thomson found was nothing less than the lightest electrically charged elementary particle. Electrons are stable; they have a negative charge and a mass of $9.1093897 \times 10^{-31}$ kg. Calling its charge “negative” is simply a convention. It was introduced by the American scientist and politician Benjamin Franklin in the 18th century. In retrospect, we might say, this was not the most fitting choice: after all, electric currents are due to electrons that propagate inside metal. So, it would have made sense to call the charge of the electron, the most important charge carrier, positive.

The charge and the mass of the electron are important constants of Nature — they are exactly the same everywhere in the universe. We usually denote the charge amount of the electron by the symbol, e , since all electrons carry precisely the same amount of charge, we say: the electric charge of the electron is quantized.

As far as the electron mass, and the masses of all other particles are concerned, it would make no sense to measure them in the unit kg or g, which makes no practical sense in microphysics. We tend to measure it in terms of energy units, specifically in electron Volts. Recall that Albert Einstein in the year 1906, discovered the equivalence of energy and mass, which he expressed in the famous relation $E = mc^2$; this suggests expressing the mass of all particles

in units of electron Volts. One electron Volt or, for short 1 eV, is the energy given to an electron as it is accelerated by an electric field measuring 1 Volt strength. If we use a voltage source of 1.5 Volt to charge up two parallel metal plates, an electron that is very close to the negatively charged plate will be accelerated in the direction of the positively charged one; and as it arrives there, it will have kinetic energy of 1.5 eV.

In many specific contexts of particle physics, the unit eV is too small. Depending on the specific application, we then use units such as kilo-electron-volts (where 1 keV = 1000 eV), Mega-electron-volts (1 MeV = 1000 keV), Giga-electron-volt (1 GeV = 1000 MeV), and Tera-electron-Volt (1 TeV = 1000 GeV). To give an example, the electrons that generate images on computer or television screens have energies of a few times 10 keV. The LEP accelerator (the so-called Large Electron Positron collider) at the European research center CERN was able to accelerate electrons up to energies of about 110 GeV until its demise in the year 2000. And Einstein's mass-energy relation lets us express the mass of an electron in energy units also: $m(e) = 0.511 \text{ MeV}$.

When it comes to practical applications, the electron is the most important elementary particle. Ever since its first discovery, it has presented important challenges to physicists. It has mass, we know, and that suggested it must also have a finite size, to be expressed by a definite radius. But experiments that are being performed with ever greater accuracy tell us that the radius is zero. That would make it as elementary an object as we can imagine: a mathematical point that does possess both a charge and a mass. Should the electron have any inner structure, that structure would have to be smaller than 10^{-17} cm — a billion times smaller than the size of an atom. Is it possible that there is a pointlike object that has both mass and charge? Mathematically speaking, a point is the result of a limiting definition: it can be imagined as a very small sphere of radius zero. We will have to imagine a tiny sphere with the mass and the charge of an electron, the radius of which we diminish until it reaches zero. This makes the electron a mathematical construction, sort of like Lewis Carroll's Cheshire Cat which, you may recall, vanishes slowly

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while leaving behind nothing but its smile: a catless smile. Let us wait and see whether future physicists who do experiments with electrons will lose their smile in the process.

Having discovered the electron, Thomson speculated that essentially all of atomic matter consists of its particles that are embedded in a somewhat diffuse, electrically positive charged medium; but this time he did not hit the nail on the head. Quite early in the 20th century, it was noticed that the mass of the atoms is mostly not tied to the electrons, but is due to a “massive nucleus”. It was Ernest Rutherford who, with his group at the University of Manchester in Great Britain, performed the decisive experiment in the year 1909. They used alpha rays emitted by a radioactive substance — even knowing that these doubly charged particles are simply nuclei of the element helium. These alpha rays traversed a gold foil in an experimental setup that was embedded in zinc sulfate casing. When an alpha particle hits a zinc sulfate molecule, it causes a small lightning to be emitted, visible to the human eye in the dark laboratory. In this fashion, it became obvious when an alpha particle, having penetrated the foil, had a close interaction with one of the atoms which scattered it such as to change its direction. Most of these scatterings happened at very small angles, but once in a while they led to a change of direction by 10 degrees or more.

Rutherford and his collaborators performed a very systematic investigation, trying to find out whether, once in a while, an alpha particle might penetrate the gold foil only to turn around and fly back — sort of like a tennis ball that bounces back from the wall. Nobody expected this to happen but, amazingly, it did. Roughly one in 8000 alpha particles did just that to the astonishment of the physicists in this group. Rutherford would recall later on: “This was the most incredible result of my related work that I experienced. It was as though we took a 15-inch grenade and shot it against a paper foil, only to see the grenade come back at the person who launched it”.

It took almost two years for Rutherford to make sense out of this phenomenon. There was only one way to understand this odd backscattering of the particles. Essentially all of the mass and the

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positive electric charge of the gold atoms in the foil had to be concentrated in a very small volume way inside the atom, making up its nucleus. But the electron which mass makes up only a tiny fraction of the atoms, moves rapidly through the atomic volume. Further experiments permitted an estimate of the size of the nucleus. It turned out to be about 10,000 times smaller than the atomic radius, or some  $10^{-12}$  to  $10^{-13}$  cm. And that indicated that the volume of the nucleus was laughably small compared with that of the atom. The atoms were mostly just empty space. When we touch the surface of a diamond, we gain the impression that it is a very dense bit of matter. And so it actually is — but its very hard appearance is due to a combination of electrical forces acting between the nuclei and the electrons. A diamond ultimately consists of mostly empty space; alpha particles can penetrate it as easily as they pass through a gold foil. Let us recall the ancient saying of Democritus: “There is nothing in existence except atoms and empty space”. He would be extremely astonished if, in a modern reincarnation, he found out that the atoms also consist of mostly empty space.

Rutherford himself often pointed out that good luck is one of the necessary ingredients for experimental physicists when they make an important discovery. Ultimately, it turned out much later that this was in fact the case in his experiment on alpha rays. As luck would have it, Rutherford was using a radioactive source that emitted alpha particles of 5 MeV — an ideal energy for the discovery of atomic nuclei. Had the energy been higher, the alpha particles would have engaged in complicated reactions with atomic nuclei. That would have made it impossible to find results which were easy to interpret. If, on the other hand, their energy had been lower than 5 MeV, the backscattering would not have been observed in the first place.

Rutherford was able to demonstrate that the scattering of alpha particles followed a simple rule: the particles were positively charged, as were the atomic nuclei. The scattering therefore was due solely to the electrostatic repulsion of these two systems. Inside the atoms, it was shown that the well-known law applied: equal charges repel each other, opposite charges attract each other. Had Rutherford performed his experiments with electron beams, he would have observed

similar scattering phenomena, with the difference that the electrons and the nuclei attracted each other. In those days, however, there was no way to generate an electron beam with energies of about 5 MeV.

Rutherford's model of atoms started a very rapid development, leading up to the model of atomic structure that we consider to be correct today: atoms consist of a positively charged nucleus surrounded by a shell of negatively charged electrons. The positive charge of the nucleus, of course, is due to protons.

The simplest atom we know of, the hydrogen atom, has just one electron providing this shell for one proton. Clearly, nucleus and electron attract each other, and it is only the steady almost circular motion of the electron that keeps it from being pulled into the proton. We might think of the hydrogen atom as of a microscopic planetary system: its center is — taking the role of our Sun — the nucleus consisting of just one proton; it is steadily circumnavigated by the electron, the stand-in for our Earth. The electron follows a circular path around the Sun — and electrostatic attraction is being cancelled by the centrifugal force which opposes it.

The hydrogen nucleus is just one proton, which permits us to study the properties of this particle in detail. Its mass was determined to amount to 938.272 MeV. This makes it almost precisely 1836 times as heavy as the electron. This atom therefore concentrates more than 99.9% of its mass in the nucleus, to this day, we do not know why the mass ratio of electron to proton is so minuscule. After all, the electric charge of a proton is precisely the same as that of the electron, once we change its sign — it is simply  $e$ . The electric charge of the atom is therefore exactly zero. This is another phenomenon we do not fully understand; we might assume that the absolute value of the electron and proton charges is slightly different in addition to their opposite signs. That, of course, would make the charge of the hydrogen atom different from zero.

The fact that hydrogen atoms are devoid of electric charge is extremely well established. In the universe, we observe large systems of matter, such as gaseous clouds, that consist mainly of hydrogen; that fact permits us to write down very precise limits for any

assumed non-zero charge of the hydrogen atom. It has to be smaller than  $10^{-21}$  times that of the proton. This limit can be set with such precision because any non-zero charge of the hydrogen atom would lead to electrostatic repulsion in hydrogen clouds. But such a repulsion has not been observed. We therefore have this remarkable result of equal but opposite charges of proton and electron, notwithstanding the fact that the physical properties of these particles are vastly different — as their extreme mass ratio makes obvious. It does tell us that there must be something the electron and proton have in common — something that mandates the equality of the absolute value of their charges. We will find that there may well be a common property at the basis of this charge phenomenon. But that is well beyond the realm of atomic physics.

All atoms, with the singular exception of hydrogen, have more complicated nuclei consisting of several particles. We might start with a special kind of hydrogen — often called “heavy hydrogen” — with an atomic nucleus of roughly twice the mass of normal hydrogen, but with the same electric charge. Its nucleus contains a second particle, a neutron, the existence of which was discovered in 1932 by the British physicist James Chadwick. Its mass was determined to be 939.565 MeV, which is about 1% heavier than that of the proton.

The fact that the masses of these two nucleons are almost the same is not coincidence. We will see that this is a consequence of special dynamical properties of theirs. Up-till now, we do not really understand why the neutron has a slightly heavier mass than the proton — it is one fact of microphysics that we cannot really explain. Initially, we might expect the opposite because the proton has an electric charge, and is therefore surrounded by an electric field. Its energy might be expected, according to Einstein’s mass/energy relation, to contribute to the mass of the proton.

The neutrons and the protons, often called nucleons, are the building blocks of all atomic nuclei. The relative numbers of neutrons and protons depend on the individual elements of interest. Take, for instance, the carbon nucleus: it usually contains six protons and six neutrons. Heavier nuclei have more neutrons than protons; e.g., the uranium nucleus has 92 protons and, usually, 146 neutrons. Inside

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the nucleus, the electrostatic repulsion between the protons would cause this compound to explode were it not for a new force of nature, the so-called strong interaction. This force is attractive between the nucleons and sees to it that protons and neutrons co-exist in the smallest space. The diameter of atomic nuclei is of the order of  $10^{-13}$  cm. That makes nuclei about 100,000 times smaller than the atom as a whole. Were we able to inflate the atomic nucleus to the size of an apple, the atom would have to attain the respectable diameter of about 10 km.

What is the basic need for the existence of this so-called strong force? Until the 1970s, this was an unsolved problem. Clearly, it has to be connected with the structure of the nucleons. Unlike the electrons that surround them, the constituent particles of the nuclei are not devoid of a structure of their own. They do have a sub-structure, as the atoms do in a way that we described above. Before we attempt to tackle this question for the nuclei, we have to deal with another important property of microphysics that is of decisive importance for the sub-structure of matter: the quantization of microphysical phenomena.

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## Chapter 3

# Quantum Properties of Atoms and Particles

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It is obvious that all atoms share the same basic structure, one hydrogen atom resembles every other hydrogen atom. This property of atoms illustrates the duality of riches and of uniformity displayed by Nature, as we said earlier on. But classical physics does not explain this feature, since its laws have no basic scale of things. Classically, there is no reason why a given electron should be at a distance of one millionth of a centimeter from the nucleus it is bound to, or rather at a thousand times that distance or a million times farther still. So what could be the reason why the electron, bound in a hydrogen atom, goes at a speed such that its distance from the nucleus is always the same, i.e., about  $10^{-8}$  cm?

In the same viewpoint, classical physics provides no explanation why atoms are stable particles: the electron has an electric charge that moves around the nucleus; so we might expect it to behave like an electromagnetic transmitter which radiates off energy in the form of electromagnetic waves. Now, the diminishing energy of the electrons would then cause the electron to drop into the nucleus — but no such thing happens. There has to be some mechanism that makes the electron move around the nucleus in a stable orbit.

It is quantum theory that provides us this mechanism, giving us the theoretical framework which permits a description of “micro-physics” (physics at very small distances). In the world of atoms

and subatomic particles, the well-known laws of normal mechanics, for which we have an intuitive understanding, no longer apply. While the German physicist Max Planck developed the first ideas of quantum mechanics in the year 1900, it took more than two decades until the implications of these ideas became clear thanks to the work of Arnold Sommerfeld, Niels Bohr, Werner Heisenberg, and Wolfgang Pauli. But to this day it has remained a mystery why quantum theory is able to describe microphysics so well. My ex-colleague at Caltech, Richard Feynman, himself a leading quantum theorist, often said: “Nobody understands quantum theory.” Niels Bohr, one of the first luminaries, put it differently: “Nobody”, he said, “understands quantum theory without turning dizzy”.

And indeed, quantum theory breaks the concepts of physical phenomena that every one of us has developed during his or her life: concepts that are deeply rooted in our intuitive understanding of physical reality become irrelevant in this framework. Microphysics permits processes that our understanding of classical physics excludes. It appears that we are not able to conceptualize the dynamics of microphysics in terms of the concepts that have evolved over many centuries. But still, quantum physics permits us to calculate observed processes with spectacular precision, even though a deep understanding has not really been achieved.

Quantum theory is defined around a tiny constant of nature, the quantum of action called  $h$ , unknown in classical physics. It has experimentally been determined to have the value  $6.6 \times 10^{-36}$ . Watt seconds: clearly a tiny value when measured in the usual units of Watts and seconds. That is the very reason why the astonishing phenomena of quantum physics do not show up in our daily lives. The name – quantum of action – is due to the fact that this constant gives a measure of physical action, where “action” is defined as a product of energy and time. This makes intuitive sense: the action of some happening can be seen by having a given energy available for a given amount of time. If that time is very short, this “action” will be very small even if the energy in the process is sizable.

One of the important implications of quantum physics says that the physical quantities that need to be known for the description of

the motion of an electron around the nucleus, such as its location and its velocity, can never be measured precisely; rather, there always remains an uncertainty which is defined by the “uncertainty relations” first noticed by Werner Heisenberg. Consequently, we must give up on trying to come up with a really exact description of the dynamics inside an atom. The only quantity we can determine is the likelihood that a given process with given parameters is happening: it is impossible to find out where an electron is at a given time, and how fast it is moving. If we concentrate our interest on some exact location of an electron, we have to give up on finding its velocity and vice versa. How indeterminate the product of location and velocity is will be given by the quantum of action. Note that such relations of lacking precision are also known in the macroscopic world — say, in the case of a moving car. But the uncertainty relations imposed by quantum theory on location and velocity of the car are so minuscule that we can safely neglect them, and well below what can be measured. That is the reason for our lack of an intuitive understanding we might have for the quantum aspects of the world around us.

In atomic physics, things are very different. It is just this “uncertainty” that determines the size of, say, a hydrogen atom. The uncertainty in the location of the electron in the atom is the same quantity that we call the diameter of the full atom which includes the electron orbits. It amounts to some  $10^{-8}$  cm. Now assume that we look at a hydrogen atom with much smaller electron orbits — say, a hundred times smaller than the one we know from stable atoms. This would mean the electron is much more precisely localized than in the natural world: the uncertainty relation defines a much larger range of velocities for the electron than in the normal atom so that, on the average, the electron will move much faster than in the “normal” atom. But higher velocities mean higher energy so that the smaller atom is more energetic by comparison. This, however, runs counter to an important principle of Nature — namely the fact that every system, including an atom, always tries to be in a state of lowest energy. Consequently, the “smaller” atom will be unstable. It will soon radiate off energy and assume a larger size until it looks like a normal atom.

In the same way, we can look at an artificial atom that has a hundred times the size of a natural atom. To create it, we would have to pull the electron away from the nucleus, and to do this, we need energy. Consequently, the energy of this new atom exceeds that of the “normal atom”. This larger atom will also, soon enough, make a transition to the “ground state”. This is the state of minimal energy. There is no way to coerce the electron into giving up even more energy. It is then the uncertainty relation between location and velocity that determines the size of the atom.

To be precise, it is not the electron’s velocity that shows up in this uncertainty relation — rather, it is its “momentum”, the product of velocity and mass. That means that the size of the electron “shell” around the nucleus depends on the electron mass. If that mass were smaller by a factor of one hundred, this shell would be larger by the same factor — that would give it a diameter of one millionth of a centimeter. If, on the other hand, it were bigger by a factor of ten thousand, the shell would have a diameter larger than that of the nucleus by only a factor of ten. This implies that the size of the atom as enforced by quantum theory gives a major element of stability to Nature. And thus quantum theory gives us an explanation for Nature’s tendency to come up with universal patterns in atomic physics, in chemistry, and in biology, notwithstanding all changes she may have to accommodate.

Quantum mechanical uncertainty makes it impossible to “follow” the electron’s motion around the nucleus. Not only that, it makes no real sense to try and define a given orbit: we can only determine the likelihood that the electron is in some given space close to the nucleus. This likelihood distribution does not at all look like an orbit — rather, it surrounds the nucleus with spherical symmetry — and its maximum is in the very center of the atom, where we know the proton is. It is defined by the wave function of the electron — and that wave function can be precisely defined by quantum theory. It describes the state of the atom fully. It sounds odd, and so it is: quantum theory does not give us information on facts. It tells us about the likelihood — but that information turns out to be precise.

There is another feature of quantum theory that manifests itself in particle physics: the existence of excited states. Say, we add energy to a hydrogen atom by irradiating it with electromagnetic waves: the electron may then jump to another state of higher energy. Such excited states have specific energies. Physicists speak of a discrete energy spectrum, the lowest state of which is called the ground state of the system. The irradiation makes the electron jump up to a higher energy state: but it will revert to the ground state after a short time, emitting electromagnetic radiation in the process. This whole process can occur only if the atom absorbs precisely the energy needed for the excitation we mentioned.

It turns out that knowledge of the excitation energy is not sufficient to fully describe the wave function of the excited atom. We need to know more, such as: what is the angular momentum of the excited atom? In its ground state, we can point it in any direction without changing its energy, because its wave function is spherically symmetric and has no angular momentum. But the excited states do have that possibility. Their possible angular momenta are quantized just like their energies — but in easier-to-determine amounts: angular momenta must be multiples of the smallest non-zero amount which is simply designated by the symbol  $\hbar = h/2\pi$  etc. For short, we often speak only of quantized angular momenta 0, 1, 2, ..., leaving the  $\hbar$  out.

The ground state of the hydrogen atom has zero angular momentum because the wave function of its electron is spherically symmetric. No direction in space has special significance. This fact alone demonstrates that there are problems with attempts at trying to understand the hydrogen atom with our intuitive notions based on classical mechanics: in that kind of notion, the electron would just orbit around the protons. But every such orbital motion would imply that the electron has some given angular momentum. Angular momentum zero would mean that the electron is at rest next to the proton; that, however, is not permitted by the uncertainty relation, which says that relegating the electron to a tiny space means it must have a large velocity, a high energy. That, again, would mean the atom cannot be in its lowest energy state, the “ground state”!

In the 1920s, physicists noticed that electrons are more complicated than they had thought before. Up until then, the “police file” for the electron had been comparatively simple: a point-like object of a well-known mass and electric charge. Once it moved, it acquired a measurable velocity and, thereby, momentum and motion energy. While at rest, its only energy was given by its mass according to Einstein’s equivalence of mass and energy,  $E = mc^2$ . But now it turned out that the electron had an added “property”: an angular momentum.

Now there is a conflict with classical physics: let’s imagine the electron is a little sphere like, say, a tiny tennis ball; now this may easily have angular momentum, whether it has linear motion or not. It may revolve around any axis, even if its center-of-gravity remains fixed. We then say, it has its proper angular momentum. The axis around which it turns defines the “direction” of this angular momentum — which has its direction just like velocity or momentum; mathematically, we speak of a “vector”. Suppose we make the radius of this spherical object smaller and smaller but keep the angular momentum constant (it is what we call a “conserved quantity”), then the sphere has to revolve faster and faster — just like a figure skater who revolves in a “pirouette” and pulls in her arms as best she can. Ultimately, we can imagine that the radius of our sphere is zero: the sphere is now a point — but the angular momentum remains the same. That means the angular velocity has to become infinitively large.

Based on this notion of a limiting effect, we can imagine that the angular momentum of a “point particle” will have a certain value. Put that together with our knowledge that quantum theory permits only certain discrete values of angular momentum to atoms. It is the same for the internal angular momentum of individual particles, for which a separate name was chosen: spin. Clearly, spin can have only certain values — and for the electron that spin was found to be non-zero: it has one-half the value of the quantity  $h$  we mentioned above. In other words: the electron has spin  $\hbar/2$ , or  $h/4\pi$ .

Now we might ask whether it makes sense to interpret this value of electron spin in terms of an angular momentum that is due to the

internal structure of this particle. That would imply some rotation of matter inside the electron. Attempts to measure such an effect have been totally futile. Contrary to angular momentum that is due to orbital motion, electron spin is purely a quantum phenomenon, devoid of a classical physics parallel. Just as the electron's mass or charge, its spin is an internal degree of freedom; a spin-less electron would make no sense. Recall that we can reduce the angular momentum of a classical object — say, of a rotating sphere — to zero, just by slowing down its rotational motion to zero; but that cannot apply to a particle's spin. The electron's spin cannot be switched on or off — it is a permanent feature of that particle.

In particle physics, it has become common to take the quantity  $\hbar$  for granted when mentioning the spin of a particle. We simply say spin-1/2, or, the electron is a spin-1/2 particle. Although spin angular momentum is of different origin from orbital angular momentum, both share the property of being vectors, quantities that have a direction. An electron at rest may have its spin point to an arbitrary direction. But quantum theory tells us that we need to consider only two directions for its spin — any given direction and its opposite. We would then speak of spin  $+1/2$  and spin  $-1/2$ . We speak of two different spin states. Should the particle's spin point in a different direction, we can easily construe its spin state as a linear combination of those two previously defined states (Fig. 3.1).



Fig. 3.1. The two different spin states  $+1/2$  on the left and  $-1/2$  on the right.

An electron orbiting an atomic nucleus can be characterized by two facts pertaining to its angular momentum properties: what is its angular momentum? and what is its spin? The first one can only

be integers — say, 0, 1, 2, ..., the latter is simply  $+1/2$  or  $-1/2$ . Quantum theory does not permit other, more arbitrary, values. The two numeric values we find are called the quantum numbers of the electron.

When detailed studies of the electron “clouds” of atoms became possible in the first quarter of the twentieth century, another peculiarity of quantum physics was discovered, beyond what classical physics could explain: In atomic physics, we might imagine that two electrons orbiting the same nucleus share the same set of quantum numbers — say, orbital angular momentum zero and spin  $+1/2$ . The laws of quantum physics would permit this coincidence, but it turns out that Nature does not. Wolfgang Pauli introduced another law of quantum physics which says that two electrons in the same atom may not share the same set of quantum numbers. Physicists call this the “Pauli principle”. It was found later on that the Pauli principle is due to the electron spin having half-integer values. Were the values integer — say, 0, 1, ... — a possibility that is not “forbidden” but is not realized in Nature — things would look different. In that case, two electrons could share the same set of quantum numbers.

There are two “nucleons”, protons and neutrons; both have spin  $1/2$ . They also have to abide by the Pauli principle: two protons or two neutrons in one and the same nucleus must not share the same quantum numbers. This fact explains many properties of nuclear structure. But there are other particles that carry integer spin numbers like 0, 1, and so on. We will discuss that later — those particles are unstable; they are produced in collisions and decay shortly thereafter. To this day, we have not found a single massive stable particle with integer spin; there is just spin-zero “particle” of light, the photon — but it has no mass.

Light also has its quantum properties, which is why we speak of “light particles”. Isaac Newton, the creator of what we call classical mechanics, told us in the 17th century that light can be described in terms of a current of “light particles”. This statement did not find a good resonance, because it turned out that light phenomena could well be described in terms of wave phenomena. This does not necessarily contradict the notion of light particles; after all, everybody has

seen waves on the surface of water ponds when we throw a stone into them. Those waves clearly consist of water molecules, of minuscule particles. It makes sense to think of a wave of light in the same way: it is ultimately made up of many minuscule particles, although these particles have no mass: the photons. When we feel the heat of bright sunshine on our skins, this heat is due to the impact of the photons which transfer their energy to our skin.

So, what is the profile of the photon? The photon is tagged simply by its energy, its mass, and its spin — just like the electron. Its electric charge is, of course, zero. But even beyond that, the photon is a very special particle: it has no mass. Einstein's theory of relativity — which we cannot quickly explain in this context — tells us that the absence of mass implies that the photon can never be at rest. It always moves, just like most managers in our society. But unlike all of those managers, it always moves at one ultimate velocity, the velocity of light.

Photons have all kinds of different energies irrespective of their shared mass and velocity; their energy depends on their frequency. Quantum theory tells us that it is simply the product of this frequency and Planck's constant  $h$ , the “quantum of action”:  $E = h\nu$ . This implies that photons of lower frequency — like red light — have less energy than photons of higher frequency — say, blue light. Both of these have less energy than photons of X-rays. The latter carry energies of a few eV (electron Volts) each.

Today, particle accelerators help us to produce photons with very high energies — say, beyond 100 GeV. Radiation made up of photons that are way more energetic than visible light are called “gamma rays”; their individual photons are “gamma quanta”. Many unstable atomic nuclei emit gamma quanta as they decay.

A high-energy photon (a gamma quantum) that penetrates into an atom may well interact with the strong electromagnetic field close to the nucleus in a very interesting way, as we show in Fig. 3.2.

In this reaction, two particles are being created from the available energy: an electron and a positron — which has the same mass, the same spin, but opposite charge. This is the antiparticle of the electron. It was discovered in 1932 in an experiment that looked