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Introduction

Particle physics is the study of the properties of subatomic particles and of the interactions that occur among them. This book is concerned with the experimental aspects of the subject, including the characteristics of various detectors and considerations in the design of experiments. This introductory chapter begins with a description of the particles and interactions studied in particle physics. Next we briefly review some important material from relativistic kinematics and scattering theory that will be used later in the book. Then we give a brief preview of the various aspects of particle physics experiments, before discussing each topic in greater detail in subsequent chapters. Finally, we give a short discussion of some of the tasks involved in analyzing the data from an experiment.

1.1 Particle physics

Particle physics is the branch of science concerned with the ultimate constituents of matter and the fundamental interactions that occur among them. The subject is also known as high energy physics or elementary particle physics. Experiments over the last 40 years have revealed whole families of short-lived particles that can be created from the energy released in the high energy collisions of ordinary particles, such as electrons or protons. The classification of these particles and the detailed understanding of the manner in which their interactions leads to the observable world has been one of the major scientific achievements of the twentieth century.

The notion that matter is built up from a set of elementary constituents dates back at least 2000 years to the time of the Greek philosophers. The ideas received a more quantitative basis in the early nineteenth century with the molecular hypothesis and the development of chemistry. By the

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end of the century most scientists accepted the idea that matter was constructed from aggregates of atoms. The discovery of radioactivity and the analysis of low energy scattering experiments in the early decades of this century revealed that atoms themselves had a structure. The experiments showed that the positive charge and most of the atomic mass was concentrated in a dense nucleus surrounded by a cloud of electrons.

The discipline of nuclear physics developed in the 1930s, particularly after the discovery of the neutron and the invention of particle accelerators. With sufficient energy the nucleus could be broken apart into its constituent protons and neutrons. At the same time physicists developed new particle detectors, such as Geiger tubes and cloud chambers, to study the properties of cosmic ray particles. The modern discipline of particle physics evolved in the late 1940s from a fusion of high energy nuclear physics and cosmic ray physics.

The chief concerns of this book are a description of the manner in which particles interact in matter, the properties of the detectors used to measure these interactions, and the fundamental considerations involved in designing a particle physics experiment. Two other very important aspects of the subject are data analysis and the interpretation of data using elementary particle theory. A brief survey of data analysis is given in the last section of this chapter. Fortunately, for particle theory an excellent introductory treatment is already available [1].

1.2 Particles and interactions

At the present, as best we can tell, four types of interactions are sufficient to explain all phenomena in physics. The interactions and their approximate relative strengths at distances $\sim 10^{-18}$ cm are [2]

1. strong nuclear, 1;
2. electromagnetic, 10^{-2};
3. weak nuclear, 10^{-5}; and
4. gravitational, 10^{-39}.

The gravitational force controls the interactions between massive bodies separated by large distances. However, the gravitational force between particles, where a typical mass is 10^{-27} kg, is so feeble that it does not appear to have a significant effect on elementary particle interactions. Thus, for particles the electromagnetic force dominates for distances down to 10^{-13} cm, where the nuclear forces begin to become important. The strong nuclear force is responsible for the binding of particles into nuclei, while the weak nuclear force is responsible for processes such as nuclear beta decay.

The electromagnetic interactions of particles can be calculated using the theory of quantum electrodynamics (QED). This is probably the most successful theory in all of physics and is capable of making extremely precise predictions. Recently a model has been developed that successfully treats the weak and electromagnetic interactions as the low energy manifestations of the breakdown of a unified electroweak interaction. A prediction of this model, which has recently been verified, is the existence of massive particles known as the $W^{\pm}$ and Z gauge bosons. Other grand unified models have been developed that assert that the electroweak and strong nuclear interactions have resulted from the breakdown of a single interaction. One consequence of these models is that the proton should have a small but finite probability of decaying.

Hundreds of new particles have been discovered in the study of high energy interactions. Many ways have been devised to group them into families with similar characteristics. One way to classify particles is by the type of interactions in which they participate. The leptons are particles that are not affected by the strong interaction. The electron, muon, and neutrino are examples of leptons. At present leptons appear to be truly elementary particles. They have no measured internal structure and are sometimes referred to as pointlike particles.

Particles that are affected by the strong interaction are known as hadrons. There are two main classes of hadrons. The baryons are hadrons with a half-integral value for the spin quantum number. The mesons, on the other hand, are hadrons with integral values of the spin quantum number. The pions are examples of mesons.

The lowest lying (least massive) baryons are the proton and the neutron. These two common constituents of nuclei are often referred to collectively as nucleons. The hyperons are unstable baryons that decay via the weak interaction and have a nonzero value for the internal quantum number known as strangeness. The lowest lying hyperon is the Λ particle. The decay chain of all unstable baryons ends with a final state containing a proton.

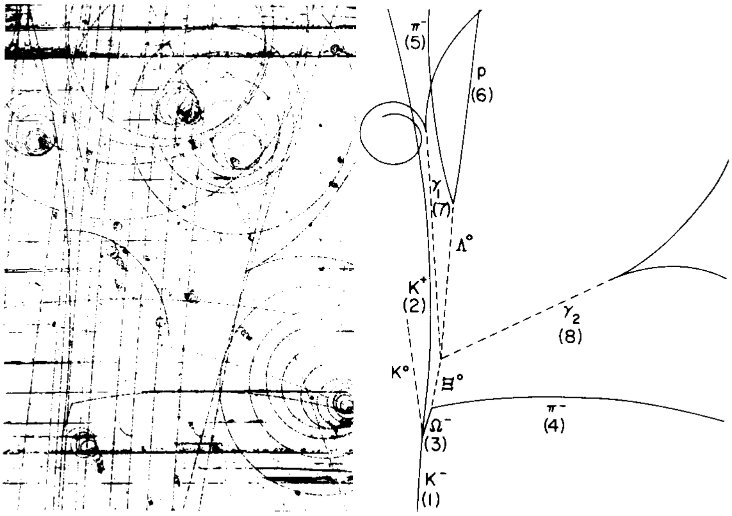
One of the early theories of the strong interaction, known as SU(3), predicted a relation among the baryon masses. Using this relation and the masses of the then-known baryons, it was possible to predict the existence of a hyperon with three units of strangeness, called the Ω^-. Figure 1.1 shows the historic bubble chamber photograph that proved the existence of the Ω^- hyperon. Its discovery marked an important milestone in our understanding of elementary particles.

The largest group of hadrons are referred to as resonances. These particles can decay via the strong interaction and thus have lifetimes on the order of 10^{-23} sec. Even traveling at the speed of light, this lifetime is much too short for the particles to travel a measurable distance in the lab. Thus, the properties of the resonances must be inferred from the properties of their longer-lived decay products.

Unlike the leptons, the hadrons are believed to have an internal structure. In the currently favored model of strong interactions (quantum chromodynamics, or QCD) hadrons are built up from pointlike spin $\frac{1}{2}$ objects known as quarks. The quarks are unlike other particles in several respects. The magnitude of their charge is one-third or two-thirds of the electron's charge, and free quarks have never been observed in scattering experiments. In the QCD model a quark attempting to leave the interior of a hadron would cause new quark–antiquark pairs to be created. The quarks and antiquarks would then recombine in such a way as to form new hadrons. Very energetic quarks would form a narrow spray of hadrons known as a jet.

Another remarkable feature of nature is the existence of antimatter. For every particle there is an antiparticle with the same mass and spin, but with opposite values for the charge and some of the internal quantum

Figure 1.1 The first bubble chamber photograph of the decay of an Ω^- hyperon. The picture was taken by a group headed by N. Samios at the 80-in. chamber at Brookhaven National Laboratory in 1964. (Courtesy of Brookhaven National Laboratory.)



numbers. A familiar example is the positron, which is the antiparticle of the electron.

Besides the leptons and the hadrons there is a third group of particles known as the gauge bosons. These integral spin particles are responsible for transmitting the basic interactions. The most well known example is the photon, which mediates the electromagnetic interaction. The weak interaction is thought to be mediated by the $W^{\pm}$ and Z vector bosons. According to QCD, the carriers of the strong interaction are massless particles known as gluons, while the gravitational interaction is thought to be mediated by spin 2 objects known as gravitons.

1.3 Relativistic kinematics

The mechanics of particle interactions must obey the laws of special relativity [3]. The velocity **v** of a particle is frequently specified in terms of the dimensionless quantity

$$\boldsymbol{\beta} = \mathbf{v}/c \tag{1.1}$$

where c is the speed of light in vacuum. The momentum and energy of the particle are given by

$$\mathbf{p} = mc\gamma\boldsymbol{\beta} \tag{1.2}$$

and

$$E = mc^2\gamma \tag{1.3}$$

where m is the mass of the particle measured in the reference frame in which it is at rest, and the auxiliary function γ is defined as

$$\gamma = (1 - \beta^2)^{-1/2} \tag{1.4}$$

The high energy behavior of various phenomena is frequently plotted as a function of γ. In these cases it may be convenient to rewrite the velocity and momentum in the form

$$\beta = [(\gamma^2 - 1)/\gamma^2]^{1/2} \tag{1.5}$$

and

$$p = mc(\gamma^2 - 1)^{1/2} \tag{1.6}$$

It is customary to measure energies in multiples of the electron volt (eV), typically MeV or GeV, at high energies. Then from Eq. 1.2 the unit of momentum is MeV/c, and from Eq. 1.3 the unit for mass is MeV/c^2. The constant c is frequently set to 1 to simplify relativistic calculations.

The energy and momentum of a particle in a second coordinate system moving with constant velocity $-\boldsymbol{\beta}_0$ with respect to the original (primed)

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system is governed by the Lorentz transformation equations [3]

$$\begin{aligned}\mathbf{p} &= \mathbf{p}' + \boldsymbol{\beta}_0\gamma\left(\frac{\gamma}{\gamma+1}\boldsymbol{\beta}_0 \cdot \mathbf{p}' + \frac{E'}{c}\right)\\ \frac{E}{c} &= \gamma\left(\frac{E'}{c} + \boldsymbol{\beta}_0 \cdot \mathbf{p}'\right)\end{aligned} \tag{1.7}$$

For the special case when the transformation takes place along the z axis, the transformation equations simplify to

$$\begin{aligned}p_x &= p'_x\\ p_y &= p'_y\\ p_z &= \gamma\left(p'_z + \beta_0\frac{E'}{c}\right)\\ \frac{E}{c} &= \gamma\left(\frac{E'}{c} + \beta_0 p'_z\right)\end{aligned} \tag{1.8}$$

The quantities $(E/c,\ \mathbf{p})$ can be interpreted as the components of a vector in a 4-dimensional space and are referred to as the energy–momentum 4-vector. The first quantity in the parentheses is denoted the 0th component.

Another important 4-vector is $(ct,\ \mathbf{x})$, where $\mathbf{x}$ is the position and t is time. The components of all 4-vectors obey transformation laws analogous to Eq. 1.8. An important consequence of the Lorentz transformation applied to this 4-vector is time dilation. Suppose that an interval of time τ elapses in a coordinate system where some particle is at rest. Time intervals in this frame are referred to as proper times. The corresponding time interval in a coordinate system moving with velocity $-\beta$ with respect to the particle (or equivalently in the frame where the particle has velocity $+\beta$) is

$$t = \gamma\tau \tag{1.9}$$

Thus, time intervals measured in a frame where the particle is moving are increased by the factor γ over the proper time intervals.

We shall identify 4-vectors by using a tilde, for example, $\tilde{a}$. The scalar product of two 4-vectors $\tilde{a}$ and $\tilde{b}$ is defined in the metric we are using as

$$\tilde{a} \cdot \tilde{b} = a_0 b_0 - \mathbf{a} \cdot \mathbf{b} \tag{1.10}$$

It follows immediately that the square of a 4-vector is

$$\tilde{a} \cdot \tilde{a} = a_0^2 - |\mathbf{a}|^2$$

As an example, consider the decay of an unstable particle into two particles with 4-momenta $\tilde{p}_1$ and $\tilde{p}_2$. The effective mass M of the system is defined to be

$$\begin{aligned} M^2 &= (\tilde{p}_1 + \tilde{p}_2)^2 \\ &= \tilde{p}_1^2 + \tilde{p}_2^2 + 2\tilde{p}_1 \cdot \tilde{p}_2 \\ &= m_1^2 + m_2^2 + 2(E_1E_2 - p_1 p_2 \cos\theta) \end{aligned} \tag{1.11}$$

where θ is the angle between the 3-vectors $\mathbf{p}_1$ and $\mathbf{p}_2$. The effective mass is a powerful tool for studying the properties of short-lived particles.

1.4 Summary of particle properties

Each of the particles mentioned previously has a unique set of properties that distinguish the particle and describe how it is affected by the fundamental interactions. These properties include

1. charge,
2. mass,
3. spin,
4. magnetic moment,
5. lifetime, and
6. branching ratios.

In addition, a full description of a particle must include the values for a set of internal quantum numbers, such as baryon number and strangeness [4]. The values of the internal quantum numbers determine which particles may be produced together in various reactions and how unstable particles can decay.

If we choose as a time interval the mean lifetime of a particle in its rest frame, then the particle lifetime in the LAB frame is generally longer due to the time dilation effect. The mean distance traveled in the LAB from production to decay is

$$\lambda_D = (p/mc)c\tau \tag{1.12}$$

Note that this grows linearly with the particle's momentum.

Suppose that N_0 unstable particles with mean decay length λ_D have been created at $x = 0$. The number of particle decays occurring in some small interval dx around the distance x is proportional to the number of particles at x and to the fractional size of the interval. Thus,

$$dN(x) = -N(x)\, dx/\lambda_D$$

from which it follows that

$$N(x) = N_0 \exp(-x/\lambda_D) \tag{1.13}$$

Thus, the decay lengths of unstable particles have an exponential distribution with a slope that depends on λ_D and hence on the $c\tau$ value of the particle. This can be useful sometimes in determining the identity of a decay sample.

We summarize in Table 1.1 the properties of the particles most com-

Table 1.1. *Properties of quasistable particles*

		Mass (MeV/c^2)	Spin ($\hbar$)	Magnetic moment	$c\tau$ (cm)	Major decay modes	Branching ratio (%)
Gauge bosons							
γ	photon	0	1	0	stable	—	—
Leptons							
ν_e	e neutrino	~0	$\frac{1}{2}$	0	stable	—	—
ν_μ	μ neutrino	~0	$\frac{1}{2}$	0	stable	—	—
e^-	electron	0.5110	$\frac{1}{2}$	$1.001\mu_B$	stable	—	—
μ^-	muon	105.7	$\frac{1}{2}$	$1.001\ (e\hbar/2m_\mu c)$	6.59×10^4	$e\bar{\nu}\nu$	100
Mesons							
π^0	pion	135.0	0	0	2.5×10^{-6}	2γ	98.8
$\pi^\pm$	pion	139.6	0	0	780.4	$\mu\nu$	100
$K^\pm$	kaon	493.7	0	0	370.9	$\mu\nu$	63.5
						$\pi^\pm\pi^0$	21.2
						$\pi^\pm\pi^+\pi^-$	5.6
K^0_S	K short	497.7	0	0	2.675	$\pi^+\pi^-$	68.6
						$2\pi^0$	31.4
K^0_L	K long	497.7	0	0	1554	$\pi e\nu$	38.7
						$\pi\mu\nu$	27.1
						$3\pi^0$	21.5
						$\pi^+\pi^-\pi^0$	12.4

Baryons							
p	proton	938.3	$\frac{1}{2}$	$2.793\mu_N$	stable	—	—
n	neutron	939.6	$\frac{1}{2}$	$-1.913\mu_N$	2.7×10^{13}	$pe^-\bar{\nu}$	100
Λ	lambda	1115.5	$\frac{1}{2}$	$-0.613\mu_N$	7.89	$p\pi^-$	64.2
						$n\pi^0$	35.8
Σ^+	sigma	1189.4	$\frac{1}{2}$	$2.379\mu_N$	2.40	$p\pi^0$	51.6
						$n\pi^+$	48.4
Σ^0	sigma	1192.5	$\frac{1}{2}$		1.7×10^{-9}	$\Lambda\gamma$	100
Σ^-	sigma	1197.3	$\frac{1}{2}$	$-1.10\mu_N$	4.44	$n\pi^-$	100
Ξ^0	cascade	1314.9	$\frac{1}{2}$	$-1.25\mu_N$	8.69	$\Lambda\pi^0$	100
Ξ^-	cascade	1321.3	$\frac{1}{2}$	$-0.69\mu_N$	4.92	$\Lambda\pi^-$	100
Ω^-	omega	1672.5	$\frac{3}{2}$		2.46	ΛK^-	68.6
						$\Xi^0\pi^-$	23.4
						$\Xi^-\pi^0$	8.0

Source: Particle Data Group, Rev. Mod. Phys. 56: S1, 1984; L. Pondrom, in G. Bunce (ed.), *High Energy Spin Physics — 1982,* AIP Conf. Proc. No. 95, 1983, p. 45.

monly encountered in particle physics. Listed are most particles that are not known to decay or that decay via the weak interaction and have a $c\tau$ value greater than 1 cm. We will refer to this group as the quasistable particles. We have also included the neutral members of the pion and sigma families, which decay by electromagnetic processes and thus have a much shorter lifetime than the other listed particles. Table 1.1 does not include the antiparticles, which have identical values for the listed properties, except for the charge and magnetic moment, which are opposite.

The mass of the photon is believed to be identically zero. Although the neutrino masses are very small, there is no compelling theoretical reason why they should be exactly zero. The spins of all particles are found to be multiples of $\hbar/2$, where $\hbar$ is Planck's constant divided by 2π. All neutrinos discovered to date have been "left handed." This means that the neutrino's spin is directed in the opposite direction from its momentum. Antineutrinos are right handed. The photon is the only particle in Table 1.1 to have a spin of 1, while the Ω^- is the only particle with spin $\frac{3}{2}$.

Particles with nonzero spin and nonzero mass have a magnetic moment associated with them. The natural unit for measuring magnetic moments is [5]

$$\mu = e\hbar/2Mc \tag{1.14}$$

where M is the particle's mass. When M equals the electron mass, μ is known as the Bohr magneton. When M is the proton mass, μ is called the nuclear magneton. Table 1.1 shows that the electron magnetic moment is $\sim m_p/m_e$ times larger than the baryon moments.

Apart from the free neutron, the longest lived of the unstable particles is the muon, with a $c\tau = 6.59 \times 10^4$ cm or $\tau = 2.2$ μs. Also listed are the major decay modes of the decaying particles and the corresponding fractions (branching ratios) for each mode.

1.5 Scattering

Most of our knowledge about the interactions between particles has come from the analysis of scattering experiments. Consider the scattering of a beam particle (b) off a target particle (t) in the laboratory (LAB) frame, as shown in Fig. 1.2a. In high energy scattering a particle or group of particles is frequently found to be produced with a momentum comparable to p_b and with a direction close to the beam direction. Such a particle is referred to as the forward or scattered particle (1). In contrast, a second particle or group of particles is frequently found with lower momentum and at a larger angle with respect to the beam direction. This particle is