Elementary particles

I.S. Hughes

2nd edition

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SECOND EDITION

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University of Glasgow

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Preface

This book is intended for undergraduates or others coming to the subject of particle physics for the first time. For this reason the only prior knowledge assumed is of the elements of quantum theory and statistical mechanics.

The story of the development of particle physics in the years since the Second World War has been one of almost continuous excitement. Much of this has been due to an unceasing interplay of experiment and theory in the best classical tradition. Few years have passed without a remarkable advance in theory or experiment, such as the discovery of the antiproton; of the strange particles; the Gell-Mann–Nishijima scheme; parity non-conservation; the difference between electron and muon neutrinos; the strongly-decaying resonances; the SU(3) symmetry scheme and the omega particle; evidence for quarks and for gluons; neutral currents; charm and beauty; electromagnetic-weak unification; the discovery of the W and Z bosons and a good many others.

This rapid progress has been a consequence of, and a justification for, parallel progress in technology and instrumentation. In the first chapter of the book I have outlined the principal techniques used in this work. I hope that this will enable the student to understand how the many experiments referred to in later parts of the book have actually been carried out, since I believe that such an understanding is essential to a proper appreciation of the subject. While I have not adopted a strictly historical approach I have felt it desirable to discuss the way in which many of the problems were originally seen and subsequently solved; as, for instance, the puzzle of the muons when first observed, the τ–θ problem and others, since the solution of the problems is itself often very instructive and aids an understanding of the phenomena.

In a book at this level many of the theoretical aspects of the subject cannot be treated in a rigorous way. I have chosen to emphasise those aspects derivable from conservation laws since they underlie much of the later theory and themselves afford an important degree of understanding.

The book has been very substantially modified compared with the first edition published in 1972. The seventies has been the decade of the leptons and the weak interaction, and new chapters (7 and 11) have been added to give fuller treatment to this side of the subject. On the other hand, the discovery of new quark flavours has deepened and extended our understanding of the quark–gluon structure of matter and this material is treated in new chapters 12 and 13. The giant step forward of the theory of electro-weak unification and its experimental verification (chapter 11) has led to increased confidence that all the forces of nature will eventually be understood in a unified way and this subject is treated briefly in a new chapter (14). In order to accommodate the new material without too greatly increasing the length of the book, some topics which are now seen to be of less importance (and results which have turned out to be wrong!) have been removed from the earlier text.

Particle physics is a very active subject in both its theoretical and experimental aspects, and in the technology of accelerators and detectors. I have tried to bring the discussion as near as possible to current work and in so doing I take the risk that some of the most recent results and ideas may prove in time to be wrong. I believe that this risk is justified by the attempt to show that the subject is very much alive and is continually generating the most fundamental and challenging problems.

I hope that this book presents the subject in sufficient depth to give the student an understanding of its fundamental nature, its fascination and its recent startling progress. In an introductory text, however, many subjects have to be dealt with superficially or not at all and a number of theoretical results presented on trust. In a subject as active as particle physics it is not entirely straightforward to recommend books for further reading, since much of the most useful material is contained in publications such as the reports of summer schools, like the annual series organised by CERN, the notes for which are published as CERN reports. However, as more advanced texts covering most of the material, I recommend *Introduction to*

High Energy Physics by D. H. Perkins (Addison–Wesley, 1982) and *Quarks and Leptons* by F. Halzen and A. D. Martin (Wiley, 1984). A good introduction to group theory, particularly as applied in particle physics, is provided in *Lie Groups for Pedestrians* by H. J. Lipkin (North Holland, 1965). I have been indebted to these texts, among others, in preparing the revised version of this book.

I am particularly grateful to Dr C. Froggatt and Dr J. Lynch for reading parts of the new text and for their comments and suggestions, and to Dr W. Morton for similar help on the earlier version of the book. It is a pleasure to acknowledge the work of Mrs Barbara Martin in typing a difficult text. I also would like to record my thanks to my wife, Isobel, for much encouragement and for considerable editorial assistance in the latter stages of the preparation of the book.

I am indebted to the authors who have provided me with figures or allowed me to reproduce figures from their papers, to the CERN photographic service and to DESY for provision of material, and to the following journals for permission to reproduce diagrams originally published therein: *Nature*; *Philosophical Magazine*; *Physical Review*; *Physical Review Letters*; *Physics Letters*; and *Nuclear Physics*.

Ian S. Hughes. July 1984.

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, *Opticks.*

My purpose is now to lead you into the Pallace where you shall have a clear and delightful view of all those various objects, and scattered excellencies, that lye up and down upon the face of the creation, whicl are only seen by those that go down into the Seas, and by no other.
Daniel Pell, Πέλαγοσ.

Contents

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Accelerators, beams and detectors

1.1 Introduction

An important part of the study of particle physics is an understanding of experimental tools – the accelerators, beams and detectors by means of which particles are accelerated, their trajectories controlled and their properties measured. There exist a limited number of types of accelerators and detectors in common use or which have in the past proved crucial to the progress of the subject. No more technical detail is included here than is essential to an understanding of the uses of these techniques in the study of particle physics. In the chapters which follow we shall assume that these techniques are familiar to the student, so that it will generally not be necessary to describe in detail the technique used in particular experiments.

1.2 Particle accelerators and beams

1.2.1 *Introduction*

Particle accelerators and their associated external beam lines are key elements in most particle physics experiments.

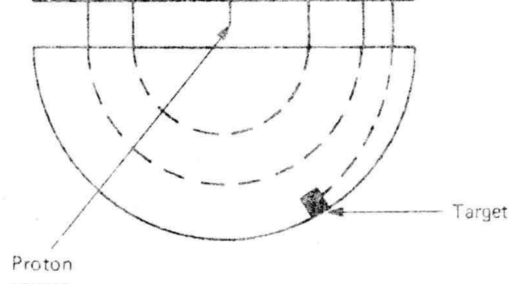
Charged particles are accelerated by passing across a region of potential difference which in practice is normally a cavity fed with radiofrequency power and phased such that the particle is *accelerated* as it passes through. Since practicable fields and dimensions are such that a single passage through the cavity can produce only a rather small acceleration, the particle must either pass through many such cavities or pass many times through the same group of cavities by guidance around a cyclic path.

In the *linear accelerator* a linear RF structure is fed with RF power from a bank of klystrons to produce a wave travelling down the structure with a velocity equal to the particle velocity so that the particle remains always on the accelerating phase of the wave throughout its flight. The largest operational linear accelerator is the two-mile-long accelerator at Stanford Linear Accelerator Centre (SLAC) which accelerates electrons to 30 GeV.

In *cyclic accelerators* a magnetic field is used to guide the particles around a cyclic path such that they repeatedly pass across the accelerating gap. In the *cyclotron*, which was an important machine in the early days of the subject, protons or heavier charged particles moved in a vacuum box containing two hollow D-shaped cavities between which could be applied an alternating potential difference (fig. 1.1). The magnetic guide field normal to the plane of the Ds caused particles of constant momentum to travel in a circular orbit of radius R, given by

$$R=\frac{pc}{Be} \qquad \begin{aligned} p &= \text{momentum} \\ e &= \text{charge} \\ B &= \text{magnetic field.} \end{aligned}$$

Fig. 1.1. Principle of operation of the cyclotron.



The frequency of the potential difference applied to the gap between the Ds must be such that particles are accelerated each time they cross the gap.

The angular frequency is easily seen to be given by

$$\omega = \frac{Be}{mc} \quad m = \text{particle mass}$$

which is independent of the particle momentum as long as the mass is constant. For high energies, of course, the mass increases due to the relativistic effect and a constant frequency is no longer adequate.

In the *synchrotron*, particles are maintained at *constant radius* in a ring-shaped vacuum chamber contained in a magnetic field. The magnet is thus also in the form of a ring and need not cover the whole circular area as in the cyclotron. Since the radius of the orbit is constant, the magnetic field must increase to hold the particles in the same orbit as their momentum increases. The circulating frequency at any moment is then given by

$$\omega_0 = \frac{Bec}{E} \quad E = \text{total particle energy.}$$

Acceleration is achieved by having the particles pass through suitably-phased RF cavities at one or more positions in the ring. In practice, the particles are always bunched in the accelerator, although several bunches may be present at the same time. In all high-energy machines the particles are first accelerated in a linear accelerator before injection to the synchrotron. For electrons, which become relativistic at very low energy, the velocity and thus the accelerating frequency is essentially constant. For protons this is not so.

1.2.2 *Colliding beams and available energy in the centre of mass*

When a particle of rest mass m and total energy E collides with another particle of the same mass at rest the energy available in the centre of mass of the two particles is (see appendix A) E' given by

$$E'^2 = s = m^2 + 2mE.$$

Thus at high energies where $E \gg m$ the energy available in the centre of mass increases only as the square root of the particle energy E, with much of the total energy going to increase of the velocity of the complete centre-of-mass system (cms). In order to obtain the very high energies in the cms necessary, for instance, to make very heavy particles like the W and Z, the energy for a *fixed-target* machine thus becomes very great. For two particles of equal mass and equal and opposite momentum, however, the centre-of-mass frame is the same as the laboratory frame and the energy available is simply

$2E$. Thus for two 50 GeV particles colliding head-on we have 100 GeV available in the centre of mass, whereas to achieve this result in a fixed-target collision would require an accelerated proton to have an energy ~5000 GeV.

Practical limits on attainable magnetic fields (presently up to ~5 T with superconducting magnets) and on ring radius have led to colliding-beam machines as the favoured way to attain the highest energies. For particles of opposite electric charge, such as electrons and positrons or protons and antiprotons, both beams can be accelerated as bunches circulating in opposite directions in the same vacuum chamber and colliding at the intersection positions where experiments are placed. For particles of the same charge, separate but intersecting rings are necessary.

In order to achieve an adequate rate of interactions the number of incident particles and the target density in a fixed-target machine must be sufficiently high. The number of interactions is approximately (for a 'thin' target)

$$N_I = N_P \cdot N_T \cdot n \cdot \sigma$$

N_I = no. of interactions/second
N_P = no. of incident particles/pulse
N_T = no. of target particles/unit area
σ = interaction cross-section
n = no. of pulses/second

$$N_T = \frac{N_A}{A} \cdot \rho \cdot t \cdot N$$

N_A = Avogadro's number
A = atomic weight
ρ = target density
t = target thickness
N = no. of target particles/atom.

We are often interested in processes with very small cross-sections ~few nanobarns (10^{-33} cm^2). A typical fixed-target experiment using a 1 m-long liquid-hydrogen target bombarded with 10^7 particles per pulse every 10 seconds will yield ~4×10^{-4} interactions per second for each nanobarn of cross-section with $N_P \cdot N_T \cdot n \sim 4 \times 10^{31}$. The full circulating beam ~10^{13} particles per pulse will yield ~40 interactions s^{-1} nb^{-1}, but such fluxes are seldom usable in experiments.

For two colliding beams the reaction rate is customarily written in terms of the 'luminosity' L. Thus the number of interactions per unit time is

$$N_I = L\sigma.$$