CHAPTER 10

Cosmic Radiation and Elementary Particles

Contents

The early workers in nuclear science found that their measuring equipment had a constant background level of radiation which could be eliminated only partially even with the aid of thick shielding walls of iron and lead. It was assumed initially that this radiation had its origin in naturally radioactive elements present in the materials in the laboratory. However, in 1911 Hess carried measuring equipment into the atmosphere with the aid of balloons and learned that this background radiation increased with altitude. Obviously, at least a component of the laboratory background radiation had its origin in some extra-terrestrial source. In recent years, test equipment carried outside of the earth's atmosphere by rockets has given us data which provide a fairly accurate picture of the composition of the radiation that comes to the earth from space.

The investigation of cosmic radiation has had a profound influence on nuclear science. When Chadwick in 1932 discovered the neutron, the picture of matter seemed complete: all matter appeared to be composed of four fundamental particles: protons, neutrons, electrons, and photons. However, through studies of the cosmic radiation Anderson discovered the *positron* (the first *antiparticle*) in the same year. Five years later Anderson and Neddermeyer discovered another new particle with a mass about one-tenth of a proton or about 200 times heavier than the electron. This particle is the *muon*, designated by μ. Since that time a large number of subatomic particles have been discovered.

10.1. Primary cosmic radiation

A rather small fraction of the cosmic radiation consists of electromagnetic radiation and electrons. The former vary in energy from a small percentage of γ-rays to a considerable intensity of X-rays, to visible light and to radiation in the radiofrequency region. The types

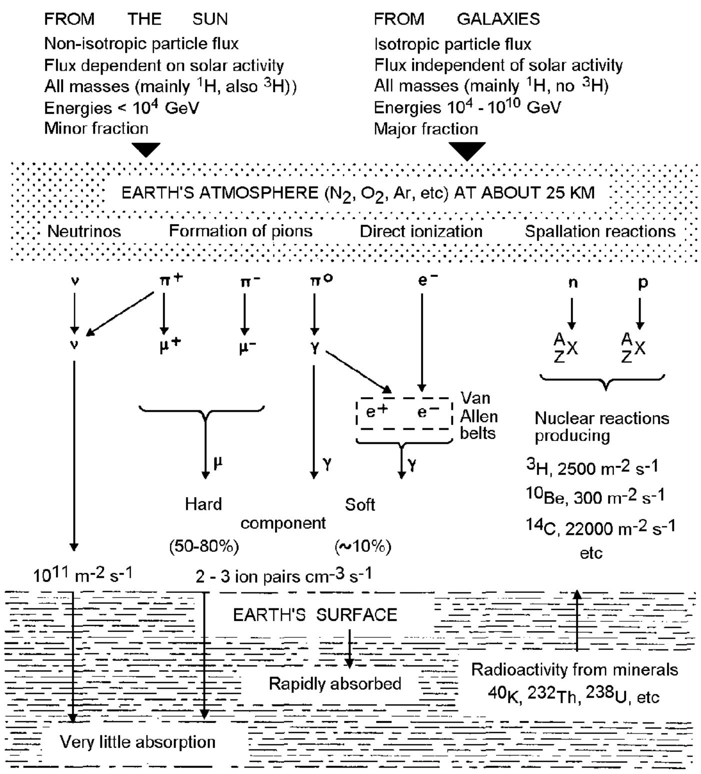


FIG. 10.1. Cosmic radiation consists of atoms and photons which react with the atmosphere leading to the formation of numerous secondary particles, some (but not all) detectable at the earth's surface.

and intensities of this radiation have been of great importance to development of models of the formation and composition of the universe.

The major part of the cosmic radiation is nuclear particles with very high energy: approximately 70% protons, 20% α-particles, 0.7% lithium, beryllium, and boron ions, 1.7% carbon, nitrogen, and oxygen ions, the residual 0.6% ions of $Z > 10$. These ions are bare nuclei prior to interaction since their kinetic energies exceed the binding energies of all of the orbital electrons.

The cosmic particle radiation can be divided by energy into two major groups (Fig. 10.1). One group has energies mainly below 1 GeV and consists primarily of protons. This group originates mainly from the sun. Its intensity varies in relation to solar eruptions since at the time of such an eruption a large amount of solar material, primarily hydrogen, is ejected into space.

The second group has energies up to 10^{10} GeV, although the intensity of the particles decreases with increasing energy, following the relation $N(E) \propto E^{-1.6}$, where $N(E)$ is the number of particles with energies in excess of E. Thus particles of 10^3 GeV have an intensity of about 10^{11} higher than particles of 10^{10} GeV. Within this high energy group

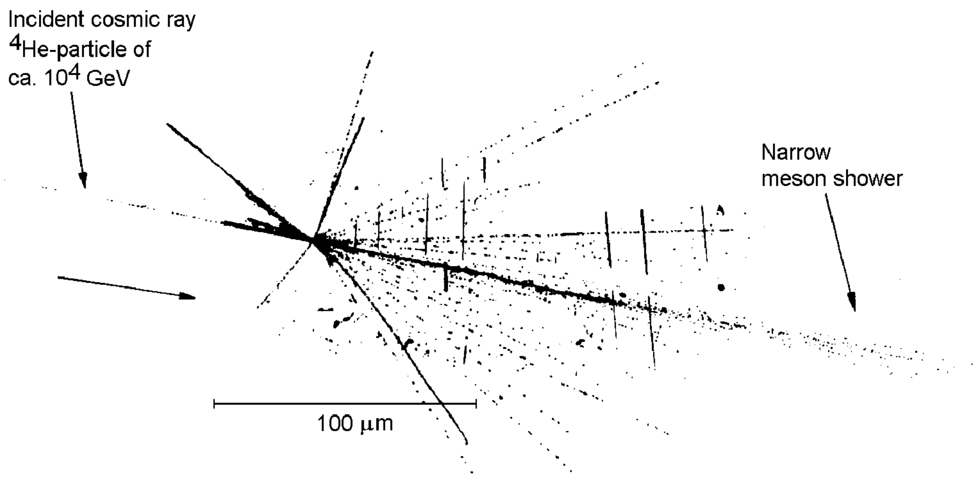


FIG. 10.2. Secondary particles produced by a 10^4 GeV helium atom in a photographic emulsion.

the particles at the lower end of the energy spectrum are assumed to originate from sources within our galaxy (the Milky Way), while the particles of the higher energy end are assumed to come from sources outside of our galaxy. Different hypotheses, which for the most part are untested, suggest that the particles come from astronomical radio sources, exploding super novae, or colliding galaxies, etc. At least a portion of this radiation is a residue of the processes involved in the original formation of the universe. It is assumed that the high energy particles obtain their tremendous kinetic energies through acceleration in the magnetic field of galactic objects (synchrotron acceleration, Ch. 13).

When the primary cosmic particles enter the earth's atmosphere, they collide with the matter of the atmosphere and are annihilated. In this annihilation process a large number of new particles are formed whose total kinetic energy is less than that of the original primary radiation but whose total rest mass is larger than that of the primary particle. A 10^4 GeV cosmic helium ion may produce a shower of 50 - 100 new highly ionizing particles, cf. Fig. 10.2. The main reaction products are particles which are known as pions, designated π.

Figure 10.3 shows the effect of high energy cosmic rays hitting the helmets of Apollo 12 astronauts. It is probable that the cosmic ray intensity will put a limit to how long man can endure in outer space: it has been calculated that in a journey to the planet Mars about 0.1% of the cerebral cortex will be destroyed. The annihilation process occurs to such an extent that below an altitude of approximately 25 km above the earth the number of primary cosmic particles has been reduced to quite a small fraction of the original intensity.

The discovery of π-mesons (or *pions*) was reported by Powell and Occhialini in 1948 after they had analyzed tracks in photographic emulsions placed for some months on a mountain top to get a high yield of cosmic ray interactions. Pions are produced in large amounts in all high energy ($\geq$ 400 MeV) nuclear reactions. In 1935 Yukawa suggested that the nucleons in a nuclide were held together through the exchange of a hypothetical particle, which we now recognize as the pion, just as hydrogen atoms in H_2 are held together through the exchange of an electron:

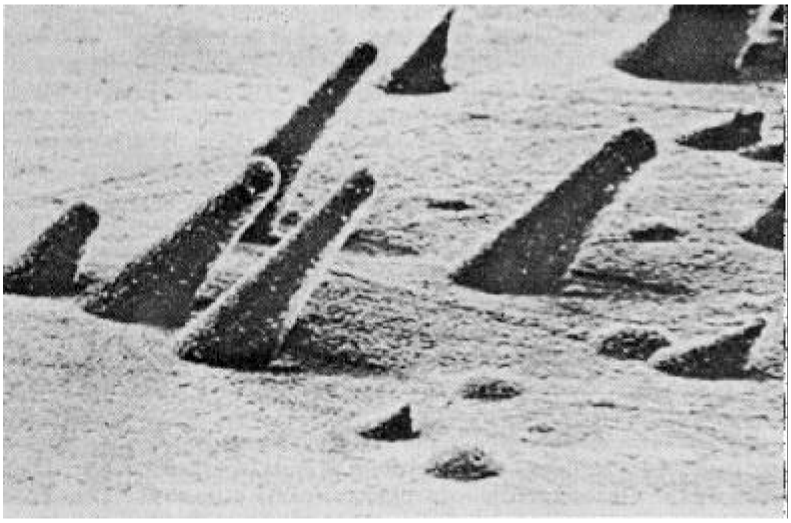


FIG. 10.3. Holes in helmets of Apollo 12 astronauts caused by high energy cosmic rays. The holes have been made visible in a microscope by etching. (From *New Scientist*, April 22, 1973.)

$$p \leftrightarrow n + \pi^{+}; \quad n \leftrightarrow p + \pi^{-}; \quad p \overset{\pi^{o}}{\leftrightarrow} p; \quad n \overset{\pi^{o}}{\leftrightarrow} n;$$

Pions are the particles of *strong interaction*. Since the pion rest mass is 0.147 u, the energy to produce a pion is at least 137 MeV (in practice, in order to conserve momentum it exceeds 400 MeV, cf. (12.4)). The pions are unstable in free form.

10.2. Secondary reactions in the earth's atmosphere

Few of the pions formed in the annihilation process reach the earth's surface. They undergo radioactive decay (life-time about 10^{-6} s) to muons and neutrinos, or they collide with other particles in the atmosphere and are annihilated. The muons have properties similar to the electron, but are unstable, decaying with a life-time of about 2×10^{-6} s to electrons and neutrinos. The collision reactions of the pions result in the formation of a large number of other particles such as electrons, neutrons, protons, and photons. Some of the electrons so formed are captured in a thick zone around the earth known as the inner van Allen belt.

The main part (50 - 80%) of the cosmic radiation which reaches the earth's surface consists of high energy muons. Muons have much less tendency to react with atomic nuclei than pions and, therefore, can penetrate the atmosphere and the solid material of the earth relatively easily. The remaining part, which is the lower energy component of the cosmic radiation that strikes the earth, consists of photons, electrons, and positrons. At sea level this part of the cosmic radiation gives rise to approximately 2 - 3 ion pairs s^{-1} cm^{-3} of air. It is this component of the cosmic radiation that gives rise to the cosmic ray portion of the natural background that is measured by nuclear detection devices in laboratories.[1] Some of the cosmic radiation interacts to make atmospheric radioactivity which is principally the nuclides ^{3}H and ^{14}C. This important radioactivity is treated in chapter 5.

10.3. Elementary particles and forces of nature

Cosmic radiation contains a large number of the kind of particles which used to be called *elementary particles*. We have so far mentioned protons, electrons, neutrons, positrons, pions, muons, photons, and neutrinos. These particles can be sorted into different classes according to their quantum properties, Table 10.1. We have here added one more particle, the *K-meson* (or *kaon*), because of its similarity to the π-meson (pion). Kaons and pions appear in cosmic rays and high-energy nuclear reactions, cf. Fig. 10.4. As we shall see later, the baryons and mesons of Table 10.1 are not elementary in a strict sense. However, to avoid confusion we will refer to the particles in Table 10.1 as elementary in the appropriate nuclear reactions (cf. later Table 10.2).

This group of elementary particles began to be considerably expanded about 1947 when physicists discovered the first of the so-called "strange" particles in cloud chamber pictures of cosmic rays. These new elementary particles were called strange because they lived almost a million million times longer than scientists had any reason to expect at that time. The population of elementary particles has literally exploded since then, as physicists have built larger and larger particle accelerators, by which it is possible to impart sufficient kinetic energy to protons so that interaction with nuclides transform a large fraction of the kinetic energy into matter. With the present limit in the 2000 GeV range (Ch. 13) it is possible to produce particles with a mass of up to ~2000 proton masses, and hundreds of new "strange" particles have been observed. Figure 10.4 is a typical picture of a reaction observed in a liquid hydrogen bubble chamber at an accelerator center.

This has created a scientific area called *elementary particle physics*. It is quite different from nuclear physics, which is concerned with composite nuclei only. A principal objective of elementary particle physics has been to group the particles together according to their properties to obtain a meaningful pattern which would describe all particles as parts of some few fundamental building blocks of nature. One step in this direction is to study how the elementary particles interact with each other, i.e. what kind of forces are involved.

Considering what an immense and incredible diverse assembly the universe is – from the cosmos to man and microbes – it is remarkable that scientists have been able to discover only four basic forces which govern the attraction and repulsion of all physical objects of nature. Let us consider these *forces of nature* in a qualitative way.

The first and weakest force of nature is that of *gravity*. This is the force that causes all objects to attract one another and is responsible for the attraction of the planets to the sun in the solar system and of the solar system to the rest of the galaxy. It is also the force that holds us to the earth. It seems paradoxical that the weakest attraction of the four basic forces of nature is the force that is responsible for the assembly of the largest objects on the greatest scale. In modern physics it is believed that all forces are carried by

[1] The remainder of the natural background comes from naturally occurring radioactive elements in the laboratory materials and surrounding building.

"something" which either can be described as a wave or as a particle (see §10.4). The carrier of the gravitational force is the *graviton*. Experimenters have tried to detect gravitational waves, but so far the results are inconclusive.

A second force of nature with which we are all relatively familiar is that of the *electromagnetic force*. The electromagnetic force is expressed by Coulomb's law and is responsible for the attraction and repulsion of charged bodies. Just as the gravitational force holds the planets in their orbits about the sun and explains the stability of the planetary systems, so the electromagnetic force explains the attraction between electrons in atoms, atoms in molecules, and ions in crystals. It is the force that holds the atomic world together. It is approximately 10^{36} times stronger than the gravitational force. If gravity is the force underlying the laws of astronomy, electromagnetism is the force underlying the laws of chemistry and biology. The carrier of the electromagnetic force is the *photon*.

The third major force in nature has been discussed briefly in chapter 3 where we called it the nuclear force. This force is also known as the *strong interaction force* and is the one responsible for holding nuclear particles together. Undoubtedly it is the strongest in nature but operates only over the very short distance of approximately 10^{-14} m. Whereas electromagnetism binds electrons to nuclei in atoms with an energy corresponding to a few electron volts, the strong interaction force holds nucleons together in nuclei with energies corresponding to millions of electron volts. The carrier of the strong interaction force is now recognized to be the *gluon*; we will return to this point in §10.7.

The fourth force is the one which is involved in the radioactive β-decay of atoms and is known as the *weak interaction force*. Like the strong interaction, this weak interaction force operates over extremely short distances and is the force that is involved in the interaction of very light particles known as *leptons* (electrons, muons, and neutrinos) with each other and as well as their interaction with mesons, baryons, and nuclei. One characteristic of leptons is that they seem to be quite immune to the strong interaction force. The strong nuclear force is approximately 10^2 times greater than the Coulombic force, while the weak interaction force is smaller than the strong attraction by a factor of approximately 10^{13}. The carrier of the weak interaction force is still a matter of considerable research; we will return to this point later.

The strong interaction manifests itself in its ability to react in very short times. For example, for a particle which passes an atomic nucleus of about 10^{-15} m in diameter with a velocity of approximately 10^8 m s^{-1} (i.e. with a kinetic energy of ~ 50 MeV for a proton and 0.03 MeV for an electron), the time of strong interaction is about 10^{-23} s. This is about the time of rotation of the atomic nucleus. The weak interaction force requires a much longer reaction time and explains why leptons such as electrons and photons do not react with atomic nuclei but do react with the electron cloud of the atom which has a diameter on the order of 10^{-10} m. There is sufficient time in passing this larger diameter for the weak interaction force to be effective.

Scientists have long doubted that all the particles produced with masses between the electron and the proton (loosely referred to as *mesons*, i.e. "intermediate"), and with masses greater than the proton (referred to as *baryons*, "heavy") really are "elementary". It was proposed that they have a substructure or constitute excited states of each other. Are they waves or particles since they serve as carriers of force. At this point it is important to understand what is meant by "particle" in nuclear physics.

10.4. Waves and particles

It is daily experience that moving bodies have a kinetic energy which involves a mass and a velocity. Less familiar is the concept of Planck (1900) in which light moves in wave packets of energy:

$$E = \mathbf{h}\nu \tag{10.1}$$

Here ν is the frequency of light with wavelength λ

$$\mathbf{c} = \nu\lambda \tag{10.2}$$

and **h** the Planck constant, 6.63×10^{-34} J s.

Einstein in the theory of the photoelectric effect, and Compton in the theory of the scattering of photons (Ch. 6), showed that photons have not only a discrete energy, but also a discrete momentum (cf. §4.2)

$$p_\nu = E_\nu / \mathbf{c} \tag{10.3}$$

Photons seem to collide with other particles as if they have a real mass and velocity as in the classical mechanical expression for momentum: $p = mv$ (4.3). If we put $v = \mathbf{c}$ and equate with (10.3) we obtain a relativistic mass of the photon as

$$m_\nu = E_\nu / \mathbf{c}^2 \tag{10.4}$$

This is the mass-energy relation of Einstein, eqn. (4.23).

There are many examples of mass properties of photons. To the two mentioned above we may add the solar pressure (i.e. photons from the sun which push atoms away from the sun and into space), which has played a significant part in the formation of our planetary system, and measurements showing that photons are attracted by large masses through the gravitational force. Thus we see the evidence for the statement in the beginning that all elementary particles must have relativistic mass, even if the rest mass is zero.

It is reasonable to assume, as de Broglie did in 1924, that since photons can behave as moving particles moving particles may show wave properties. From the previous equation, we can devise that the wavelength of such *matter waves* is

$$\lambda = \mathbf{h}/mv \tag{10.5}$$

This relation is of importance in explaining nuclear reactions, and has led to practical consequences in the use of electron diffraction and in the development of electron microscopy.

The wave and particle properties of matter complement each other (the *complementarity principle*; N. Bohr, 1928). Throughout this book we use models based on wave properties and sometimes on particle properties, depending on which more directly explain the particular phenomenon under discussion.

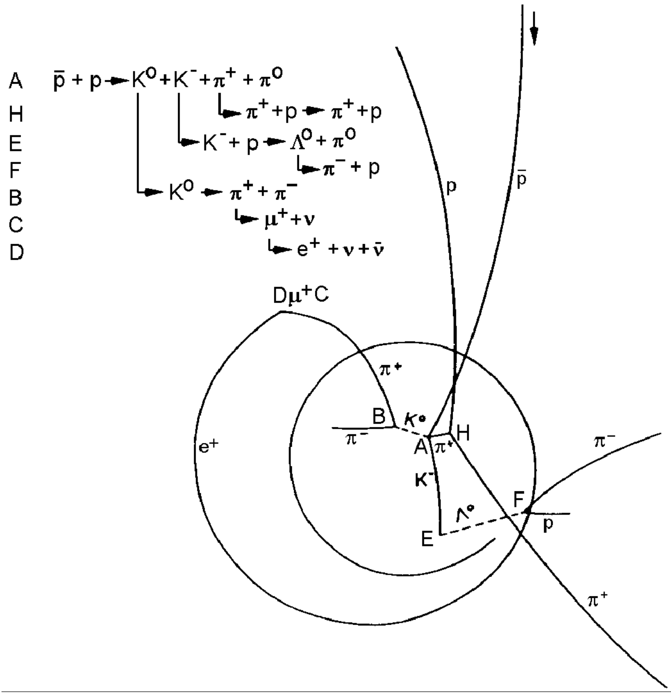


FIG. 10.4. The reaction products of an annihilated antiproton as seen in the CERN liquid hydrogen bubble chamber. (*Annual report 1961*, CERN).

10.5. Formation and properties of some elementary particles

The track formed by a moving particle in the magnetic field of a bubble chamber is characterized by its width, length and curvature. From a kinematic analyses of the tracks it is possible to determine the mass and charge of the particles involved. Further, as seen at points A–B and E–F in Figure 10.4, the interruption of a track can indicate an uncharged particle, as they do not form visible tracks. From a knowledge of the tracks formed by known particles, "strange tracks" can be analyzed to identify new particles in bubble chamber pictures and to assign their properties. All these properties have to be quantized, so new quantum states have been introduced, like baryon number, statistics, symmetry, parity, hypercharge, isospin, strangeness, color, etc. in addition to spin. It is found that many of the particles observed are sensitive to only one or two of the forces of nature (§10.3), which serves as an additional aid in their classification. Nevertheless, the array of properties assigned to the hundreds of "elementary particles" which have been discovered resembles the situation when 40 radioelements were reported between uranium and lead, as described in chapter 1.

Before we proceed to the order which has evolved from this picture we must describe some of the concepts used to define these particles. It has been practical to divide the particles according to their masses: (i) *baryons* are the "heavy" ones (protons, neutrons,

TABLE 10.1. *Common "elementary particles" in nuclide reactions*

Class	Name	Symbol	Rest mass (MeV)	Rest mass (u)	Life time (s); decay mode
Baryons† (nucleons): S, A-yes, P+, s=½	neutron	n	939.6	1.008665	889; → $p+e^-+\bar{\nu}_e$
	proton	p	938.3	1.007276	stable
Mesons: S, A-no, P-, s=0	K-meson (kaon)	K^+, K^-	493.7	0.530009	≈ 10^{-8}; $K^+\rightarrow\mu^++\nu_\mu$, $\pi^++\pi^0$, etc.††
	π-meson (pion)	π^+,π^0,π^-	139.6†††	0.149867	≈ 10^{-8}; $\pi^-\rightarrow\mu^-+\bar{\nu}_\mu$††
Leptons††††: W, A-no, P-no, s=½	muon	μ^-	105.6	0.113366	2×10^6; → $e^-+\nu_e+\nu_\mu$
	electron	e^-	0.5110	0.0005486	stable
	neutrino	ν_e, ν_μ	0?	0?	stable
Photon: W, A-no, P-no, s=1	photon, gamma	hν γ	0	0	stable

S=Strong interaction; W=Weak interaction; A-yes=baryon number conserved; P± =conservation of parity and parity sign; P-no=parity not conserved; s=spin quantum number. All these particles have their anti-particles, except for the photon and mesons, which are their own anti-particles.
†Baryons include the nucleons (n and p), hyperons (also called "strange baryons", with m_0 1116 for Λ^0 to 1673 MeV for Ω^-, and lifetimes ≈ 10^{-10} s), and all nuclei. †† K^- and π^+ decay into corresponding anti-particles in a similar way. ††† π^0 rest mass is 135.0 MeV. †††† See also Table 10.2.

hyperons and nuclei), (ii) *leptons* are the "light"ones (the electron, the neutrino and the muon); (iii) *mesons* have "intermediate" masses; these include the π-meson, the K-meson, etc. The baryons and the mesons have also been considered as *hadrons*, "hard" or "strong" particles as they take part in the strong nuclear force. Such properties were used to develop a table of elementary particles, Table 10.1.

All the particles in Table 10.1 have *spin*[1]. Quantum mechanical calculations and experimental observations have shown that each particle has a fixed spin energy which is determined by the *spin quantum number s* (s = ½ for leptons and nucleons). Particles of non-integral spin are called *fermions* because they obey the statistical rules devised by Fermi and Dirac, which state that two such particles cannot exist in the same closed system (nucleus or electron shell) having all quantum numbers the same (referred to as *the Pauli principle*). Fermions can be created and destroyed only in conjunction with an anti-particle of the same class. For example if an electron is emitted in β-decay it must be accompanied by the creation of an anti-neutrino. Conversely, if a positron – which is an anti-electron – is emitted in the β-decay, it is accompanied by the creation of a neutrino.

Fermions are the *building blocks* of nature. There is another group of "particles" called *bosons*, to which the photon and mesons belong. The bosons are the *carriers of forces*. When two fermions interact they continually emit and absorb bosons. The bosons have an even spin (0, 1, etc), they do not obey the Pauli principle, and they do not require the formation of anti-particles in their reactions.

All the particles mentioned have their *anti-particles* (designated by a bar above the particle symbol), except the photon and the mesons, who are their own antiparticles. We may think about *antimatter* as consisting of antiprotons and antineutrons in an antinucleus surrounded by antielectrons (i.e. positrons). Superficially, there would be no way to distinguish such antimatter from our matter (sometimes called *koino matter*). It has been proposed that the universe is made up of matter and antimatter as a requirement of the principle of *symmetry*. In that case some galaxies, which perhaps can be observed, should be made up of antimatter. When such antimatter galaxies (or material expelled from them) collide with koino matter galaxies, both types of matter are annihilated and tremendous amounts of energy released.

In order to reach the goal of a comprehensive yet simple theory of the composition of all matter, the properties of the neutrinos and the quark theory must be considered.

10.6. The neutrino

The neutrino plays an essential role in the models of elementary particles and in the theory of the formation and development of the universe. The existence of the neutrino was predicted by Pauli in 1927 but it was not proven until 1956 when Reines and Cowan detected them in experiments at the Savannah River (USA) nuclear reactor. Since neutrinos are emitted in the β-decays following fission, nuclear reactors are the most intense neutrino sources on earth. The detector in the discovery experiments consisted of a scintillating solution containing cadmium surrounded by photomultipliers to observe the scintillations which occurred as a consequence of the following reactions:

[1] Spin is an intrinsic property of elementary particles, sometimes thought of as a rotation.

$$\bar{\nu} + {}^{1}H \rightarrow n(fast) + e^{+}$$

$$e^{+} + e^{-} \rightarrow 2\gamma_1$$

$$n\ (thermal) + {}^{113}Cd \rightarrow {}^{114}Cd + \gamma_2$$

The γ's emitted are of different energy; the γ_1 is 0.51 MeV, but γ_2 much higher. There is also a time lag between the γ's because of the time required for the fast neutrons to be slowed down to thermal energy. The detection system allowed a delay time to ascertain a relation between γ_1 and γ_2 (delayed coincidence arrangement). When the reactor was on, 0.2 cpm were observed, while it was practically zero a short time after the reactor had been turned off thereby demonstrating the formation of neutrinos during reactor operation.

Since the 1950s it has become clear that neutrinos exist as several types. In β^- decay an "anti-neutrino" is formed, while a "neutrino" is emitted in β^+ decay. Both these neutrinos are now referred to as *electron neutrinos*, $\bar{\nu}_e$ and ν_e, respectively.

The pions formed in nuclear particle reactions are unstable and decay with a life-time of 3×10^{-8} s into a *muon* and a μ neutrino:

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

The mass of the muon is 0.1135 u (105.7 MeV). The muon is also unstable and has a life-time of 2×10^{-6} s; it decays into an electron, an e neutrino and a μ anti-neutrino:

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_e + \bar{\nu}_{\mu}$$

In 1979 Reines, Sobel and Pasierb made new neutrino measurements with a detector containing heavy water so that the neutrinos would either split the ^{2}H atom into a proton and a neutron, or convert it into two neutrons. Both reactions would only be sensitive to the ν_e; by measuring the neutron yield, the number of ν_e's could be calculated and compared to the known ν_e flux from the reactor. The two different decays could be followed by measuring the time delays between neutron capture and γ emission (see Ch. 8). The ratio of these two measurements was only 0.43 ± 0.17, i.e. half of that expected. The explanation proposed was that the two types of neutrinos interchange, or oscillate between the ν_e and the ν_{μ} states, thus only 50% of the expected number would be observed.

Since then a third kind of neutrino, the tau neutrino, ν_{τ}, has been postulated. Thus it is now believed that here are three types of neutrinos: (i) the electron neutrino, ν_e, which accompanies β decay, (ii) the muon neutrino, ν_{μ}, which accompanies pion decay, and (iii) the tau neutrino, ν_{τ}, which is only involved in very high energy nuclear reactions. The three kinds of neutrinos all have their anti particles. They have spin, no charge ("quark charge zero"), but possibly a small mass. They react very weakly with matter, the reaction cross section (cf. Ch. 16) being of the order of 10^{-43} cm^2, depending on neutrino energy (cross section increases as the square of the energy).

Various attempts have been made to determine the neutrino rest mass, for example by measuring the decay of soft beta emitters like tritium, or double β decay as $^{82}Se \rightarrow {}^{82}Kr$. The present limit for the mass is set as < 18 eV. The three kinds of neutrinos are in a steady exchange, ν_e to ν_μ to ν_τ etc, i.e. they oscillate between the various states. Since most neutrino detectors are sensitive to only the ν_e, detectors have registered only 1/3 of the expected number of solar neutrinos. There has been time for the fusion neutrinos to equilibrate as it takes the neutrinos several hundred thousand years to diffuse from the solar core. The flux of neutrinos is copious at the earth's surface, about 10^{11} s^{-1} m^{-2}.

A large international collaboration ("Gallex") is setting up a neutrino detection station in a rock facility in the Mont Blanc. Some ^{71}Ga atoms in 30 tons of gallium metal is expected to react with solar neutrinos to form ^{71}Ge ($t_{½}$ 11.4 d) which is to be converted to the gaseous hydride, GeH_4, and counted in a proportional detector. About 1 atom of ^{71}Ge formed per day is expected.

In 1987 a large underground neutrino detector near Fairport, Ohio, in a few seconds registered a sudden burst of 8 events. Taking into account that the normal background rate is about 2 events per day, which is believed to be caused by neutrinos produced in the sun's fusion reactions, this was an exceptional occurrence not only because of the event rate but also because the source was located outside our solar system and was a bright new supernova, SN1987A, appearing in the Large Magellanic Cloud. This was a lucky observation because the previous "near by" supernova was observed in 1604 by Johannes Kepler. The neutrino observation preceded the optical confirmation and it has been calculated that about 10^{58} neutrinos were released in the explosion.

One of the most significant effects of the neutrino mass relates to the mass of the Universe. According to the Big Bang Theory of the origin of the Universe (see Ch. 17) there should be as many neutrinos as there are photons in the microwave background radiation remaining from the Big Bang, or about 100 million times as many neutrinos as other particles. If these neutrinos have a mass $>$ 10 eV they would constitute the dominant mass in the Universe. This would mean that there would be enough mass in our Universe for gravitational attraction eventually to overcome the present expansion, and consequently we would have a closed, or possibly pulsating universe, instead of a universe which will continue to expand infinitely.

10.7. Quarks and the Standard Model

All particles are considered to be possible states in which matter can condense. These states are related to the force that forms them. In this sense the solar system is a state of gravitational force, an atom is a state of electromagnetic force, and a nucleon is a state of the strong interaction force. A particle can represent a positive energy state of a system while its analog antiparticle represents the negative state of the same system. Some regular patterns have been formed for the elementary particles which indicate that many of them in fact may only be exited states of the same particle, differing in quantum numbers such as spin (or "hyper charge"); in fact hundreds of such states are now known. For example, the neutron has a mass corresponding to 939 MeV and spin 1/2, and there is a baryon with mass 1688 MeV and spin 5/2 with all its other properties like those of the neutron: the heavier particle must be a highly excited state of the neutron.

Though many attempts have been made to unify all particles into one simple theory, this has not succeeded until recently when the quark theory was developed. To explain this we have to go back somewhat in time.

The spin of a charged particle leads to the formation of a *magnetic moment* directed along the axis of rotation. It was discovered in the late 1930s that the magnetic moment of the proton spin ($M_p = 1.41 \times 10^{-26}$ J T^{-1}) is about 1/700 of the electron spin ($M_e = 9.27 \times 10^{-24}$ J T^{-1}), although theory predicts a ratio of 1/1836 (= M_p/M_e; see §6.2). Also, the neutron has a negative magnetic moment ($M_n = -0.97 \times 10^{-26}$ J T^{-1}). The only explanation scientists could offer for this deviation was that the proton is not an evenly charged rotating sphere, but contains some "internal electrical currents", and also the neutron must contain some internal charges, which balance each other to appear uncharged. Thus, it was doubtful that protons and neutrons were truly elementary.

Around 1960 Hofstadter and co-workers at the large Stanford Linear Accelerator Center (SLAC, Ch. 13) proved that both the proton and the neutron have an uneven internal nuclear charge density. This came from studies of the scattering of high energy electrons (~ 1 GeV) against protons and neutrons. It was suggested by Gell-Mann that this could mean that the proton and neutron were composed of smaller particles with fractional charge and mass which he called *quarks*. The intense search for such particles (leading to the discovery of many new "elementary" particles) culminated in the late 1970s in experiments in which still higher electron energies (4 - 21 GeV) were used and the energy and scattering angle of the electrons measured. These revealed that the nucleons had a hard internal scattering center with charges 1/3 that of the electron and masses 1/3 that of the nucleon. These particles, quarks, are held together by *gluons*, which are carriers of the nuclear force.

These results have led to the *Standard Model* of the building blocks of matter. According to this model all matter on Earth – and likely in the Universe – (and including our own bodies) consists of > 99% of quarks with associated gluons. The rest is electrons.

Elementary particles come in only two kinds: quarks and leptons. There are only six quarks and six leptons, see Table 10.2. The leptons are the electron, e, the muon, μ, and the *tauon* (tau particle), τ, and their respective neutrinos. The quarks and leptons are grouped together in *three families* (or generations) of two quarks and two leptons each. This makes 12 elementary building blocks, or 24 if one counts their anti particles; Table 10.2 only refers to our matter (i.e. koino matter). The leptons and quarks all have different properties and names, sometimes also referred to as *colors*. The physical theory relating these particles to each other is therefore named *Quantum Chromo Dynamics* (QCD).

All matter in nature belongs to the first family, which consist of two leptons, the electron and electron-neutrino, and the up-quark and the down-quark. The proton is made up of 2 up- and 1 down-quark, giving it a charge of +1 and mass 1, while the neutron is made up of 1 up- and 2 down-quarks giving it a charge of 0 and mass of 1:

$$n = u^{+2/3} + d^{-1/3} + d^{-1/3}$$

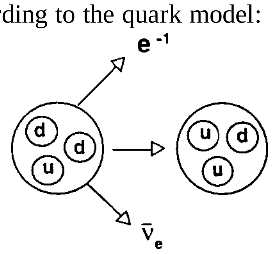
$$p = u^{+2/3} + u^{+2/3} + d^{-1/3}$$

Table 10.2. *Classification and properties of elementary particles according to the Standard Model.*

Basic nature	Family	Name and symbol	Forces	Charge involved	Rest mass
Basic building blocks of nature	I	Leptons: electron, e	EM,W	±1	0.511 MeV
		e-neutrino, ν_e	W	0	< 18 eV
		Quarks: up	EM,W,S	$+2/3$	$1/3$ u
		down	EM,W,S	$-1/3$	$1/3$ u
Formed in Big-Bang, cosmic rays and high-energy accelerators	II	Leptons: muon, μ	EM,W	±1	105.6 MeV
		μ-neutrino, ν_μ	W	0	0?
		Quarks: charm	EM,W,S		
		strange	EM,W,S		
	III	Leptons: tau, τ	EM,W	±1	
		τ-neutrino, ν_τ	W	0	0?
		Quarks: top (or truth)	EM,W,S		
		bottom (or beauty)	EM,W,S		
Carriers of force: *bosons*; s = 0, 1, .. Pauli princ. not valid		Photon, γ	EM	0	0
		Pion, π	S	0, ±1	137 MeV
		Gluon	EM,W,S		
		W^+, W^-, Z^0	W		

EM = electromagnetic force, W = weak interaction, S = strong interaction.

where u and d represent the up and down quarks, respectively. The neutron decay (§4.4.5) can be written according to the quark model:



$$d^{-1/3} \longrightarrow u^{+2/3} + e^{-1} + \bar{\nu}_e$$

i.e. a d-quark is transformed into a u-quark with the simultaneous emission of an electron and an anti-neutrino.

In all reactions the lepton number must be conserved: the total number of leptons minus anti-leptons on each side of a decay or reaction process must be the same. A similar law is valid for the quarks. In the reaction above several quantum numbers are obeyed: (i) the charge is the same on both side, (ii) the lepton number is zero on both sides (none = electron minus anti-neutrino), (iii) the quark number is conserved. The elementary reactions in Figure 10.4 can all be described in terms of lepton and quark transformations.

All hadrons contain 3 quarks, while all mesons are made up of 2 quarks or antiquarks. The quarks move around in the nucleus, which makes it difficult to observe these minute particles: if an atom had the size of the earth, the size of the quark would be about half a

TABLE 10.3. *Forces of nature and their exchange particles*

Force	Relative strength	Range	Exchange particle	Spin	Rest mass
1. The nuclear force (the strong force)	1	10^{-14} m	gluon	1	0
2. The electromagnetic force	10^{-2}	long	photon	1	0
3. The weak force	10^{-13}	very short	Z^0 W^+, W^-	1 1	91.2 GeV 79.9 GeV
4. Gravitation	10^{-38}	very long	graviton	2	0

cm. The quarks can not appear free but must appear together in groups of two or three.

The second family in Table 10.2 contains the "heavy electron", the muon and the muon neutrino, and the charm and the strange quarks. The third family contains the tau particle, the tau electron, and the two quarks referred to as top (or truth) and bottom (or beauty). These quarks can only be produced in high energy particle reactions.

By combination of quarks and leptons, the true elementary particles of nature, it is possible to systematize all known particles. The success of this theory, founded on good experimental evidence, has been so great that its name, the Standard Model of matter, is justified.

The force between two particles arises from the exchange of a "mediator" that carries the force at a finite speed: one of the particles emits the mediator, the other absorbs it. The mediator propagates through space and, briefly, is not lodged with either particle. These mediators have the same properties as the elementary particles – mass, electric charge, spin – so physicists often call them particles as well, even though their role in nature is quite different from that of the elementary particles. The mediators are the mortar that binds the particle building blocks together.

Three kinds of mediators – or exchange forces, as we have called them – are known in the nuclear world: photons which are involved in the electromagnetic force, gluons which are the mediators of the strong nuclear force, and the weak force mediators, which underlies the radioactive decay. We know now a great deal about the photons and the gluons, but little about the weak force. The weak force mediators are the W^+, W^- and Z^0 "particles". A high energy electron is supposed to be able to emit a Z^0, and then a positron can absorb the electron: the particles annihilate each other, leaving the Z^0 momentarily free. Afterwards the Z^0 must decay back into a pair of elementary particles, such as an electron and positron, or a quark and an antiquark. Z^0 particles are produced in high energy proton-antiproton colliders; recently researchers at the CERN and SLAC laboratories were able to determine the Z^0 mass to 91.2 GeV. This is the heaviest known unit of matter.

We conclude this chapter by Table 10.3, which summarizes the forces of nature and the corresponding exchange particles.

10.8. Exercises

10.1. What proof exists that some cosmic rays do not come from the sun?
10.2. (a) What is the primary cosmic radiation hitting earth's atmosphere? (b) Does it penetrate to the earth's surface?
10.3. What background from cosmic radiation is expected for an unshielded 100 ml ion chamber which exhibits an area of 100 cm^2 perpendicular to the direction of the cosmic radiation?
10.4. Which type of mesons are released in high energy particle interactions, and why?
10.5. (a) What kinds of forces exist in nature? (b) How does the weak interaction manifest its properties?
10.6. (a) What are bosons and how do they differ from fermions? (b) Does the difference have any practical consequence?
10.7. What proof exists that the photon has matter properties?
10.8. How can the neutrino be detected?

10.9. Literature

Cosmic radiation

S. FLÜGGE (ed.), Kosmische Strahlung, *Handbuch der Physik*, Band XLV 1/1, Springer-Verlag, Berlin, 1961.
G. BURBIDGE, The origin of cosmic rays, *Sci. Am.* **215**, Aug. 1966.
A . WEBSTER, The cosmic background radiation, *Sci. Am.* **231**, Aug. 1974.
D. D. PETERMAN and E. V. BENTON, High LET particle radiation inside Skylab command module, *Health Physics* **29** (1975) 125.

Elementary particles

B. P. GREGORY, *Annual Report 1974*, CERN.
LANDOLT - BÖRNSTEIN, *Properties and Production Spectra of Elementary Particles*, Neue Serie I, **6**, Springer Verlag, 1972.
S. WEINBERG, Unified Theories of Elementary Particle Interaction, *Sci. Amer.*, **231** (1974) 50.
M. JACOB and P. LANDSHEFF, The Inner Structure of the Proton, *Sci. Amer.*, **242** (1980) 66.
K. S. KRANE, *Introductory Nuclear Physics*, J. Wiley & Sons, 1988.
J. R. REES, The Stanford Linear Accelerator, *Sci. Am.* Oct. 1989.
C. RUBBIA and M. JACOB, The Z^0, *Amer. Scient.*, **78** (1990) 502.