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High-Energy Particles

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To the memory of my father

Rino Rossi

who awoke my interest in science.

Preface

I HAVE WRITTEN this book with two objectives. First: to give a comprehensive account of our present knowledge concerning high-energy phenomena, to describe its historical development, and to explain the research methods peculiar to this field. Second: to provide the active investigator with a report on current problems in high-energy physics and present him with a collection of formulas, tables, and graphs useful to his work.

The selection of the material for inclusion in the book was the result of a compromise between conflicting requirements. In order to give adequate emphasis to topics at the very focus of current interest, I have had sometimes to go beyond well established facts. However, the volume and diversity of the subject matter have led me to disregard a number of developments, some of which may eventually prove to be important.

I based my treatment of electromagnetic interactions on theory, presenting the experimental data mainly as a check of the theoretical results. As for the nuclear interactions, I followed a purely experimental approach, since I felt that available theories were not sufficiently well established to provide a solid basis for the interpretation of such interactions. I used the same procedure in discussing the properties of mesons, a subject closely related to that of nuclear interactions.

The theory of cascade showers appears in considerable detail. Shower theory, even though limited in scope, is quite important as a research tool. Moreover, it has a considerable intrinsic interest as a mathematical problem and provides a model for the treatment of still unsolved questions, such as the propagation of high-energy nucleons through matter.

To write a book on a rapidly expanding subject is not an easy task. In order to keep abreast of current developments in the most important topics, I had to forego a thorough search of the literature concerning some items of lesser consequence. Thus I have often quoted from material on hand, including my own work and that of my collaborators.

In the preparation of the sketches for the illustrations I benefited from the expert advice of Professor G. Kepes of the Massachusetts Institute of Technology's Architecture Department. With his help I have tried to make the illustrations an integral part of the book and have devised ways of increasing their effectiveness. The preservation of uniformity of general style and of symbols for the illustrations was part of this plan.

Production of the book was greatly facilitated by the generous cooperation of many individuals. Physicists in various laboratories supplied advance information on their researches and contributed original photographs and drawings. Professor D. Menzel read much of the manuscript. I profited greatly from his constructive suggestions regarding the style. Many of my students helped in collecting material for the subjects discussed, and corrected the manuscript. Among them I wish to mention M. Annis, M. A. Clark, H. Courant, V. Henri, R. Rediker, and R. Safford. Professor K. I. Greisen of Cornell University read and checked the manuscript. His comments and suggestions were invaluable. Louise Shepard typed the manuscript, and interpreted my notes with great efficiency and skill. S. Olbert corrected the proofs. Theodore Lortscher did an excellent job of interpreting the sketches and preparing the finished illustrations. N. Romanelli, of the Prentice-Hall staff, edited the manuscript with great care and competence. To all of these persons, and to the many who contributed their suggestions I express my deep appreciation.

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I

Introduction

1.1. ***The role of elementary particles in physics.*** The study of elementary particles holds a central position in contemporary physics. One might even be tempted to say that the problem of elementary particles is today *the* problem of physics. One may take the view that, once having learned the properties of elementary particles and the laws governing their behavior, the student of natural phenomena will merely have to apply these laws to more or less complex systems of elementary particles.

The scientist of tomorrow would probably regard such an extreme view as naive. Indeed, even now common sense warns us that the properties of complex systems, for example, those that form a living cell, may well be more than the sum of the properties of their ultimate constituents. It is nevertheless true that, since all matter is an aggregate of protons, neutrons, and electrons, an understanding of the properties of these elementary particles is a prerequisite to the understanding of the properties of matter. It is also true that the study of elementary particles is basic to the understanding of radiation phenomena, for one may regard any kind of radiation as a flux of elementary particles. Still another reason for our interest in elementary particles lies in the well-known fundamental relation that exists between elementary particles and fields of force. For example, photons are quanta of the electromagnetic field. Therefore the properties of photons are intimately related to the properties of the electric and magnetic forces acting between charged particles. The so-called π-mesons very likely bear the same relation to nuclear forces as photons do to electromagnetic forces. If this surmise proves to be correct, knowledge of the properties of π-mesons will help us to understand the laws governing the forces that hold nuclei together.

Table 1 lists the elementary particles whose existence is demonstrated by present experimental evidence. In this table, the mass of each particle is given in terms of the electron mass ($m_e = 9.105 \cdot 10^{-28}$ g), its electric charge in terms of the electron charge ($|e| = 4.802 \cdot 10^{-10}$ e.s.u.) and its spin in terms of $h/2\pi$.

Protons, neutrons, and negative electrons (or *negatons*) are the constituents of matter, and photons are quanta of the electromagnetic field,

Table 1. Elementary particles

Name	Symbol	Mass	Electric Charge	Spin
Photon	γ	0	0	1
Negaton	e^-	$m_e = 9.105 \cdot 10^{-28}$ g	$-e = -4.802 \cdot 10^{-10}$ e.s.u.	½
Positon	e^+	m_e	$+e$	½
μ-meson	μ^+	$\sim 209 m_e$	$+e$	½
	μ^-	$\sim 209 m_e$	$-e$	½
π-meson	π^+	$\sim 276 m_e$	$+e$	0
	π^-	$\sim 276 m_e$	$-e$	0
	π^0	$\sim 266 m_e$	0	0
Proton	p	$1836 m_e$	$+e$	½
Neutron	n	$1838 m_e$	0	½
Neutrino	ν	0	0	½

or light quanta. Positive electrons (or *positons*) are identical to negatons, except for their opposite sign of charge. Positive electrons have an ephemeral life in matter because of their tendency to combine with ordinary negative electrons, an event leading to the disappearance of the two electrons and to the production of photons.

Neutrinos have never been detected directly because their interactions with matter are extremely weak. However, the principles of conservation of energy, momentum, and spin require the emission of particles corresponding to the description of neutrinos in a number of elementary processes.

Mesons are particles with masses intermediate between those of the electron and proton. All mesons are intrinsically unstable; i.e., they decay spontaneously in much the same way that radioactive atoms do. Their mean lives vary from a maximum of about $2 \cdot 10^{-6}$ seconds (μ-mesons) to a minimum of less than 10^{-13} seconds (neutral π-mesons). Their modes of disintegration and their mean lives, τ, appear below in Eqs. 1:

$$\begin{aligned} \mu^{\pm} &\longrightarrow e^{\pm} + 2\nu && (\tau = 2.1 \cdot 10^{-6}\ \text{sec}), \\ \pi^{\pm} &\longrightarrow \mu^{\pm} + \nu && (\tau = 2.65 \cdot 10^{-8}\ \text{sec}), \\ \pi^{0} &\longrightarrow 2\gamma && (\tau < 10^{-13}\ \text{sec}). \end{aligned} \tag{1}$$

The existence of μ-mesons and of charged π-mesons has been demonstrated by the direct observation of their tracks in cloud chambers and photographic emulsions. Evidence for the existence of neutral π-mesons comes from the observation of the photon pairs arising from their disintegration.

In addition to the elementary particles described above, recent experiments indicate the existence of other kinds of particles (τ-mesons, V-particles). These particles are both charged and neutral, are very short lived, and are heavier than π-mesons, for π-mesons appear to be among their disintegration products. Their properties are still largely unknown; also the number of different species is not yet determined.

1.2. ***High-energy particles and their interactions.*** In this volume we propose to describe the fundamental properties of the elementary particles listed above and their behavior at high energies.

High-energy phenomena play an especially important role in the physics of elementary particles. In the first place, most and possibly all elementary particles can be created by materialization of energy. Indeed, this phenomenon and the phenomena of spontaneous decay are the only known sources of those elementary particles, which do not exist in ordinary matter. For example, negaton-positon pairs can be produced by materialization of photons passing through the intense electric field of nuclei, according to the reaction

$$\gamma \rightarrow e^+ + e^-. \tag{2}$$

As another example, photons, interacting with protons, can produce π-mesons according to the reaction

$$\gamma + p \rightarrow n + \pi^+. \tag{3}$$

From Einstein's equivalence principle, the production of a particle of mass m (or of a group of particles whose total mass is m) requires the expenditure of an amount of energy given by the equation

$$E = mc^2. \tag{4}$$

For the production process to occur, this energy must be concentrated in the interacting particles, or in one of them if the other is at rest, as often happens. Thus a photon must have an energy greater than one million electron volts (1 Mev) in order to produce an electron pair (Eq. 2) because the rest energy of an electron is approximately 0.5 Mev. The minimum energy of a photon capable of producing a π-meson (Eq. 3) is approximately equal to the rest energy of the π-meson: $m_\pi c^2 = 141$ Mev. (Other requirements raise this minimum energy slightly; see § 7.12).

A second reason for the interest of physicists in high-energy phenomena is that one can usually interpret the interactions of high-energy particles with matter without taking detailed account of the particular manner in which protons, neutrons, and electrons are bound together to form the nuclei and atoms of the target material. Therefore high-energy interactions bring to light the fundamental properties of the elementary particles more directly than low-energy interactions, in whose interpretation the complex structure of matter plays a dominant role.

Consider, for example, the interactions of photons with electrons and assume first that the photon energy is of the order of several electron volts. Electrons whose binding energy is less than the energy of the photons may absorb the photon and break loose from the atom (ionization process). Electrons whose binding energy is greater than the energy of the photon may still absorb the photon by going over into a quantum orbit of higher energy (excitation process). This process, however, can happen only if the energy of the photon equals the energy difference between the initial and the final quantum states of the electrons. Electrons that satisfy neither of the two conditions specified above are unable to absorb the photon. Therefore the character of the interaction between a photon and an electron depends critically on the structure of the atom to which the electron belongs. In fact it is more appropriate to consider the interaction as one between the photon and the atom as a whole rather than between the photon and one of the atomic electrons.

But now suppose, instead, that the energy of the photon is large compared with the binding energy of electrons in atoms. In this case the electrons behave essentially as if they were free. The interaction between a photon and an electron may be described as an elastic collision in which the photon transfers part of its energy and momentum to the electron, originally at rest. The laws of this phenomenon, known as the *Compton effect,* depend exclusively on the fundamental properties of electrons and photons.

As a second example, consider the interactions of neutrons with nuclei. At energies smaller than the binding energies of neutrons and protons in nuclei, the probabilities of nuclear absorption and nuclear scattering depend critically on the nuclear structure. The nucleus as a whole participates in the interaction. A given nucleus may offer a very large cross-section for the absorption of neutrons, while a nucleus of somewhat similar constitution may have a negligible cross-section. However, when the neutron energy is large compared with the binding energy the situation becomes much simpler. In fact it seems that one can interpret the observed interactions by considering the collisions of the incident neutrons with the individual neutrons and protons that form the nuclei. In these collisions the two interacting particles behave approximately as if they were free. Therefore the result of an interaction between a high-energy neutron and a complex nucleus depends on the fundamental properties of protons and neutrons, on the total number of protons and neutrons in the target nucleus, and on the volume of space that they occupy. It does not depend critically on the manner in which neutrons and protons are bound together in the nucleus.

The forces that come into play in the interaction of high-energy particles with matter are of two different kinds: electromagnetic forces and nuclear forces. Accordingly one distinguishes between *electromagnetic interactions* and *nuclear interactions.*

Typical examples of electromagnetic interactions are: the energy loss of charged particles in their collisions with atomic electrons (ionization loss); the production of photons by charged particles in their passage through the electric field surrounding nuclei (*radiation loss* or *bremsstrahlung*); the phenomena of *Compton effect* and *pair production* (or materialization) which we have already had occasion to mention.

Radiation processes of electrons and materialization of photons combine to produce the so-called *cascade showers.* Assume, for instance, that a high-energy electron is incident upon matter. It will soon produce a high-energy photon, which, in turn, will undergo materialization. The newly produced electrons as well as the original one (if they have sufficient energy) will produce more photons. Thus the number of particles (electrons and photons) rapidly increases as the radiation progresses through matter. At the same time, however, the average energy of the individual particles decreases until electrons are no longer capable of radiating photons and are eventually absorbed by ionization loss, and photons are no longer capable of producing pairs and, after undergoing further degradation by Compton scattering, are eventually absorbed by photo-effect. At this point the shower dies out. Showers, of course, may be initiated by photons as well as by electrons.

Typical examples of the nuclear interactions are the collisions between neutrons and neutrons, protons and protons,* and protons and neutrons. At sufficiently high energies these collisions may give rise to charged and neutral π-mesons. At energies below the threshold for meson production the only result of the collision is a transfer of energy and momentum between the incident particle and the target particle. If the latter belongs to a complex nucleus, the nucleus will be disrupted.

Not all of the interactions between elementary particles fall as clearly into the category of electromagnetic interactions or into the category of nuclear interactions as those listed above. Sometimes both electromagnetic forces and nuclear forces come into play. Examples of such intermediate cases are the photo-disintegration of nuclei and the photoproduction of mesons. In both cases a perturbing force of electromagnetic character modifies the state of a system, working against the non-electromagnetic forces that determine the structure of this system. Somewhat arbitrarily we have chosen to discuss the first of the two phenomena mentioned above in the chapter dealing with electromagnetic interactions, the second in the chapter dealing with nuclear interactions.

1.3. ***Cosmic rays as a source of high-energy particles.*** Until the recent development of electro-nuclear machines, cosmic rays were

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* In the proton-proton scattering, however, the electric repulsion also plays a significant part, unless the energy of the incident proton is very large.

practically the only source of high-energy particles available to physicists. Today there exist laboratory sources of particles with energies up to several hundred Mev and some of the machines under construction may reach energies of several Bev (1 Bev = 10^9 ev). However, most of our present knowledge concerning the properties of high-energy particles was obtained through the study of cosmic-ray phenomena and, for a long time to come, cosmic rays will probably retain their monopoly over the energy region beyond 10 Bev. Thus the physics of high-energy particles is still to a great extent cosmic-ray physics. Hence this book will deal largely with the results of cosmic-ray studies. In order to facilitate the understanding of the material to be presented in the following chapters, we outline here very briefly the general picture of cosmic-ray phenomena, as it takes form from the data assembled during almost forty years of research.

The earth's atmosphere is under the continuous bombardment of high-energy particles coming from outer space. These particles are the *primary cosmic rays*. As they penetrate into the atmosphere, primary cosmic rays lose energy and gradually disappear on colliding against the oxygen and nitrogen atoms of the air. At the same time, however, they give rise to secondary rays mostly different in nature from the primary particles and, of course, of lower average energy. Thus, at each point within the atmosphere, one finds a radiation consisting partly of primary particles, partly of secondary particles. This radiation may be denoted as the *local cosmic radiation*.

The primary cosmic radiation consists of protons, α-particles and, to a smaller extent, heavier nuclei. The energy spectrum of protons obeys approximately the following empirical law:

$$N(E) = \frac{A}{(E + 5.3)^{1.75}}, \tag{5}$$

where E is the kinetic energy (measured in Bev), $N(E)$ is the number of protons with energy greater than E, and A is a constant. From the meager experimental information available to this date, it seems that the energy distributions of α-particles and of heavier nuclei are not very different from that of protons.

The magnetic field of the earth prevents charged particles of energy lower than a certain limit from reaching the atmosphere and thus cuts off the low-energy end of the primary spectrum. The cut-off energy depends on the nature of the particles, and is different at different geomagnetic latitudes and in different directions. For example, for protons in the vertical direction the geomagnetic cut-off occurs at about 14 Bev near the geomagnetic equator and about 1.5 Bev at 50° geomagnetic latitude.

The protons and the complex nuclei of the primary radiation undergo nuclear collisions in the atmosphere. In these collisions they disrupt the target nuclei, thus producing secondary protons and neutrons. They also generate π-mesons, both charged and neutral. Neutral π-mesons disintegrate immediately into photons, which then multiply into showers. Charged π-mesons disintegrate into μ-mesons and neutrinos. Mu-mesons interact with nuclei very weakly. Therefore they lose energy almost exclusively by ionization until they decay into electrons and neutrinos or until they reach the earth's crust and bury themselves underground. Thus the local cosmic radiation in the atmosphere contains protons, neutrons, π-mesons, μ-mesons, electrons, and photons. Both electrons and photons are mainly the products of cascade showers initiated by photons arising from the decay of neutral π-mesons, and by electrons arising from the decay of μ-mesons.

The relative intensities of the various components change rapidly as the radiation propagates through the atmosphere. Near the top of the atmosphere the primary radiation still predominates, and therefore most cosmic-ray particles are protons and neutrons (either free or bound in complex nuclei). The number of these particles, however, decreases rapidly with decreasing altitude. At the same time the number of electrons and photons increases rapidly and goes through a maximum somewhere between 13 and 20 kilometers, depending on whether one considers only vertical rays or includes also rays coming in inclined directions. In the region of the maximum, electrons and photons greatly outnumber all other cosmic-ray particles. Below the maximum, the electron-photon component, too, begins to decrease rapidly with decreasing altitude. The μ-meson component decreases much less rapidly than either the electron-photon component or the proton-neutron component. The reason is that μ-mesons do not undergo radiation losses comparable to those of electrons, nor do they undergo nuclear collisions as do protons or neutrons. Thus μ-mesons become relatively more and more abundant as the altitude decreases, until near sea level they account for more than half of the total number of the charged cosmic-ray particles. Pi-mesons, of course, are very scarce everywhere in the atmosphere because of their short mean life ($\sim 2.65 \cdot 10^{-8}$ sec).

Figure 1 shows the estimated intensities of various components of cosmic rays at 50° geomagnetic latitude and at different altitudes. In this illustration the abscissa represents the atmospheric depth (i.e., the atmospheric pressure in g cm^{-2}). The ordinates give the numbers of particles of different kinds incident from nearly vertical directions upon one square centimeter of horizontal area per second and per steradian. Some of the intensities shown are the result of fairly accurate determinations; others represent only crude estimates.

When a primary particle of particularly high energy strikes the atmosphere, it initiates a chain of interactions that continues through many successive generations and thus gives rise to a very large number of secondary rays. Among these, electrons and photons are the most abundant, but protons, neutrons, and mesons are also present. This phenomenon is called an *extensive air shower* (or an Auger shower). Records exist of extensive air showers containing as many as 10^8 secondary particles at a given level. The energy of a primary particle capable of producing a shower of this size is of the order of 10^{17} ev. The concentration of the shower particles is greatest near the axis of the shower (i.e., the line representing the continuation of the trajectory of the primary particle) and decreases gradually with the distance from the axis. Near sea level, one-half of all shower particles are within a radius of the order of 100 meters from the shower axis.

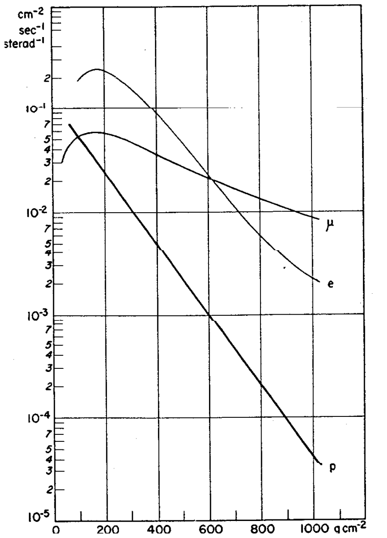

Fig. 1.3.1. Vertical intensities of various comsic-ray components at 50° geomagnetic latitude, as functions of atmospheric depth. Curve e: positive and negative electrons of energy greater than 10 Mev. Curve μ: μ-mesons of all energies. Curve p: protons of kinetic energy greater than 400 Mev. The last curve represents a crude estimate.

We wish to emphasize that while the picture presented above is almost certainly correct in its main features, it may well prove inaccurate in more than one important detail. For example, high-energy nuclear interactions may give rise to photons directly as well as through the intermediary of neutral π-mesons. Also, it is possible that V-particles and other unstable particles heavier than π-mesons, which we have neglected, may play a significant role in the chain of events accompanying the propagation of cosmic rays through the atmosphere.

In this volume we are interested in cosmic rays mainly as a source of high-energy particles. Therefore we do not intend to analyze critically the experimental and theoretical data on which the general interpretation of cosmic-ray phenomena is based. Nor do we propose to discuss in detail the genetic relations between the various components of cosmic rays. The complex phenomena of air showers are also outside the scope of our subject, even though the study of air showers is the only source of information on the properties of particles with energies of the order of 10^{15} ev or more.

Those important aspects of cosmic-ray research that are disregarded in the present work form the subject of another volume now in preparation.