6 Hadronic Processes

Shocks or reconnection sites in GRBs also accelerate protons and other ions besides leptons (electrons and positrons). These non-thermal ions would interact with photon fields, magnetic fields, and other baryons (protons or neutrons) to generate neutrinos and photons through strong, weak, and electromagnetic interactions. This chapter summarizes these physical processes. In §6.1, the brief history of particle physics is reviewed and the main ingredients of the standard model are summarized. Several hadronic processes, including proton (ion) synchrotron radiation and inverse Compton, $p\gamma$, and *pp/pn interactions* are discussed in §6.2.

6.1 Standard Model of Particle Physics

6.1.1 Brief History

The field of elementary *particle physics* was born in 1897, when the electron was discovered. Over the years new particles have been continuously discovered, and new theories developed. One may list the milestones in the development of the particle physics as follows:[1]

- In 1897, J. J. Thomson discovered the *electron*, marking the birth of elementary particle physics;
- In 1908, Rutherford discovered the *nucleus*, and named the lightest nucleus as the *proton*;
- In 1914, Bohr theorized the structure of hydrogen atoms;
- In 1932, Chadwick discovered the *neutron*;
- In 1900–1905, Planck and Einstein theorized and discovered the *photon* through the photoelectric effect;
- In 1947, Powell and colleagues discovered the *pions* and *muons*, with pions being *mesons* theorized earlier by Yukawa in 1934;
- The *anti-particles* were theorized by Dirac in 1927, and the *positron* (anti-particle of the electron) was discovered by Anderson in 1932;

[1] Since this is not a book on particle physics, we do not refer to original papers. Interested readers can find details in books of particle physics, for example, *Introduction to Elementary Particles* by David Griffiths (Griffiths, 2008).

Table 6.1 Elementary particles

Particle	First generation	Second generation	Third generation	$Q/\|e\|$
Quarks	$u(\bar{u})$ (up)	$c(\bar{c})$ (charm)	$t(\bar{t})$ (top)	$+\frac{2}{3}[-\frac{2}{3}]$
(anti-quarks)	$d(\bar{d})$ (down)	$s(\bar{s})$ (strange)	$b(\bar{b})$ (bottom)	$-\frac{1}{3}[+\frac{1}{3}]$
Leptons	$e[e^{+}]$	$\mu[\mu^{+}]$	$\tau[\tau^{+}]$	$-1[+1]$
(anti-leptons)	$\nu_e[\bar{\nu}_e]$	$\nu_\mu[\bar{\nu}_\mu]$	$\nu_\tau[\bar{\nu}_\tau]$	0[0]

- In 1930, mysterious β-decay experiments drove Pauli and Fermi to theorize the *neutrinos*, which were decisively proven experimentally in the early 1950s;
- *Strange particles* (e.g. $K^{\pm,0}$, Λ, $\Sigma^{\pm,0}$, $\Xi^{\pm,0}$, ..., partially made of *strange quarks* $s/\bar{s}$) were discovered in the period 1947–1960;
- The quark model was proposed in 1964 by Gell-Mann and Zweig;
- A heavy meson J/ψ was announced by Ting/Richter in November 1974, which later led to the discovery of the *charm quarks* $(c/\bar{c})$;
- Starting from 1975, evidence of the third generation of quarks, *bottom quarks* $(b/\bar{b})$ and *top quarks* $(t/\bar{t})$, was collected;
- In 1995, the top quark was robustly discovered;
- The theory of *intermediate vector bosons* has been developed since the work of Yukawa in 1934, but *W bosons* (mediators of weak interaction) were discovered in 1983;
- The *standard model of particle physics* was established in 1978; it includes 12 leptons, 12 quarks (each has 3 flavors), 12 mediators, and at least 1 *Higgs boson*;
- In 2013, the European Organization for Nuclear Research (CERN) collaboration announced the discovery of the Higgs boson.

6.1.2 Elementary Particles (Fermions)

According to the *standard model* of elementary particles, all matter is fundamentally composed of *quarks* and *leptons*. These are *fermions*, which have *half-integer spin* (1/2 spin multiplied by an odd number), and obey the Pauli exclusion principle and *Fermi–Dirac statistics*. There are three generations of particles (Table 6.1 and Fig. 6.1). For each generation, there is one quark (u, c, or t for the first, second, or third generations, respectively) that carries a positive charge of $Q = +2/3$, and another quark (d, s, or b for the first, second, or third generations, respectively) that carries a negative charge of $Q = -1/3$. Here charges are in units of the absolute value of the electron charge. Each quark has a corresponding anti-quark which carries the opposite charge of the original quark but is otherwise the same. For each quark or anti-quark, there are three different flavors (red, green, and blue, vs. anti-red, anti-green, and anti-blue) distinguished by their *colors*.[2]

[2] The color charge is similar to the electric charge. It denotes the fundamental unit of charges participating in the *strong interaction* rather than the electromagnetic interaction. It does not have any connection with visual colors.

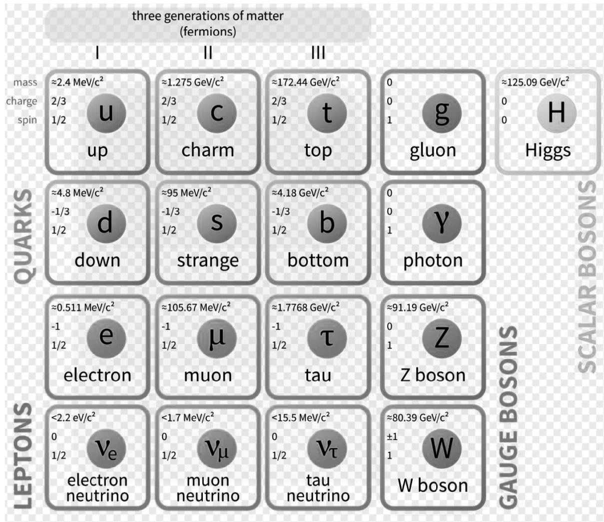

Figure 6.1 A chart of fundamental particles and their properties in the standard model. Reproduced from https://en.wikipedia.org/wiki/Standard_Model with permission.

The first-generation particles (some of which are the ingredients of the normal matter we experience in daily life) include up and down quarks (u, d), electrons e, and electron neutrinos ν_e (which are produced via weak interactions), and their anti-particles ($\bar{u}$, $\bar{d}$, e^+, and $\bar{\nu}_e$). An atom is composed of one (for hydrogen) or more electron(s) and a nucleus. A nucleus is composed of one or more proton(s) plus a certain number of neutron(s). Each proton and neutron is composed of three first-generation quarks: for example, the *proton* is $p = uud$, with a total charge $Q = 2/3 + 2/3 - 1/3 = +1$, and the *neutron* is $n = udd$, with a total charge $Q = 2/3 - 1/3 - 1/3 = 0$.

In the leptonic world, *electrons/muons/taus* are negatively charged. They interact with positively charged baryons and make atoms and molecules. Each has an anti-particle that is positively charged. Another type of lepton is the *neutrino*, with six different species ($\nu_e/\bar{\nu}_e$, $\nu_\mu/\bar{\nu}_\mu$, $\nu_\tau/\bar{\nu}_\tau$). They are generated in weak interactions to conserve *lepton number*. For example, in the β-decay interaction $n \rightarrow p + e + \bar{\nu}_e$, a neutron ($Q = 0$) decays to a proton ($Q = +1$) and an electron ($Q = -1$), so that electric charge is conserved. However, generating one electron makes the leptonic number +1. One needs to generate another lepton $\bar{\nu}_e$ with lepton number -1 to conserve the lepton number.

6.1.3 Boson Mediators and Fundamental Interactions

There are four fundamental interactions in nature: strong, electromagnetic, weak, and gravitational interactions. The relative strengths of the four interactions are

$$\text{Strong} : \text{EM} : \text{Weak} : \text{Gravity} \sim 1 : 10^{-2} : 10^{-13} - 10^{-7} : 10^{-39}.$$

Notice that the weak interaction strength is energy dependent, and varies over a wide range.

Table 6.2 Four fundamental interactions and boson mediators

Interaction	Boson mediator	Spin	Rest mass	Charge
Strong	(gluons, G)	1	0?	0
Electromagnetic	photons, γ)	1	0	0
Weak	$W^{\pm}$, Z_0	1	80.4 GeV/c^2, 91.2 GeV/c^2	± 1, 0
Gravity	(graviton, g)	2	0?	0

Bosons carry an *integer spin* (0 or whole numbers), and follow *Bose–Einstein statistics*. At least for strong, EM, and weak interactions, the interactions can be understood as the exchange of *boson mediators*. A well-known example is that EM interactions are processes that exchange *photons*. Weak interactions are well described by hadrons and leptons of all kinds exchanging $W^{\pm}$ *or* Z^0 *bosons*, while strong interactions can be described by color charges exchanging gauge boson mediators called *gluons*. Gravity may be also described by a gauge theory. If so, the gravitational interaction may be understood as mass "charges" exchanging an imaginary boson called the *graviton*.

Mass is the effective "charge" of gravitational interaction. The origin of the masses of fundamental particles is mysterious. According to the standard model of particle physics, there is another elementary boson particle called the Higgs, which is the smallest possible excitation of the *Higgs field*, an imaginary field permeating everywhere in the universe. Different particles have different interaction strengths with this Higgs field, so that they attain different masses. The Higgs boson was discovered in 2013, and it has a mass of $\sim$125 GeV$/c^2$.

Table 6.2 summarizes the four interactions and the properties of the different types of boson mediators. Figure 6.1 is a chart of fundamental particles in the standard model, and Fig. 6.2 is a cartoon picture of the four fundamental interactions.

6.1.4 Hadrons: Baryons and Mesons

Hadrons are sub-atomic particles made of quarks. *Hadrons* include *baryons* (composed of three quarks) and *mesons* (composed of one quark and one anti-quark).

Baryons include the proton ($p = uud$, $m_p = 938.272$ MeV$/c^2$), neutron (udd, $m_n =$ 939.565 MeV$/c^2$), and many *strange particles* that are partially composed of strange quarks[3] (s) such as $\Lambda^0 = uds$, $\Sigma^+ = uus$, $\Sigma^0 = uds$, $\Sigma^- = dds$, $\Xi^0 = uss$, $\Xi^- = dss$, etc.[4]

The above-mentioned baryons typically have spin 1/2. In reality, baryons with spin 3/2 can be also temporarily formed. For example, with u and d quarks, four types of Δ *baryons*,

[3] This is because strange quarks have the third lowest mass/energy, $m_s \approx 95$ MeV$/c^2$ (compared with $m_u \approx$ 2.3 MeV$/c^2$ and $m_d \approx 4.8$ MeV$/c^2$). The other three types of quarks are much heavier: $m_c \approx 1.275$ GeV$/c^2$, $m_b \approx 4.18$ GeV$/c^2$, and $m_t \approx 173.07$ GeV$/c^2$. Baryons with contributions from other quarks must be generated on a much larger energy scale.

[4] Λ^0 and Σ_0 have the same quark content. The difference is their isospin, which is 0 for Λ^0 and 1 for Σ^0.

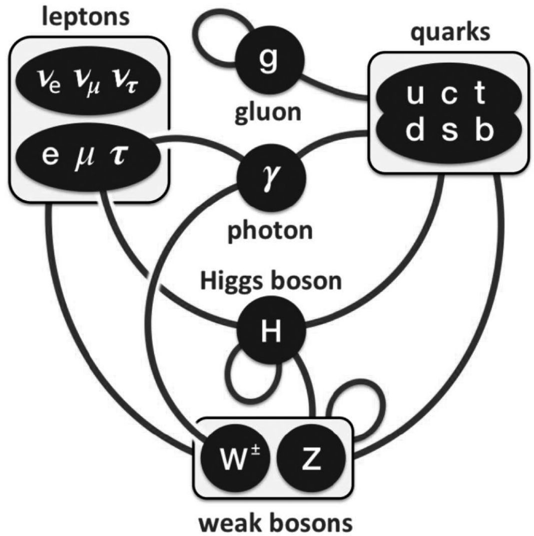

Figure 6.2 A cartoon picture of four fundamental interactions. Charged particles (e^-/e^+, μ^-/μ^+, τ^-/τ^+, quarks, and $W^\pm$) undergo electromagnetic interaction through exchanging photons; all hadrons (made of quarks) and leptons undergo weak interaction through exchanging $W^\pm$ or Z^0 bosons; quarks undergo strong interaction through exchanging gluons; all particles with mass interact with the Higgs to gain their masses. Reproduced from https://en.wikipedia.org/wiki/Standard_Model with permission.

or Δ-*resonances*, can be formed with spin 3/2 instead of 1/2. These are $\Delta^{++} = uuu$, $\Delta^+ = uud$, $\Delta^0 = udd$, and $\Delta^- = ddd$. Δ^+ and Δ^0 are the higher energy equivalent of p and n, respectively, but there is no lower energy equivalent of Δ^{++} and Δ^-, since those states are forbidden by the Pauli exclusion principle. The mass of all Δ baryons is about $m_\Delta \approx 1.232\ \mathrm{GeV}/c^2$. There are also spin 3/2 baryons invoking s quarks, e.g. Σ^*, Ξ^*. Spin 3/2 baryons decay into their lower energy counterparts plus a π meson (pion).

Mesons include pions ($\pi^+ = u\bar{d}$, $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$, $\pi^- = d\bar{u}$, $m_{\pi^\pm} = 139.570$ MeV, $m_{\pi^0} = 134.977$ MeV), kaons ($K^+ = u\bar{s}$, $K^- = s\bar{u}$, $K^0 = d\bar{s}$, $\bar{K}^0 = s\bar{d}$, $m_{K^\pm} = 493.68$ MeV, $m_{K^0} = 497.65$ MeV), etc. Mesons eventually decay into leptons and neutrinos, so that hadron number is *not* conserved.

6.2 Hadronic Processes

6.2.1 Proton Synchrotron and Inverse Compton

As charged particles, protons (more generally ions) can radiate similarly to electrons via synchrotron and inverse Compton mechanisms via EM interactions. All the formulae for electron synchrotron/IC processes apply to protons, except that the electron mass m_e has to be replaced by the proton mass m_p, which is about 1836 times more massive. The radiation power is therefore much lower.

The power is directly related to the "Thomson" cross section. For protons, the cross section is smaller by a factor $(m_e/m_p)^2$ than for electrons, i.e.

$$\sigma_{\mathrm{T},p} = \sigma_{\mathrm{T},e} \left(\frac{m_e}{m_p}\right)^2 \simeq 1.97 \times 10^{-31}\ \mathrm{cm}^2, \tag{6.1}$$

as compared with $\sigma_{\mathrm{T},e} \simeq 6.65 \times 10^{-25}\ \mathrm{cm}^2$. So unless the total energy carried by protons is much larger than the total energy carried by electrons, proton synchrotron and IC emission is much weaker than that of electrons.

6.2.2 Photomeson Interaction: $p\gamma$

Hadronic interactions invoking strong and weak interactions can become important when the energy of a system exceeds the rest masses (also called "chemical potentials" even though they describe hadronic reactions instead of chemical reactions) of various particles (typcially above GeV).

The simplest interaction is called *photomeson interaction*, or *$p\gamma$ interaction*. An energetic proton interacts with a photon with large enough energy and produces pions. A $p\gamma$ interaction most likely proceeds at the "Δ-resonance", when a proton $p(= uud)$ turns into its higher energy equivalent particle $\Delta^+(= uud)$ with spin 3/2, and Δ^+ subsequently decays to mesons and then leptons and neutrinos. The $p\gamma$ interaction cross section is enhanced at the Δ-resonance.

A $p\gamma$ interaction can be written (Exercise 6.1)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n\pi^+ \rightarrow n\mu^+\nu_\mu \rightarrow ne^+\nu_e\bar{\nu}_\mu\nu_\mu, & \text{fraction } 1/3, \\ p\pi^0 \rightarrow p\gamma\gamma, & \text{fraction } 2/3. \end{cases} \tag{6.2}$$

The fractions going to the π^+ and π^0 channels are 1/3 and 2/3, respectively. The π^+ typically carries $\sim 1/5$ of the p energy. Each lepton shares $1/4$ of the π^+ energy, which is $\sim 1/20$ of the p energy.

Following the method discussed in §5.4.1, one can derive the kinematic condition of the Δ-resonance, $p\gamma \rightarrow \Delta^+$, i.e.

$$(E_p + E_\gamma)^2 - (\mathbf{p}_p + \mathbf{p}_\gamma)^2 c^2 = E_{\Delta^+}^2 - \mathbf{p}_{\Delta^+}^2 c^2. \tag{6.3}$$

Noting $\beta_p \simeq 1$, $E_p^2 - \mathbf{p}_p^2 c^2 = m_p^2 c^4$, $E_{\Delta^+}^2 - \mathbf{p}_{\Delta^+}^2 c^2 = m_{\Delta^+}^2 c^4$, and $E_\gamma^2 - \mathbf{p}_\gamma^2 c^2 = 0$, one gets the Δ-*resonance* condition (Exercise 6.2):

$$2E_p E_\gamma (1 - \cos\theta_{p\gamma}) = (m_{\Delta^+}^2 - m_p^2)c^4 = 0.638\ (\mathrm{GeV})^2, \tag{6.4}$$

or

$$E_p E_\gamma = 0.319\ (\mathrm{GeV})^2 (1 - \cos\theta_{p\gamma})^{-1}. \tag{6.5}$$

At the Δ-resonance, the *$p\gamma$ interaction cross section* is

$$\sigma_{p\gamma\rightarrow\Delta'} \simeq 5 \times 10^{-28}\ \mathrm{cm}^2 \simeq 500\ \mu\mathrm{b}, \tag{6.6}$$

where the unit $\mu\mathrm{b} = 10^{-30}\ \mathrm{cm}^2$ is the "micro-barn", and the unit "barn" is defined as $1\ \mathrm{b} = 10^{-24}\ \mathrm{cm}^2$.

The $p\gamma$ interactions can also occur above the Δ-resonance. So the condition for $p\gamma$ interactions should be

$$E_p \cdot E_\gamma \gtrsim 0.16\ (\mathrm{GeV})^2. \tag{6.7}$$

The cross section above the Δ-resonance regime is only a factor of a few smaller, so the contributions from above the Δ-resonance can be substantial. When direct pion production and multiple-pion production channels are considered, on average roughly equal fractions of $p\gamma$ interactions would go to the π^+ and π^0 channels. The channel fractions 1/3 and 2/3 should then be modified to 1/2 and 1/2 in Eq. (6.2).

6.2.3 pp/pn Interactions

At a large enough energy, baryons can interact with other baryons to produce mesons. The simplest cases are *pp and pn interactions*. These interactions may generate different kinds of intermediate mesons, which subsequently decay to leptons and neutrinos.

Some example pp/pn interactions include (Exercise 6.1):

$$\begin{aligned} pp &\to pn\pi^+/K^+ \to pn\mu^+\nu_\mu \to pne^+\nu_e\bar{\nu}_\mu\nu_\mu, \\ pn &\to pp\pi^-/K^- \to pp\mu^-\bar{\nu}_\mu \to ppe^-\bar{\nu}_e\nu_\mu\bar{\nu}_\mu, \\ pn &\to nn\pi^+/K^+ \to nn\mu^+\nu_\mu \to nne^+\nu_e\bar{\nu}_\mu\nu_\mu. \end{aligned} \tag{6.8}$$

Free neutrons would subsequently decay:

$$n \to pe^-\bar{\nu}_e. \tag{6.9}$$

The mean total *cross section for pp* in the TeV–PeV range is

$$\langle\sigma_{pp}\rangle \simeq 6 \times 10^{-26}\ \mathrm{cm}^2, \tag{6.10}$$

which is about 2 orders of magnitude higher than that of the $p\gamma$ process. However, since the number density of photons is usually much higher than that of protons/neutrons in a GRB environment, the $p\gamma$ mechanism is usually the dominant hadronic interaction process. The pp/pn processes can be important in a dense environment, such as in the jet that is still propagating inside the progenitor star of the GRB.

Exercises

6.1 Check the $p\gamma$ and pp interaction equations (Eqs. (6.2) and (6.8)) for electric charge and leptonic number conservations.

6.2 Derive the kinematic condition of $p\gamma$ interactions at the Δ-resonance (Eqs. (6.5) and (6.7)).