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Elementary Particle Physics

Concepts and Phenomena

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Preface

This book grew—how could it be otherwise?—out of a series of lectures which the author held at the University of Heidelberg. The purpose of these lectures was to give an introduction to the phenomenology of elementary particles for students both of theoretical and experimental orientation. With the present book the author has set himself the same aim. The reader is assumed to be familiar with ordinary nonrelativistic quantum mechanics as presented, e.g., in the following books: *Quantum Mechanics*, by L.I. Schiff (McGraw-Hill, New York, 1955); *Quantum Mechanics*, Vol. I, by K. Gottfried (W.A. Benjamin, Reading, Ma., 1966).

The setup of the present book is as follows. In the first part we present some basic general principles and concepts which are used in elementary particle physics. The reader is supposed to learn here the "language" of particle physics. An introductory chapter deals with special relativity, of such fundamental importance for particle physics, which most of the time is high energy, i.e., highly relativistic physics. Further chapters of this first part deal with the Dirac equation, with the theory of quantized fields, and with the general definitions of the scattering and transition matrices and the cross-sections.

The phenomenology of elementary particles is today dominated by gauge theories. The central issue of the present book is to make the reader familiar with the corresponding physical principles. We have tried to put a certain order into the presentation of these concepts, going from the simple to the more complicated cases. Thus, in the second part of the book we deal with quantum electrodynamics (QED), the most simple gauge theory, where the gauge group is Abelian and unbroken. The third part of the book is dedicated to the phenomena of strong interactions, to the world of quarks and gluons. There we encounter for the first time a non-Abelian gauge theory, quantum chromodynamics (QCD), where the gauge group is more complicated than in the QED case, but still unbroken. In the fourth part we deal with the theory of electroweak interactions, where we also have a non-Abelian gauge group but as a new phenomenon the spontaneous breaking of the gauge symmetry. In the final chapter we make some cursory remarks concerning developments in the theory of elementary particle physics going beyond the so-called standard model.

Everywhere in this book we have tried to emphasize physical points of view and considerations. For these reasons we have chosen the interaction picture to describe scattering processes. This is legitimate also in quantum field theory if all intermediate calculations are thought to be done in the regularized theory. Our special aim was to provide the reader with all necessary knowledge enabling him to do actual calculations related to problems in elementary particle phenomenology. On the other hand, students not specializing in elementary particle physics should be able to get an overview of the field by reading a few chapters easily picked out by their titles. It was not our aim to give a detailed presentation of quantum field theory. For this we can refer the reader, e.g., to the following text books: *Relativistic Quantum Fields*, by J.D. Bjorken and S.D. Drell (McGraw-Hill, New York, 1965); *Quantum Field Theory*, by C. Itzykson and J.-B. Zuber (McGraw-Hilll, New York, 1980). Readers wanting to broaden their knowledge on the experimental aspects of high energy physics are referred, e.g., to the book: *Introduction to High Energy Physics* by D.H. Perkins (Addison-Wesley, Reading, Ma., 1982). Finally, we would like to mention a few books where the reader can find presentations of topics in particle phenomenology which were of central interest some years ago and which could not be dealt with in too much detail in the present book: *High Energy Hadron Physics* by M.L. Perl (Wiley, New York, 1974); *An Introduction to Regge Theory and High Energy Physics* by P.D.B. Collins, (Cambridge University Press, Cambridge, 1977); *Elementary Particle Physics* by G. Källen (Addison-Wesley, Reading, Ma., 1964).

References to original literature are indicated in the text by the name of the first author and the year of publication. The corresponding complete references are collected at the end of the book. References to experimental results are always understood as giving examples illustrating theoretical developments, not in the sense that the author wants to ascribe any priorities. Numbers for physical quantities are, if not otherwise indicated, taken from "Review of Particle Properties" (Particle Data Group, *Phys. Lett.* **170B**, 1, 1986).

This book was originally published in German. The author would like to thank first of all the colleagues who helped to put together the original version, in particular, B. Stech, D. Gromes, I. Bender, W. Wetzel, M. Wirbel, and A. Reiter. Such a book would have been impossible without the kind help of many colleagues from experimental physics. The author expresses his gratitude to B. Naroska, J. Drees, C. Geweniger, J. Heintze, J. von Krogh,

A. Putzer, K. Schubert, and A. Wagner, as well as their collaborators. Special thanks are due to J. Heintze for allowing the use of one of his original drawings. The author would also like to thank the students attending his lecture courses for posing many questions which helped to clarify the ideas and the presentation. The English translation would have been impossible without the untiring efforts of A. Lahee and W. Wetzel, and the author would like to express his deep gratitude to them. Thanks are also due to all collaborators involved in producing this book, first at Vieweg-Verlag for the German version and then at Springer-Verlag for the English version. Finally, the author would like to thank his wife for her understanding and encouragement during this whole enterprise.

Abbreviations

CERN	Centre Europeén de la Recherche Nucléaire; European Nuclear Research Center, Geneva, Switzerland
CESR	Cornell Electron–Positron Storage Ring, Ithaca, NY, U.S.A. (Center of mass energy ca. 10 GeV)
DESY	Deutsches Elektronen–Synchrotron; German Electron Synchrotron, Hamburg, Federal Republic of Germany
DORIS	Electron–Positron Storage Ring at DESY (Center of mass energies initially 2–7 GeV, now ca. 10 GeV)
FNAL	Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.
HERA	Electron–Proton Storage Ring (Currently under construction at DESY. Center of mass energy ca. 300 GeV)
ISR	Proton–Proton Storage Ring at CERN (Closed 1984. Center of mass energy ca. 20–60 GeV)
KEK	National Laboratory for High Energy Physics, Tsukuba, Japan
LEP	Electron–Positron Storage Ring (Currently under construction at CERN. Center of mass energy ca. 100 GeV)

PEP	Electron–Positron Storage Ring at SLAC (Center of mass energy ca. 30 GeV)
PETRA	Electron–Positron Storage Ring at DESY (Closed 1986. Center of mass energies ca. 14–45 GeV)
SLAC	Stanford Linear Accelerator Center, Stanford, Ca. U.S.A.
SLC	Electron–Positron Collider (Near completion at SLAC. Center of mass energies ca. 100 GeV)
SPEAR	Electron–Positron Storage Ring at SLAC (Center of mass energies ca. 2–7 GeV)
$Sp\bar{p}S$	Proton–Antiproton Storage Ring at CERN (Center of mass energy ca. 600 GeV)
TEVATRON	Proton–Antiproton Storage Ring at FNAL (Center of mass energy ca. 1800 GeV)
TRISTAN	Electron–Positron Storage Ring at KEK (Center of mass energy ca. 50 GeV)
UNK	Proton Accelerator under construction at Serpukhov, USSR (Proton energies up to 3000 GeV)

Notation and Symbols

$=$	equals
$\equiv$	identically equals
$\cong$	approximately equals
$\sim$	essentially equal to or equivalent
$\propto$	proportional
$\in$	is contained in
T	transpose
$\dagger$	Hermitian conjugate
sr	steradian
eV	electron volt; 1 keV $= 10^3$ eV, 1 MeV $= 10^6$ eV, 1 GeV $= 10^9$ eV, 1 TeV $= 10^{12}$ eV
f	Fermi; 1 f $= 10^{-13}$ cm
b	Barn; 1 b $= 10^{-24}$ cm^2
s	second
Hz	Hertz; 1 Hz $= 1\ \text{s}^{-1}$, 1 MHz $= 10^6\ \text{s}^{-1}$
$\sum$	summation
$\sum'$	summation over final states and average over initial states
c number	complex number
c.c.	complex conjugate
h.c.	Hermitian conjugate
$\boldsymbol{x} = (x^j)$	three-vector. The components are labeled with Latin indices ($j = 1, 2, 3$)

$x = (x^\mu)$	four-vector. The components are labeled with Greek indices ($\mu = 0, 1, 2, 3$)
$d^3x = dx^1\, dx^2\, dx^3$	volume element in ordinary three-dimensional space
$dx = dx^0\, dx^1\, dx^2\, dx^3$	volume element in Minkowski space
$\mathbf{A} = (A_{ij})$	matrix or operator with matrix elements A_{ij}
$[\mathbf{A}, \mathbf{B}] = \mathbf{AB} - \mathbf{BA}$	commutator
$\{\mathbf{A}, \mathbf{B}\} = \mathbf{AB} + \mathbf{BA}$	anticommutator
$\det \mathbf{A}$	determinant of matrix $\mathbf{A}$
$\mathrm{Tr}\{\mathbf{A}\}$	trace of matrix $\mathbf{A}$
ε^{ijk}	totally antisymmetric symbol in three dimensions ($\varepsilon^{123} = 1$)
$\varepsilon_{\mu\nu\rho\sigma}$	totally antisymmetric symbol in four dimensions ($\varepsilon_{0123} = 1$)
δ_{ij}	Kronecker delta; $\delta_{ij} = 1$ for $i = j$; $\delta_{ij} = 0$ for $i \neq j$
$\delta(x)$	Dirac delta function ($-\infty < x < \infty$); $\delta(x) = 0$ for $x \neq 0$, $\int_{-\infty}^{\infty} dx\, \delta(x) = 1$
$\theta(x)$	theta function ($-\infty < x < \infty$); $\theta(x) = 0$ for $x < 0$, $\theta(x) = 1$ for $x > 0$
$O(E)$	terms of order E

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