The Physics of Elementary Particles

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Preface

This book is primarily intended for physics students who will not become particle physicists, and a deliberate attempt has been made to emphasize those parts of particle physics which are applications of principles shared by other branches of physics or which may be useful in other branches of physics. However, for the student who may wish to pursue the study of particle physics further, some suggestions for further reading are given, and it is hoped that this book is a suitable bridge to the advanced texts of particle physics.

This book has grown out of lecture courses given to third year undergraduate students and fourth (final honours) year students. The later chapters of the book contain material that has been presented in various seminars. A result of these diverse origins of the book is that the material becomes more difficult as the reader progresses further through the main text.

To enable the book to be used by readers with varied amounts of preparation, some material has been placed in appendices. The appendices, in part, consist of material that students could reasonably be expected to know, but frequently do not know. Other reference material has also been placed in the appendices.

The exercises, given at the end of each chapter, should be regarded as an essential part of the book, as some topics are dealt with more in the exercises than in the main part of the text. Answers to even-numbered exercises are given at the end of the book.

A few references are given and are listed at the end of each chapter. The references have been chosen mainly on the basis of possible usefulness to the student. An attempt has been made to keep the list of references small so that there is some chance of the student looking at some of them.

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Contents

Familiar particles 1

1 Introduction

From the study of atomic physics and low-energy nuclear physics, a great deal has been learned about certain elementary particles. We begin by briefly reviewing the properties of the familiar elementary particles of atomic physics.

According to the special theory of relativity, reviewed briefly in Appendix A, each particle obeys the energy–momentum relation

$$E^2 = c^2(p^2 + M^2c^2) \tag{1.1}$$

where M is the mass of the particle when at rest, p is the momentum and E is the total energy of the particle. For a particle at rest

$$E = Mc^2 \tag{1.2}$$

2 Photons

(1) The work of Planck on black-body radiation showed that light of frequency ν occurs in quanta, called photons, each having energy

$$E = h\nu \tag{2.1}$$

Equation (2.1) was also confirmed by the photoelectric effect. The relation between energy and momentum in electromagnetic radiation yields for the momentum of the photon

$$p = E/c = h\nu/c \tag{2.2}$$

Equation (2.2) was confirmed experimentally in the study of the Compton scattering of a photon by a free electron.

From equation (2.2)

$$E^2 = c^2p^2 \tag{2.3}$$

and so the photon has a rest mass of zero.

Other properties of photons learnt from atomic physics are:

(2) Photons can be created and destroyed in arbitrary numbers, as, for instance, in bremsstrahlung – when a charged particle is accelerated, as by hitting a target, photons are given off.

(3) The analysis of black-body radiation shows that photons obey Bose–Einstein statistics – they are bosons. There can be an arbitrary number of photons in a given state, and the wave function of a system of photons must be symmetric with respect to interchange of any two photons.

(4) The photon has spin 1. (More accurately, the square of the angular momentum of the photon has the value

$$2\hbar^2 = 1(1+1)\hbar^2$$

It is convenient to refer to a particle whose square of the angular momentum is

$$s(s+1)\hbar^2$$

as having spin s.)

There are two spin states for the photon, with $m_s = \pm 1$. $m_s \hbar$ is the z-component of the angular momentum, and the z-axis is taken along the direction of motion of the photon. These two spin states correspond to the two types of circularly polarized light. There is no spin state with $m_s = 0$.

The usual result from atomic spectroscopy of there being $2s+1$ spin states for spin s holds only for a particle for which a frame of reference can be found in which the particle is at rest, and so holds only for particles with non-zero rest mass. No rest frame can be found for the photon which moves with the velocity of light c in all reference frames.

3 Electrons

(1) The electron, symbol e, was the first elementary particle to be discovered. It has negative charge $-e$ (where $e = 1{\cdot}6022 \times 10^{-19}$ C) and mass

$$M_e = 9{\cdot}1096 \times 10^{-28} \text{ g}$$

Masses can be measured in the units of energy by using the rest energy Mc^2 in place of the mass M. In this way, the rest mass of a particle is frequently given in MeV (million electron volts) (see

Appendix H). For the electron,

$$M_e = 0{\cdot}511 \text{ MeV}$$

(2) The study of atomic spectra showed that the electron has two spin states. The electron has non-zero rest mass, and the number of spin states must be $2s+1$ where s is the spin. Thus the electron has spin

$$s = \tfrac{1}{2}$$

(3) Electrons obey Fermi–Dirac statistics; they are fermions. The wave function of a system of electrons is antisymmetric with respect to the interchange of any two electrons; and so there can be at most one electron in a given state – the Pauli exclusion principle. The Pauli exclusion principle can be illustrated by considering a system of two (non-interacting) electrons, one in a state with wave function ψ and the other in a state with wave function ϕ. Then the total wave function Ψ, antisymmetric with respect to the interchange of electrons 1 and 2, is

$$\Psi(\mathit{1}, \mathit{2}) = \psi(\mathit{1})\phi(\mathit{2}) - \phi(\mathit{1})\psi(\mathit{2})$$

where *1* and *2* stand for all the coordinates (including spin) of electrons 1 and 2 respectively. We see that if $\phi = \psi$, then

$$\Psi = 0$$

– the two electrons cannot occupy the same state.

(4) Electric charge is conserved, and so electrons are not arbitrarily created or destroyed. The creation or destruction of an electron is always accompanied by the creation or destruction of some other particle or particles, as we shall see in more detail later.

4 Protons

(1) The proton, symbol p, which is the nucleus of the hydrogen atom, has charge $+e$ and mass

$$M_p = 938{\cdot}3 \text{ MeV}$$

(2) The study of molecular hydrogen showed that the two protons in the hydrogen molecule could be arranged in two different ways. The spins of the two protons could be parallel as in orthohydrogen, or antiparallel as in parahydrogen. Each proton had two possible spin orientations relative to the spin of the other proton, and so, like the electron, the proton has spin $\frac{1}{2}$.

(3) In orthohydrogen, the wave function is symmetric with respect to interchange of the spins of the two protons since the two spins have the same direction, and experiment showed that the wave function was antisymmetric with respect to the interchange of the spatial coordinates of the two protons; so that the wave function is antisymmetric with respect to complete interchange of the two protons. In parahydrogen, the wave function is also antisymmetric with respect to complete interchange of the two protons, being antisymmetric with respect to interchange of the protons' spins, and symmetric with respect to interchange of their spatial coordinates.

So protons obey Fermi–Dirac statistics; they are fermions; the Pauli exclusion principle applies to protons – there can be at most one proton in any given state.

5 Neutrons

The neutron has symbol n and mass $M_n = 939{\cdot}6$ MeV.

In 1930 Bothe and Becker discovered a very penetrating radiation given off when beryllium was bombarded with α particles; this penetrating radiation was thought to be γ rays. In 1932 I. Joliot-Curie and J. F. Joliot-Curie found that this radiation knocked out protons from hydrogen-rich material, and they suggested that this was due to Compton scattering – i.e. that the protons were recoiling from scattering γ rays. However, this explanation required the penetrating radiation to consist of extremely energetic γ rays, but with no explanation of where such energy came from.

In 1932 Chadwick showed that the recoiling protons had been hit by neutral particles of approximately the same mass as the proton. He called these neutral particles neutrons. The reaction occurring when beryllium was bombarded with α particles was

$$_2\mathrm{He}^4 + {}_4\mathrm{Be}^9 \rightarrow {}_6\mathrm{C}^{12} + {}_0n^1$$

The existence of the neutron was also needed to explain observations of molecular spectra, which showed, for instance, that the wave functions of nitrogen molecules were symmetric with respect to the interchange of the two N^{14} nuclei, and consequently that the N^{14} nuclei were bosons. This could not be understood if the N^{14} nucleus was to be made up only of protons and electrons, as this would require 14 protons and 7 electrons, which constitutes an odd number of fermions. A system made up of an odd number of fermions is itself a fermion; for the interchange of two such systems can be carried out by interchanging their constituent fermions, and each interchange of two fermions changes the sign of the total wave function. In this way, it is also seen that a system made up of an even number of fermions will be a boson. Then the N^{14} nucleus is a boson if made up of 7 protons and 7 neutrons, assuming that the neutron is a fermion.

From the study of nuclear physics, it is found that neutrons obey the Pauli exclusion principle and so are fermions, and also that the neutron has spin $\frac{1}{2}$.

It should be noted that particles with half-odd-integer $[(2n+1)/2]$ spins are fermions, and that particles with integral spin are bosons (Gamow, 1959). The proton and neutron have similar properties in many ways, and it is convenient to introduce the term 'nucleon' signifying either a neutron or a proton. This aspect of the neutron and proton will be discussed more fully in Sections 17 and 18.

The particles dealt with above, the photon, electron, proton and neutron, are sufficient for dealing with all of molecular and atomic physics. A few more particles are needed in the description of nuclear physics, a description that is still far from complete as our understanding of nuclear forces is very limited in comparison to our understanding of the forces in atomic and molecular physics. Finally, we shall encounter a seemingly never ending collection of particles in dealing with high-energy physics.

It might be argued that an understanding of the particles of high energy physics is an unnecessary luxury, and that we have sufficient understanding of our environment in terms of the familiar particles of atomic and molecular physics. However, we should remember that we do not yet understand nuclear forces, and so do not really understand why our surroundings are as they are, instead of being just clouds of hydrogen. In astronomy and cosmology, there are still many unsolved problems, such as the nature of quasars – the peculiar intense sources of energy which seem to be so small that it is difficult to understand how their great energy arises. It is very probable that the knowledge about elementary particles gained from high energy physics is relevant to the understanding and solution of problems in astronomy and cosmology. The science of elementary particles is an essential part of modern science with important consequences for other parts of science.

6 Conservation laws and invariance principles

In classical mechanics, conservation laws appear almost as an afterthought. For both the path of history, and the usual path trodden by the student, the equations of motion were first encountered, and the laws of conservation of momentum and conservation of mechanical energy were derived from the equations of motion. The conservation laws were then extended; for instance, the law of conservation of energy was extended to include chemical energy and electrical energy. However, in practical applications, the conservation laws are extremely useful, as they enable us to say something about complicated systems even when we do not know the detailed equations of motion of the systems. For instance, a full description of the collision of two automobiles would be very complicated, but we do know that momentum is conserved in such a collision. Similarly, in the case of collisions of particles, although we do not know the details of the interactions, energy, momentum and angular momentum are conserved in the collisions.

In high energy physics, where the equations of motion are as yet unknown, conservation laws are extremely important. The conservation laws of classical mechanics, conservation of energy, momentum and angular momentum, hold also in quantum mechanics. As we shall see later, there are also additional conservation laws in quantum mechanics.

Another aspect of the importance of conservation laws is that they are related to invariance principles or symmetry principles. An invariance principle states that the laws of physics remain unchanged (are invariant) for certain changes in circumstances. Or in the case of a particular system, an invariance property or symmetry property of the system is some operation that can be carried out on the system which does not alter the physics of the system.

As an example, the laws of physics are invariant under spatial translations. An experiment performed in London should yield the same answer as an experiment performed in New York. Also, the laws of physics are invariant under time translations; an experiment performed today should yield the same answer as the same experiment performed last year.

In both classical mechanics (Landau and Lifshitz, 1969) and quantum mechanics (Feynman, 1965) invariance principles lead to conservation laws. For instance, invariance under spatial translations implies conservation of momentum; invariance under time translations implies conservation of energy; invariance under rotations implies conservation of angular momentum.

A large part of the study of elementary particles has been the search for further symmetries or approximate symmetries.

The treatment given here of the historical development of particle