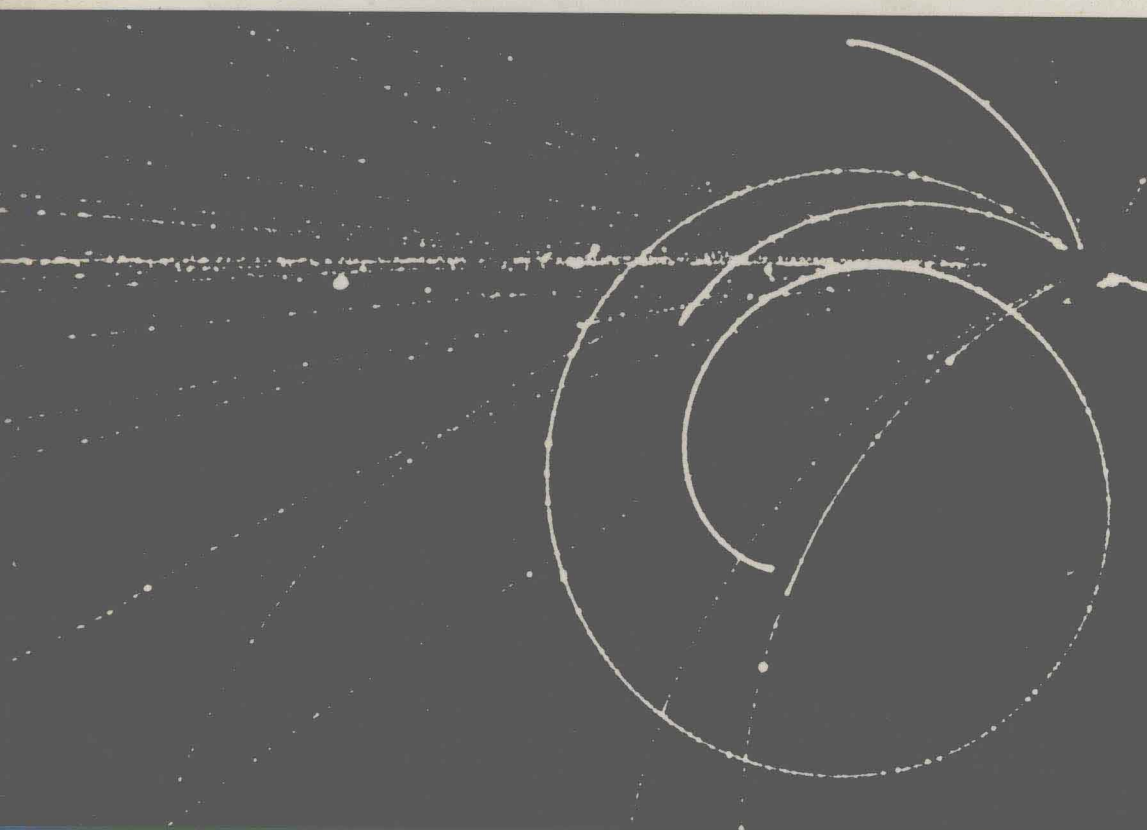


Third Edition

Introduction to High Energy Physics



Donald H. Perkins

THIRD EDITION

Introduction to High Energy Physics

DONALD H. PERKINS

University of Oxford



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The cover image shows the interaction of a 200-GeV proton in a xenon gas target placed in a streamer chamber. See page 54 for further description. *Courtesy of V. Eckhardt, MPI, Munich.*

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THIRD EDITION

***Introduction to
High Energy Physics***

Now the smallest Particles of Matter may cohere by the strongest Attractions, and compose bigger Particles of weaker Virtue. . . . There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out. *

Newton, *Optics* (1680)

Les Philosophes qui font des systèmes sur la secrète construction de l'univers, sont comme nos voyageurs qui vont a Constantinople, et qui parlent du Sérail: Ils n'en ont vu que les dehors, et ils prétendent savoir ce que fait le Sultan avec ses Favorites.

Voltaire, *Pensées Philosophiques* (1766)

To My Family

For their patience, forbearance, and encouragement

PREFACE TO THE THIRD EDITION

The main intention behind this book has been to present the more important aspects of the field of high-energy physics, or particle physics, at an elementary level. The content is based on courses of lectures given to undergraduates in Oxford specializing in nuclear physics, but the book would also serve as an introductory text for first-year graduate students in experimental high-energy physics. I have tried to make the coverage as broad as possible while keeping the text to a reasonable length.

Since the first edition was written sixteen years ago, high-energy physics has undergone many revolutionary developments, and both the volume and range of the subject has increased many times. This has meant a substantial rewriting of the text and a modest expansion in length. The interrelation between different aspects of the subject is now so strong that the division of the material under the various chapter headings has perforce been rather arbitrary.

The first chapter presents basic introductory ideas, the historical development, and a brief overview of the subject; the second and third chapters deal with experimental methods, conservation laws, and invariance principles—just as in the first edition. The following chapters deal in turn with the main features of the interactions between hadrons; the description of the hadrons in terms of quark constituents, and discussion of the basic interactions—electromagnetic, weak and strong—between the lepton and quark constituents. The final chapter discusses unification of the various interactions. During the last few years, the astrophysical and cosmological implications of results and ideas from high-energy physics have become important and indeed vital to our understanding of the development of the universe. I have tried to convey some of the flavor of this connection, since it will clearly help to shape the trends in high-energy physics in the foreseeable future.

As in the first edition, the interplay between experiment and theory has been emphasized, and some discussion given of key experiments in the field. Long theoretical treatments have been avoided, and for much of the mathematical detail the student is referred to Appendices or other texts. Some knowledge of elementary quantum mechanics is assumed, but generally the material has been presented from the empirical viewpoint, with a minimum of formalism and using an intuitive approach. Physics is about numbers, and I have taken the view that it was more important that a student should know how to calculate a cross-section or a decay rate, in order of magnitude, than how to derive a complicated formula (usually based on

assumptions of questionable validity) without any real idea on how to confront it with experiment. In the same spirit, I have included a list of (mostly numerical) problems for each chapter, together with worked solutions at the end of the book.

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DONALD H. PERKINS

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CHAPTER 1

Introduction and Overview

1.1. INTRODUCTION

High-energy physics deals basically with the study of the ultimate constituents of matter and the nature of the interactions between them. Experimental research in this field of science is carried out with giant particle accelerators and their associated detection equipment. High energies are necessary for two reasons: First, in order to localize the investigations to the very small scales of distance associated with the elementary constituents, one requires radiation of the smallest possible wavelength and highest possible energy; second, many of the fundamental constituents have large masses and require correspondingly high energies for their creation and study.

Fifty years ago, only a few “elementary” particles—the proton and neutron, the electron and neutrino, together with the electromagnetic field quantum (the photon)—were known. The universe as we know it today appears indeed to be composed almost entirely of these particles. However, attempts to understand the details of the nuclear force between protons and neutrons, as well as to follow up the pioneering discoveries of new, unstable particles observed in the cosmic rays, led to the construction of ever larger accelerators and to the observation of many hundreds of new unstable particle states, collectively called hadrons (strongly interacting particles).

neutrino [nju:ˈtri:nu] 中微子

Out of this seeming chaos has emerged a rather simple picture:

- (i) All matter is composed of fundamental spin- $\frac{1}{2}$ fermion constituents—the *quarks*, with fractional electric charges ($+\frac{2}{3}e$ and $-\frac{1}{3}e$), and the *leptons*, like the electron and neutrino, carrying integral electric charges. Neutrons and protons are built from quarks, three at a time.
- (ii) These constituents can interact by exchange of various fundamental *bosons* (integral spin particles) which are the carriers or quanta of four distinct types of fundamental interaction or field. Gravity is familiar to everyone, yet on the scales of mass and distance involved in particle physics, it is by far the least important of the four. Apart from gravity, *electromagnetic* interactions account for most extranuclear phenomena in physics (because electromagnetic forces have the longest range) and lead to the bound states of atoms and molecules. *Weak* interactions are exemplified by the extremely slow process of radioactive β -decay of nuclei. *Strong* interactions are postulated to hold together the quarks in a proton, and their residual effects apparently account for the interactions between neutrons and protons, that is, for the nuclear binding force. Both weak and strong interactions are of short range (less than or of order one *fermi* or *femtometer*, $1 \text{ fm} = 10^{-15} \text{ m}$).

There are many unusual, even bizarre, aspects of this picture. The fractionally charged quarks have not been observed as free particles, and seem to be permanently confined in hadrons. Quarks come in a variety of types or *flavors* (six are known) as do the leptons (three types of charged and of neutral leptons). We neither understand the mechanism of confinement, nor the real reason for the “Xerox copies” of quark and lepton flavors, when the universe, on the basis of what we see today, seems to be constructed predominantly from just two types of quark and one neutral and one charged lepton.

The multiplicity of quark and lepton flavors is paralleled by the existence of the four types of fundamental interaction. Here, some real progress has been made. There are good grounds for supposing that some, perhaps all, the interactions are *unified*, that is, different aspects of one single interaction. The weak and electromagnetic interactions appear to have the same intrinsic coupling of fermion constituents to the respective mediating bosons—they are different aspects of a single *electroweak* interaction. Compared with electromagnetism (mediated by the massless photon field with infinite range), the weakness of the weak interactions is ascribed to their short-range nature (they are mediated by massive bosons W^\pm , Z^0 , whose mass is found to be of order 100 proton masses). At high enough energies and

momentum transfers, well above such a mass scale, electromagnetic and weak interactions should have the same actual strength.

Why the high-energy symmetry is badly broken at low energy, and the respective bosons have such widely differing masses, is still an unsolved problem. The important point however is that the strengths of the different interactions are not fixed once and for all; they depend on energy scales. At high energies, strong interactions appear to grow weaker, and the strong and electroweak interactions may also merge at the colossal energy of 10^{15} GeV.

The study of particle physics is considered to be intimately connected with evolution of the universe. We believe the universe originated in a “big bang” expansion of an energy bubble, from which all types of particles—quarks, leptons and quanta—were created. Today, we are left with the expanded, cooled remnant. So, our search toward higher energies is also a look backward in time to the very earliest stages of creation, which determined the characteristics of the universe we find today.

1.2. FERMIONS AND BOSONS

One of the most fundamental concepts underlying our analysis of the interactions of particles and fields is the spin-statistics theorem (Pauli 1940), connecting the statistics obeyed by a particle with its spin angular momentum. Particles with half-integral spin ($\frac{1}{2}\hbar, \frac{3}{2}\hbar, \dots$) obey Fermi-Dirac statistics and are thus called fermions, while those with integral spin ($0, \hbar, 2\hbar, \dots$) obey Bose-Einstein statistics and are called bosons.

The statistics obeyed by a particle determines the symmetry of the wavefunction ψ describing a pair of identical particles, say 1 and 2, under interchange. If the particles are identical, then the square of the wavefunction, $|\psi|^2$, giving the probability of particle 1 at one coordinate and particle 2 at another, will be unaltered by the interchange $1 \leftrightarrow 2$. Thus,

$$\psi \xrightarrow{1 \leftrightarrow 2} \pm \psi.$$

The following rule holds:

$$\begin{aligned} \text{Identical bosons: } \quad \psi \xrightarrow{1 \leftrightarrow 2} + \psi & \quad \text{symmetric} \\ \text{Identical fermions: } \quad \psi \xrightarrow{1 \leftrightarrow 2} - \psi & \quad \text{antisymmetric} \end{aligned} \tag{1.1}$$

In order to make use of this rule, the total wavefunction of the pair can be expressed as a product of functions depending on spatial coordinates and spin orientation:

$$\psi = \alpha(\text{space}) \beta(\text{spin}). \tag{1.2}$$



Figure 1.1 Examples of the decay sequence $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ in G5 emulsion exposed at Pic du Midi. The constancy of range ($\simeq 600 \mu\text{m}$) of the muon implies two-body decay at rest of the pion: $\pi^+ \rightarrow \mu^+ + \nu_\mu$. The first examples of pion decay were observed by Lattes, Muirhead, Occhialini, and Powell in 1947. Note the very dense ionization of both pion and muon tracks near the end of the range, compared with the thin track of the relativistic electron, as well as the lateral deflections (Coulomb scattering) of the muon as it traverses the emulsion.

The spatial part, α , could describe orbital motion of one particle about the other, and can then be represented by a spherical harmonic function $Y_l^m(\theta, \phi)$, as described in Chapter 3. Interchange of the space coordinates of particles 1 and 2 (leaving spin alone) is equivalent to the replacement $\theta \rightarrow \pi - \theta$, $\phi \rightarrow \phi + \pi$, and introduces a factor $(-1)^l$ multiplying α , where l is the orbital quantum number. Thus, if l is even (odd), the function α is symmetric (antisymmetric) under interchange. As also indicated in