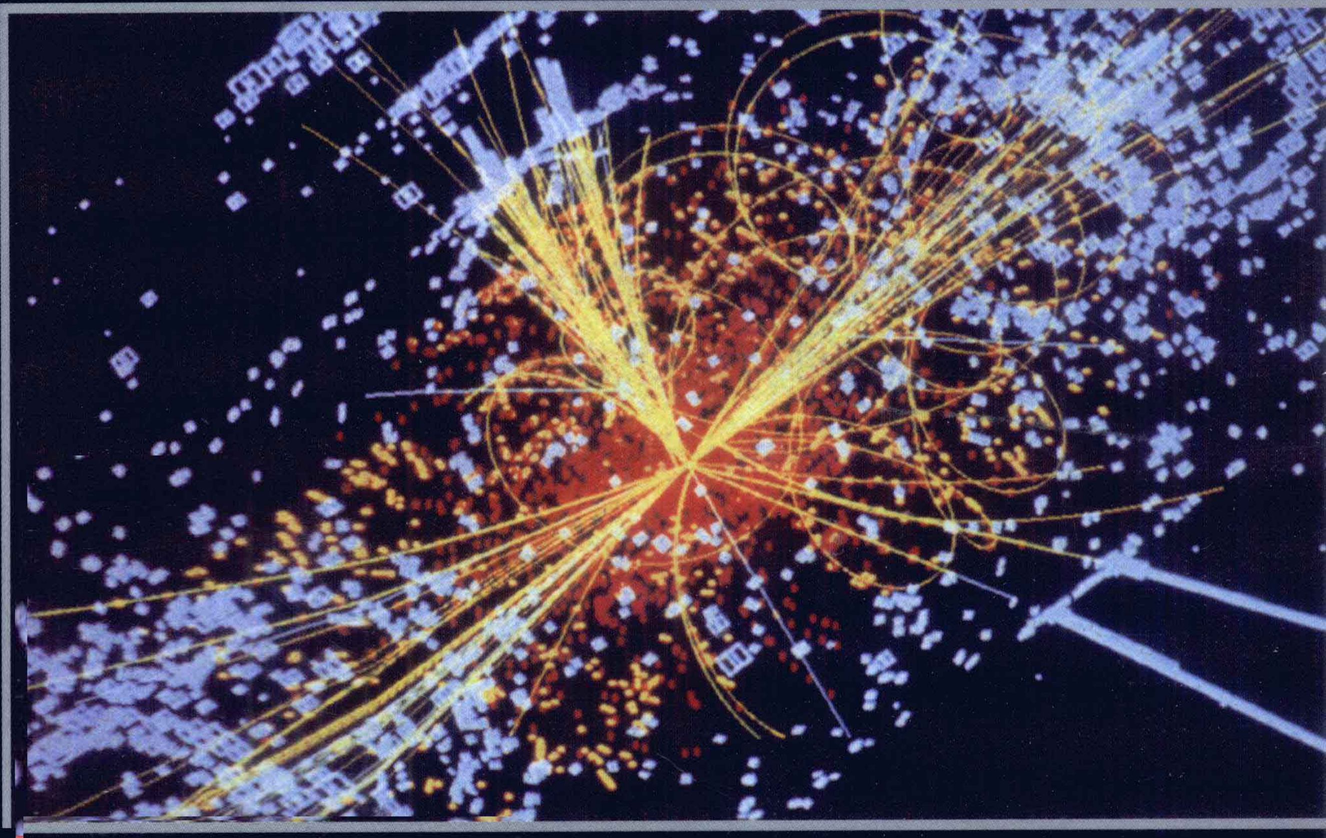
Guy D. Coughlan, James E. Dodd, Ben M. Gripaios

The Ideas of Particle Physics

An Introduction for Scientists

Third edition

粒子物理概念　第3版



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Over the two decades since this book was first published, many outstanding questions in particle physics have been answered, but our increasingly sophisticated level of understanding has led to even deeper questions. In 1983, the discovery of the W and Z bosons provided firm evidence of the correctness of the Standard Model. This marked the beginning of the end of the phase of particle physics which extended the methods of quantum electrodynamics, formulated at the end of the 1940s, to both the weak and strong nuclear forces. But a quantum theory of the other known force, gravity, was lacking.

By the second edition in 1991, the increasingly well-observed structure of quarks, leptons and gauge bosons had established the Standard Model beyond reasonable doubt. But the 'first string revolution' of 1984 had opened up the possibility that a whole class of string theories could be candidates for a more fundamental theory incorporating gravity.

Since that time, another decade of experiment has confirmed the Standard Model and its generation structure with impressive accuracy. But the recently confirmed phenomenon of neutrino oscillations (and so neutrino mass) is definitely beyond its scope. Also, cosmological observations now indicate that as much as 96 percent of the Universe is made up of unknown sources of 'dark matter' and 'dark energy'. Furthermore, yet another string revolution has resulted in a new understanding of string theories as the limit of 'M-theory', whose exact structure is not yet known.

The next few years will see the operation of the Large Hadron Collider at CERN which promises an eventful decade of both confirmation and, perhaps, surprise. The main goal of observing the Higgs boson would provide the final piece in the Standard Model jigsaw. But there is also a very likely possibility of finding evidence of supersymmetric particles (the missing dark matter of the Universe?) or other new physics beyond the Standard Model. Either of these will herald the dawn of a new era in particle physics.

On the basis of the advances described in this third edition, the physics of the current century may be as profoundly exciting as that of the last.

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To our families

Preface

The last thirty years have seen an enormous advance in our understanding of the microscopic world. We now have a convincing picture of the fundamental structure of observable matter in terms of certain point-like elementary particles. We also have a comprehensive theory describing the behaviour of and the forces between these elementary particles, which we believe provides a complete and correct description of nearly all non-gravitational physics.

Matter, so it seems, consists of just two types of elementary particles: quarks and leptons. These are the fundamental building blocks of the material world, out of which we ourselves are made. The theory describing the microscopic behaviour of these particles has, over the past decade or so, become known as the 'Standard Model', providing as it does an accurate account of the force of electromagnetism, the weak nuclear force (responsible for radioactive decay), and the strong nuclear force (which holds atomic nuclei together). The Standard Model has been remarkably successful; up until a year or two ago all experimental tests have verified the detailed predictions of the theory.

The Standard Model is based on the principle of 'gauge symmetry', which asserts that the properties and interactions of elementary particles are governed by certain fundamental symmetries related to familiar conservation laws. Thus, the strong, weak and electromagnetic forces are all 'gauge' forces. They are mediated by the exchange of certain particles, called gauge bosons, which are, for example, responsible for the interaction between two electric charges, and for the nuclear processes taking place within the sun. Unsuccessful attempts have been made to fit the only other known force – gravity – into this gauge framework. However, despite our clear understanding of certain macroscopic aspects of gravity, a microscopic theory of gravity has so far proved elusive. Moreover, recent experiments in neutrino physics cannot be explained within the Standard Model, showing beyond doubt that there must be a theory beyond the Standard Model, and that the Standard Model itself is only an approximation (albeit a very good one) to the true theory.

The above picture of the microworld has emerged slowly since the late 1960s, at which time only the electromagnetic force was well understood. It is the story of the discoveries which have been made since that time to which this book is devoted. The telling of the story is broadly in chronological order, but where appropriate this gives way to a more logical exposition in which complete topics are presented in largely self-contained units. The advances described in Parts 6–9, for example, were made more or less simultaneously, but no attempt is made here to relate an accurate history. Instead, we focus on the logical development of the individual topics and give only the main historical interconnections.

Our main concern in writing this book has been to communicate the central ideas and concepts of elementary particle physics. We have attempted to present a comprehensive overview of the subject at a level which carries the reader beyond the simplifications and generalisations necessary in popular science books. It is aimed principally at graduates in the physical sciences, mathematics, engineering, or other numerate subjects. But we must stress that this is *not* a textbook. It makes no claim whatsoever to the precision and rigour required of a textbook. It contains no mathematical derivations of any kind, and no complicated formulae are written down (other than for the purpose of illustration). Nevertheless, simple mathematical equations are frequently employed to aid in the explanation of a particular idea, and the book does assume a familiarity with basic physical concepts (such as mass, momentum, energy, etc.).

This book is organised in ten parts each consisting of four or five short chapters. However, Part 10 is more substantial. Dealing with the most exciting of current research topics, it consists of ten chapters which are rather longer than average and which will require more time and concentration on the part of the reader. We draw the reader's attention to the Glossary (Appendix 2), which gives concise definitions of the most important of particle physics nomenclature. It should prove useful as a memory prompt, as well as a source of supplementary information.

The story begins in Part 1 at the turn of the century when physicists were first beginning to glimpse the remarkable nature of ordinary matter. Out of this period came the two elements essential for the understanding of the microworld: the theories of special relativity and quantum mechanics. These are the unshakeable foundations upon which the rest of the story is based.

Part 2 introduces the four known fundamental forces, and is followed by a more detailed discussion of the physics of the strong and weak (nuclear) forces in Parts 3–5. It was the desire to understand the weak force, in particular, which led eventually to recognition of the role of gauge symmetry as a vital ingredient in theories of the microworld. Gauge theory is the subject of Part 6, which introduces the Glashow–Weinberg–Salam theory of the electromagnetic and weak forces. This theory, often called the 'electroweak model', has been spectacularly verified in many experiments over the past two decades. The most impressive of these was the discovery at CERN in 1983 of the massive $W^{\pm}$ and Z^0 gauge bosons which mediate the weak force.

At about the same time as the electroweak model was being developed, physicists were using 'deep inelastic scattering' experiments to probe the interior of the proton. These experiments, which are described in Part 7, provided the first indication that the proton was not truly elementary, but composed of pointlike objects (called quarks). As the physical reality of quarks gained wider acceptance, a new gauge theory was formulated in an attempt to explain the strong forces between them. This theory is called 'quantum chromodynamics' and attributes the strong force to the exchange of certain gauge bosons called gluons. It is described in Part 8. Together, quantum chromodynamics and the Glashow–Weinberg–Salam electroweak theory constitute the 'Standard Model' of elementary particle physics.

Part 9 describes early experiments involving collisions between electrons and positrons. These experiments were instrumental in confirming the physical reality of quarks and in testing many of the predictions of quantum chromodynamics and the electroweak theory.

Part 10 begins by summarizing the Standard Model and describes the many tests of the model performed in electron–positron colliders over the past two decades. The recent neutrino experiments, which show that there must be a theory beyond the Standard Model, are then discussed. Finally, we address the question of what this theory may be, using ideas from current research, such as grand unification, supersymmetry and string theory.

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Part 1

Introduction

1
Matter and light

1.1 Introduction

The physical world we see around us has two main components, matter and light, and it is the modern explanation of these things which is the purpose of this book. During the course of the story, these concerns will be restated in terms of material particles and the forces which act between them, and we will most assuredly encounter new and exotic forms of both particles and forces. But in case we become distracted and confused by the elaborate and almost wholly alien contents of the microworld, let us remember that the origin of the story, and the motivation for all that follows, is the explanation of everyday matter and visible light.

Beginning as it does, with a laudable sense of history, at the turn of the last century, the story is one of twentieth-century achievement. For the background, we have only to appreciate the level of understanding of matter and light around 1900, and some of the problems in this understanding, to prepare ourselves for the story of progress which follows.

1.2 The nature of matter

By 1900 most scientists were convinced that all matter is made up of a number of different sorts of atoms, as had been conjectured by the ancient Greeks millennia before and as had been indicated by chemistry experiments over the preceding two centuries. In the atomic picture, the different types of substance can be seen as arising from different arrangements of the atoms. In solids, the atoms are relatively immobile and in the case of crystals are arranged in set patterns of impressive precision. In liquids they roll loosely over one another and in gases they are widely separated and fly about at a velocity depending on the temperature of the gas; see Figure 1.1. The application of heat to a substance can cause phase transitions in which the atoms change their mode of behaviour as the heat energy is transferred into the kinetic energy of the atoms' motions.

Many familiar substances consist not of single atoms, but of definite combinations of certain atoms called molecules. In such cases it is these molecules which behave in the manner appropriate to the type of substance concerned. For instance, water consists of molecules, each made up of two hydrogen atoms and one oxygen atom. It is the molecules which are subject to a specific static arrangement in solid ice, the molecules which roll over each other in water and the molecules which fly about in steam.

The laws of chemistry, most of which were discovered empirically between 1700 and 1900, contain many deductions concerning the behaviour of atoms and molecules. At the risk of brutal over-simplification the most important of these can be summarised as follows:

(1) Atoms can combine to form molecules, as indicated by chemical elements combining only in certain proportions (Richter and Dalton).

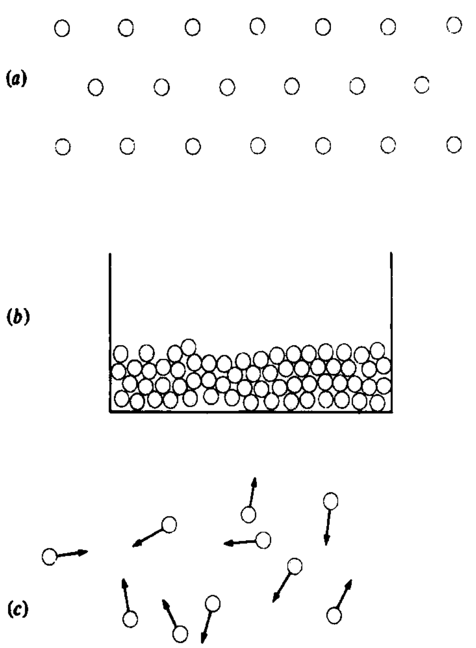

Fig. 1.1. (*a*) Static atoms arranged in a crystal. (*b*) Atoms rolling around in a liquid. (*c*) Atoms flying about in a gas.

(2) At a given temperature and pressure, equal volumes of gas contain equal numbers of molecules (Avogadro).
(3) The relative weights of the atoms are approximately multiples of the weight of the hydrogen atom (Prout).
(4) The mass of each atom is associated with a specific quantity of electrical charge (Faraday and Webber).
(5) The elements can be arranged in families having common chemical properties but different atomic weights (Mendeleeff's periodic table).
(6) An atom is approximately 10^{-10} m across, as implied by the internal friction of a gas (Loschmidt).

One of the philosophical motivations behind the atomic theory (a motivation we shall see repeated later) was the desire to explain the diversity of matter by assuming the existence of just a few fundamental and indivisible atoms. But by 1900 over 90 varieties of atoms were known, an uncomfortably large number for a supposedly fundamental entity. Also, there was evidence for the disintegration (divisibility) of atoms. At this breakdown of the 'ancient' atomic theory, modern physics begins.

1.3 Atomic radiations

1.3.1 *Electrons*

In the late 1890s, J. J. Thomson of the Cavendish Laboratory at Cambridge was conducting experiments to examine the behaviour of gas in a glass tube when an electric field was applied across it. He came to the conclusion that the tube contained a cloud of minute particles with negative electrical charge – the electrons. As the tube had been filled only with ordinary gas atoms, Thomson was forced to conclude that the electrons had originated within the supposedly indivisible atoms. As the atom as a whole is electrically neutral, on the release of a negatively charged electron the remaining part, the ion, must carry the equal and opposite positive charge. This was entirely in accord with the long-known results of Faraday's electrolysis experiments, which required a specific electrical charge to be associated with the atomic mass.

By 1897, Thomson had measured the ratio of the charge to the mass of the electron (denoted *e/m*) by observing its behaviour in magnetic fields. By comparing this number with that of the ion, he was able to conclude that the electron is thousands of times less massive than the atom (and some 1837 times lighter than the lightest atom, hydrogen). This led Thomson to propose his 'plum-pudding' picture of the atom, in which the small negatively charged electrons were thought to be dotted in the massive, positively charged body of the atom (see Figure 1.2).

1.3.2 *X-rays*

Two years earlier in 1895, the German Wilhelm Röntgen had discovered a new form of penetrating radiation, which he called X-rays. This radiation was emitted when a stream of fast electrons (which had not yet been identified as such) struck solid matter and were thus rapidly decelerated. This was achieved by boiling the electrons out of a metallic electrode in a vacuum tube and accelerating them into another electrode by applying an electric field across the two, as in Figure 1.3. Very soon the X-rays were identified as another form of electromagnetic radiation, i.e. radiation that is basically the same as visible light, but with a much higher frequency and shorter wavelength. An

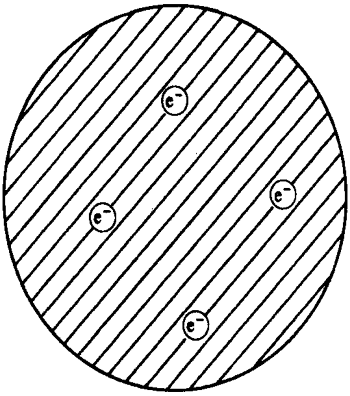

Fig. 1.2. Thomson's 'plum-pudding' picture of the atom.

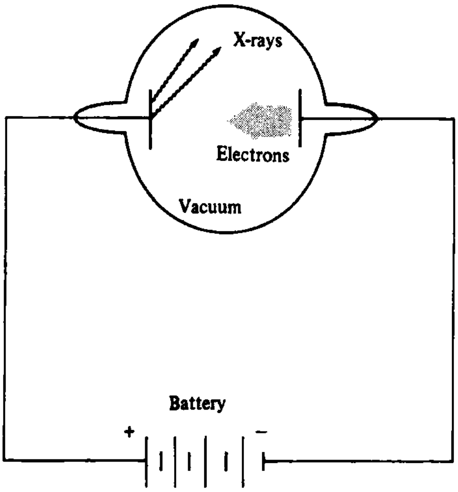

Fig. 1.3. The production of X-rays by colliding fast electrons with matter.

impressive demonstration of the wave nature of X-rays was provided in 1912 when the German physicist Max von Laue shone them through a crystal structure. In doing so, he noticed the regular geometrical patterns characteristic of the diffraction which occurs when a wave passes through a regular structure whose characteristic size is comparable to the wavelength of the wave. In this case, the regular spacing of atoms within the crystal is about the same as the wavelength of the X-rays. Although these X-rays do not originate from within the structure of matter, we shall see next how they are the close relatives of radiations which do.

1.3.3 *Radioactivity*

At about the same time as the work taking place on electrons and X-rays, the French physicist Becquerel was conducting experiments on the heavy elements. During his study of uranium salts in 1896, Becquerel noticed the emission of radiation rather like that which Röntgen had discovered. But Becquerel was doing nothing to his uranium: the radiation was emerging spontaneously. Inspired by this discovery, Pierre and Marie Curie began investigating the new radiation. By 1898, the Curies had discovered that the element radium also emits copious amounts of radiation.

These early experimenters first discovered the radiation through its darkening effect on photographic plates. However, other methods for detecting radiation were soon developed, including scintillation techniques, electroscopes and a primitive version of the Geiger counter. Then a great breakthrough came in 1912 when C. T. R. Wilson of the Cavendish Laboratory invented the cloud chamber. This device encourages easily visible water droplets to form around the atoms, which have been ionised (i.e. have had an electron removed) by the passage of the radiation through air. This provides a plan view of the path of the radiation and so gives us a clear picture of what is happening.

If a radioactive source such as radium is brought close to the cloud chamber, the emitted radiation will trace paths in the chamber. When a magnetic field is placed across the chamber, then the radiation paths will separate into three components which are characteristic of the type of radiation (see Figure 1.4). The first component of radiation (denoted α) is bent slightly by the magnetic field, which indicates that the radiation carries electric charge. Measuring the radius of curvature of the path in a given magnetic field can tell us that it is made up of massive particles with two positive electric charges. These particles can be identified as the nuclei of helium atoms, often referred to as α particles. Furthermore, these α particles always seem to travel a fixed distance before being stopped by collisions with the air molecules. This suggests that they are liberated from the source with a constant amount of energy and that the same internal reactions within the source atoms are responsible for all α particles.

The second component of the radiation (denoted γ) is not at all affected by the magnetic field, showing that it carries no electric charge, and it is not stopped by collisions with the air molecules. These γ-rays were soon identified as the close relatives of Röntgen's

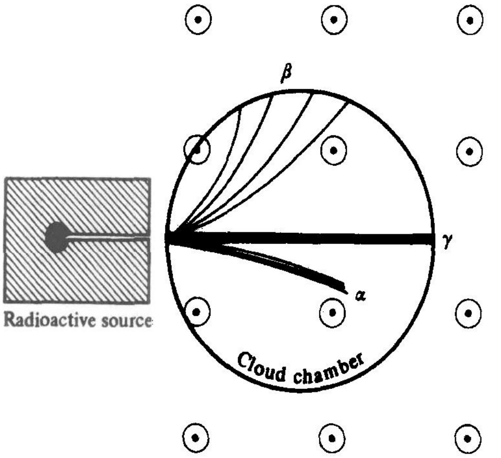

Fig. 1.4. Three components of radioactivity displayed in a cloud chamber. ⊙ signifies that the direction of the applied magnetic field is perpendicular to, and out of the plane of, the paper.

X-rays but with even higher frequencies and even shorter wavelengths. The γ-rays can penetrate many centimetres of lead before being absorbed. They are the products of reactions occurring spontaneously within the source atoms, which liberate large amounts of electromagnetic energy but no material particles, indicating a different sort of reaction to that responsible for α-rays.

The third component (denoted β radiation) is bent significantly in the magnetic field in the opposite direction to the α-rays. This is interpreted as single, negative electrical charges with much lesser mass than the α-rays. They were soon identified as the same electrons as those discovered by J. J. Thomson, being emitted from the source atoms with a range of different energies. The reactions responsible form a third class distinct from the origins of α- or γ-rays.

The three varieties of radioactivity have a double importance in our story. Firstly, they result from the three main fundamental forces of nature effective within atoms. Thus the phenomenon of radioactivity may be seen as the cradle for all of what follows. Secondly, and more practically, it was the products of radioactivity which first allowed physicists to explore the interior of atoms and which later indicated totally novel forms of matter, as we shall see in due course.

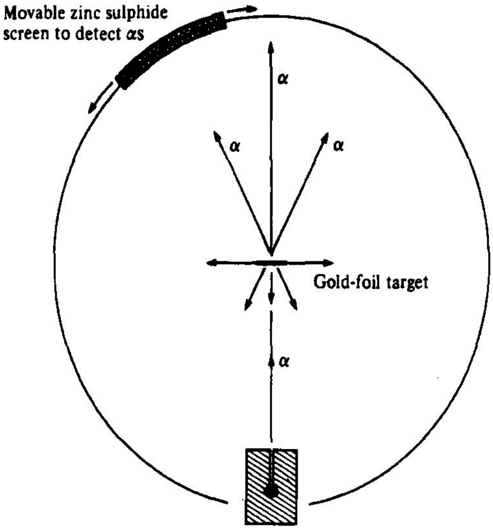

Fig. 1.5. The Geiger and Marsden experiment. According to Rutherford's scattering formula, the number of α particles scattered through a given angle decreases as the angle increases away from the forward direction.

1.4 Rutherford's atom

In the first decade of the twentieth century, Rutherford had pioneered the use of naturally occurring atomic radiations as probes of the internal structure of atoms. In 1909, at Manchester University, he suggested to his colleagues, Geiger and Marsden, that they allow the α particles emitted from a radioactive element to pass through a thin gold foil and observe the deflection of the outgoing α particles from their original paths (see Figure 1.5). On the basis of Thomson's 'plum-pudding' model of the atom, they should experience only slight deflections, as nowhere in the uniformly occupied body of the atom would the electric field be enormously high. But the experimenters were surprised to find that the heavy α particles were sometimes drastically deflected, occasionally bouncing right back towards the source. In a dramatic analogy attributed (somewhat dubiously) to Rutherford: 'It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you!'

The implication of this observation is that a very strong repulsive force must be at work within the atom. This force cannot be due to the electrons as they are over 7000 times lighter than the α particles and so can exert only minute effects on the α-particle trajectories.