Abstracts

Chapter 1: The discovery of the atomic nucleus
This chapter deals with the early years of nuclear physics, starting with Henri Becquerel's first observation of radioactivity until the discovery of the atomic nucleus by Ernest Rutherford. The derivation of Rutherford's formula for α scattering off a point-like spin-0 nucleus is given as an introduction to the concepts of cross section and natural units.

Chapter 2: The nuclear radius
The structure of the nucleus has been studied by scattering point-like projectiles such as energetic electrons and observing the diffraction pattern in electron-nucleus scattering, from which the nuclear radius can be determined. Models for the nuclear density distribution are described. Shifts in the binding energies of muons captured in atomic orbits can also be measured. The electromagnetic structure of the nucleon has been studied with electron-proton scattering which involves both charge and magnetic moment interactions.

Chapter 3: Nuclear masses
The periodic table of elements, the abundance of elements in nature and mass spectroscopy are presented. Two important models to calculate the nuclear binding energy are discussed in detail. The Fermi gas model takes the Pauli exclusion principle for spin-$\frac{1}{2}$ fermions into account. The short range of the nuclear force and the incompressibility of nuclear matter are comparable to those of water. Hence the nuclear binding energy can be calculated with the liquid droplet model to also predict that iron is the most stable element.

Chapter 4: Radioactive decay
The basic concepts of radioactive decay are introduced, such as the mean lifetime and the partial width of a radioactive nucleus or unstable particle. The decay law is applied to radioactive decay chains. The experimental methods to measure the lifetime are discussed. The partial and total widths are introduced and their relation to the decay branching ratio and the lifetime is discussed.

Chapter 5: Nuclear stability
After a survey of the main radioactive decay modes we discuss the selection rules and lifetimes for γ-decay. The continuous β-decay spectrum is presented for isotopes with odd or even number of neutrons or protons, and double β-decay is introduced. There are four α-decay series. The derivation of the mean lifetime for α-decay is given in terms of the tunnel effect. The americium-beryllium radioactive source of neutrons is presented. Induced fission is described, together with the working principle of nuclear reactors. Radiation dosimetry is also briefly discussed.

Chapter 6: The nuclear shell model
We go one step further in nuclear physics and introduce the shell model which describes how the nucleon spins and angular momenta contribute to the nuclear spin. The shell model reproduces the observed "magic" sequence of proton and neutron numbers for

which the nuclear binding is strongest. The nuclear spin is obtained from the atomic hyperfine splitting induced by the interaction between nuclear and electronic spins. The shape of a deformed nucleus (oblate or prolate) is determined by measuring its electric quadrupole moment.

Chapter 7: Elementary particles
This overview on the Standard Model of particle physics introduces the fundamental constituents of matter and their interactions through the three basic forces. The strong, electromagnetic and weak forces are mediated by the exchange of gauge bosons, while the Higgs boson endows particles with mass. The fundamental particles are confined in hadrons, such as the proton and the pion. The conservation of baryon and lepton numbers is introduced. Typical lifetimes and cross sections are given. Feynman diagrams conveniently depict the interactions and couplings between particles. Hypothetical physics beyond the Standard Model is briefly discussed.

Chapter 8: Relativistic kinematics
The mathematical tools described here are needed in the following chapters. The Lorentz transformation between inertial systems is described and illustrated with the neutral and charged pion decays. We derive the transformation of the energy from the laboratory into the center-of-mass reference frame and show that very high energies can only be achieved with colliding beams. The invariant mass and the proper time are defined. In the last section we introduce the concept of rapidity used at high energy colliders.

Chapter 9: Accelerators and detectors
The experimental tools described here are needed in the following chapters. After describing the various types of accelerators we describe the CERN facilities that provide proton, electron, antiproton and heavy ion beams. The basics of charged particle and photon detection are explained, with emphasis on practical formulas needed to design detectors. The working principles of detectors are explained which track, identify and measure the momenta of charged particles and photons.

Chapter 10: The quark model
The quarks and antiquarks are assembled to build the observed hadrons. The discovery of the prominent ones is reviewed. The properties of the hadron multiplets made of the light u, d, and s quarks are discussed. We describe the discovery of the c and b quarks and elaborate on the spectrum of bound heavy quark-antiquark pairs, and discuss properties of the strong binding force. The colour degree of freedom and its experimental evidence are introduced. The discovery of the t quark in high energy collisions is described.

Chapter 11: Conservation laws
Symmetries lead to conservation laws and global phase invariance which play a crucial role in particle physics. Parity P, charge conjugation C and time reversal T are introduced, which are symmetries of the strong interaction. The transversality of the photon is derived and applied to the decay of the neutral pion and to determine the relative parity

between fermion and antifermion. The quest for the electric dipole moment of the neutron and for CPT violating asymmetries between matter and antimatter are discussed.

Chapter 12: Hadronic interactions
We deal with hadronic reactions and decays and take this opportunity to introduce the concept of phase space. The two-body phase space, the differential cross section for two-body reactions and the partial widths of two-body decays are derived. Dalitz plots are introduced for three-body processes and are illustrated with data from several reactions. The concept of isospin conservation and charge independence in strong interactions is developed and applied to nucleon-nucleon and pion-nucleon scattering.

Chapter 13: Weak interactions
We deal with the weak interaction and its selection rules in nuclear and particle physics. The discovery of the neutron and a measurement of its lifetime are described. The various classes of β-decays are classified in terms of strength and the energy spectrum of the electron is computed for the strongest ones. The weak coupling constants are introduced and partial decay widths derived. The discovery of parity violation in nuclear β-decay is described as well as pion and muon decays. Methods to measure the muon spin g-factor are discussed.

Chapter14: Neutrinos
This chapter is entirely devoted to neutrinos. The discovery of the three neutrino flavours and mass measurements are described, together with the operation principles of magnetic spectrometers. The fusion mechanism in the sun is explained. The experimental evidence for left-handed neutrinos is described. Double β-decay might reveal whether neutrinos are of the Dirac or Majorana type. The observation of neutrino oscillation is reviewed. The formalism for three-neutrino oscillation is developed and the influence of their interaction with matter is discussed.

Chapter 15: The Dirac equation
The mathematical tools developed here are needed to deal with the Standard Model in the following chapters. The relativistic Dirac equation is introduced and the associated matrix formalism reviewed that will be needed to calculate first order transition amplitudes in scattering and decays. The concepts of handedness and chirality are discussed. One of the main consequences of the Dirac equation was the existence of antimatter. The discovery of the positron and of the antiproton is described.

Chapter 16: The electroweak interaction
After demonstrating experimentally the left-handed structure of β-decay we introduce the weak isospin and the observation of neutral currents with neutrino beams. The absence of flavour changing neutral currents is explained by postulating the existence of the charm quark. The quark mixing matrix is introduced. We then illustrate local gauge invariance in electromagnetism with the experimental evidence for the vanishing photon mass. A model is described for the symmetry breaking leading to massive gauge bosons in weak

interactions. We construct the Glashow-Weinberg-Salam model which unifies the electromagnetic and weak interactions and predicts the masses of the gauge bosons.

Chapter 17: Applications of the standard model

The formalism developed in the previous two chapters is applied to deep-inelastic electron-deuterium scattering data, from which the weak mixing angle can be derived. The discovery of the gauge bosons at CERN's proton-antiproton collider is described. Their widths are calculated and compared with data. The discovery of the Higgs boson is reviewed, together with some of its properties already measured at the LHC. Measurements on neutrino-electron scattering also access the weak mixing angle. We use this opportunity to introduce deep inelastic neutrino scattering and investigate the inner structure of the nucleon revealed through the weak interaction.

Chapter 18: Deep inelastic electron-proton scattering

The inner structure of the nucleon is investigated with the electromagnetic interaction by using deep inelastic electron-nucleon scattering. The Rosenbluth formula introduced in the first chapter is derived and applied to electron-quark scattering. The inner structure of the nucleon is compatible with that observed with neutrinos. The proton and neutron are composed of spin-$\frac{1}{2}$ point-like constituents with fractional charges. Gluons carry about 50% of the nucleon mass.

Chapter 19: The $K^0 - \overline{K}^0$ system

We deal with the fascinating quantum mechanical oscillation between the two neutral kaons. The discovery of the short-lived and long-lived components and measurements of their lifetimes are described. The tiny mass difference between the two states is obtained by measuring the oscillation frequency. The regeneration of the short-lived component in an absorber is explained. The observation of CP violation and its origin in oscillation and decay are described. Matter can be distinguished from animatter by measuring asymmetries in the semileptonic decays of the neutral kaons. An experiment reporting the violation of time reversal invariance is described.

Chapter 20: The $B^0 - \overline{B}^0$ system

This last chapter deals with flavour oscillations in the neutral B systems ($b\overline{d}$ and $b\overline{s}$) observed recently at electron-positron and high energy colliders. More details are given on the quark mixing matrix and the associated unitarity triangles. The formulas for oscillations are derived and the measurement principles at asymmetric colliders explained. The formalism of CP violation is developed and the large CP violating effect observed in the $b\overline{d}$ system is presented. Its origin and a measurement of one of the angles of the unitary triangle are described.