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The Universe

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THE UNIVERSE

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PREFACE

The universe is the largest system of all. It consists of elementary particles bound together by gravitational, electromagnetic and nuclear forces. Its structural hierarchy in space (from atomic nuclei to supergalaxies) and its evolutionary sequence (from the fireball to the diversity of present forms) is governed by the properties of elementary particles and their interactions. This book is an attempt to interpret the structure and evolution of the universe in terms of elementary particles and of their interactions.

This book is intended to present a background for students in astronomy and related sciences, such as geophysics, meteorology, plasma physics, chemistry, nuclear physics, space sciences and some others. The universe forms a general framework for all the phenomena studied by these sciences.

It was possible to squeeze an extensive range of topics from various disciplines into one book of acceptable size only under some severe limitations: (a) no references are given; (b) arguments are shortcut; (c) quantities are often expressed in the order of magnitude; and (d) formulae have been limited to a minimum. Often more hypotheses or theories exist for a phenomenon. We have chosen only one. The preference for a theory or hypothesis may be personal and the theory itself may later prove incorrect. But, many theories about a particular phenomenon would cover many pages and might lead to confusing effects.

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JOSIP KLECZEK

Ondřejov, March 1975

TABLE OF CONTENTS

CHAPTER 1

ELEMENTARY PARTICLES

The matter of our universe consists of elementary particles. Bodies – whether it be our own body or a star – are systems of elementary particles differing in their number and degree of organization. The existence of elementary particles – also called fundamental particles – must therefore be felt in all phenomena in the universe. The physics of elementary particles offers a deeper understanding and a more profound insight into the structure and evolution of individual bodies like atoms, molecules, crystals, rocks, planets, stars, stellar systems, and the whole universe. That is why the study of elementary particles is of fundamental importance for contemporary physics in general and for astrophysics in particular.

1.1. Properties

We can never see elementary particles and never hope to describe them in a familiar way. We can only see the tracks they leave behind – tiny black clumps of silver in a photographic emulsion (Figure 1.5), bubbles of gas in rapidly expanded liquid hydrogen (Figure 1.1) a brief flash of light in a scintillator or a spark in a spark chamber. Enormous quantities of experimental material have been accumulated and interpreted theoretically in terms of particle properties.

Some of the properties are extensions of concepts from classical mechanics (e.g. mass, energy, electrical charge), while others stem from relativistic mechanics (proper time, proper length). Modern theory (quantum mechanics) had to introduce supplementary concepts (like spin, leptonic charge, baryonic charge, isotopic spin, strangeness, parity, quantum of action, annihilation, pair production, Pauli exclusion, wave-particle duality) to describe properties and behavior of elementary particles.

A set of numbers characterizes each particle, differentiates it from the other particles, and describes its properties. Some properties are constant and characteristic of the particle (rest mass, electric charge, spin, leptonic charge, baryonic charge, strangeness, isotopic spin, parity) while others are related to the surrounding world (momentum, angular momentum, total energy).

1.1.1. MASS

Mass is the quantity of matter in a body. It determines the magnitude of gravitational force (e.g. its weight) and is a measure of resistance to acceleration by any force (that is to say inertia). The mass of elementary particles is very small. Therefore they may be easily accelerated to velocities much higher than those we know from practical experience with relatively much more massive bodies. Particles with zero mass (such as photons) move with the highest velocity, i.e. the velocity of light, immediately after their birth.

The lightest particle with non-zero mass is the electron. Its mass, $m_e = 9 \times 10^{-28}$ g, is often used as the unit for measuring masses of all the other particles. The mass of the proton is $m_p = 1836\ m_e$, and that of the neutron, $m_n = 1838.6\ m_e$. Masses and other characteristic values for elementary particles may be found in Figure 1.3.

1.1.2. ENERGY

The concept of energy has been used since about 1700 when it was called *facultas agendi* which means capacity of a body for doing work. It may have different forms such as kinetic, thermal, electric, chemical, gravitational, nuclear, radiative and rest energy of mass. Its total amount remains the same although it changes its form like an actor on stage. Due to its great variability it governs the whole hierarchy of the universe, determines structure in space and evolution in time of all bodies and systems, from elementary particles up to clusters of galaxies. The great diversity of energy transformation may be reduced however to a few interactions of elementary particles as will be discussed in Chapter 2.

A particle with rest mass m_0 moving with velocity v in a reference system (e.g. the walls of a laboratory, satellite, Sun, center of Galaxy) has an energy

$$E = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{1.1}$$

For small velocities Equation (1.1) reduces to

$$E \approx m_0 c^2 + \tfrac{1}{2} m_0 v^2 \tag{1.2}$$

and at rest

$$E = m_0 c^2. \tag{1.3}$$

The term $m_0 c^2$ is the rest energy and $\frac{1}{2} m_0 v^2$ in Equation (1.2) is the kinetic energy of the moving particle. A particle with kinetic energy comparable to its rest energy is called a relativistic particle. The velocity of a relativistic particle is an appreciable fraction of the velocity of light. While the total energy (Equation (1.1) or (1.2)) of the moving particle depends on its motion relative to its surroundings, the rest energy (Equation (1.3)) is a characteristic independent of motion. Equation (1.3) expresses the equivalence of energy and mass. When a system of particles (a body) has lost energy ΔE, then according to Equation (1.3) its mass has decreased by $\Delta m = \Delta E / c^2$. The process of squeezing out energy from matter by mass decrease is of interest not only for astronomers but for any inhabitant of the Earth. The chemical processes (such as burning of fossil fuels) are very inefficient, because they lead to a relative decrease $\Delta m/m$ of only 10^{-10} or so. Nuclear reactions (such as those in stars) are more efficient because the relative mass decrease is of the order of 10^{-3}. By a gravitational contraction of a star even a few tenths of its rest energy may be released. However, the most efficient process is annihilation of matter and antimatter with complete conversion of the rest energy into radiation. Particles associated with radiation, i.e. photons, have zero rest mass.

1.1.3. MOMENTUM

The momentum of a particle with mass m_0 and velocity v is

$$p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{1.4}$$

which for small velocities $v \ll c$ reduces to the classical expression $p = m_0 v$. A relation between energy and momentum

$$\frac{E^2}{c^2} = p^2 + m_0^2 c^2 \tag{1.5}$$

follows from Equations (1.1) and (1.4). For zero-mass particles

$$p = \frac{E}{c}. \tag{1.6}$$

Conservation of momentum and energy applied to the decay of particles has allowed determination of their mass.

1.1.4. SPIN

Particles have their own angular momentum called spin. It is an intrinsic property and cannot be changed. We visualize the spin as gyroscope rotation. Conservation of angular momentum in decay or production reactions permits the determination of the spin of involved particles. Its values may be 0, $1\,\hbar$, $2\,\hbar$ for bosons or $\frac{1}{2}\hbar$, $\frac{3}{2}\hbar$ for fermions. The unit of spin is $\hbar = h/2\pi = 1.05 \times 10^{-27}$ g cm^2 s^{-1}. For a particle with spin j its angular momentum around some axis is restricted to integrally separated numbers from $-j$ to $+j$. For example a particle with spin $j = \frac{3}{2}$ may be found in a magnetic field with angular momentum $\frac{3}{2}$ or $\frac{1}{2}$ or $-\frac{1}{2}$ or $-\frac{3}{2}$ and no other value is possible.

Particles are divided in two groups according to spin: fermions with half-integer spin (at the left in Figure 1.3) and bosons with integer spin (right part of the figure). The behaviour of fermions is governed by the Pauli principle which leads among other things to degeneration of very dense matter, e.g. in white dwarfs.

1.1.5. ELECTRIC CHARGE

Electric charge is an important characteristic of elementary particles, but its true nature is not yet known. Some particles bear a positive charge (e.g. proton), others are negatively charged (e.g. electron) and the rest have no charge (e.g., neutron, neutrino, photon). The quantity of charge -1.6×10^{-19} coulomb – is the smallest, indivisible and natural unit of electricity, attributed with incredible precision to all charged particles irrespective of the other properties like mass, spin, etc. If a difference should be found, then it must be less than 10^{-17} of the electron charge.

Electric charge is the source of electric forces in the surrounding space i.e. of the electrostatic field. When in motion it gives rise to magnetic forces (magnetic field). If accelerated it emits photons, quanta of the electromagnetic field.

Electric charge Q is conserved in all processes ($\Delta Q = 0$). It cannot be destroyed nor created. This explains why an electron left by itself cannot decay into a lighter particle: there exists none with electric charge.

1.1.6. BARYONIC NUMBER

The heavy particles (in the upper left corner of Figure 1.3) are called baryons. Left to themselves the baryons decay. The only stable baryon is the proton. If it decays at all then its lifetime should be longer than 10^{22} yr as shown by experiments. Such processes as

$$(\mathrm{p} \rightarrow \mu^{+} + \gamma \qquad \text{or} \qquad \mathrm{p} \rightarrow \mathrm{e}^{+} + \gamma) \tag{1.7}$$

have *never* been observed, though they are energetically possible and the electric charge would be conserved. In all observed processes the number of baryons is always conserved. To describe the baryon conservation the baryonic number N has been introduced:

$$N \begin{cases} +1 & \text{for baryons (proton, neutron, hyperons)} \\ -1 & \text{for antibaryons (antiproton, antineutron, antihyperons)} \\ 0 & \text{for all other particles (mesons and leptons)} \\ >+1 & \text{for nuclei } (N \text{ equal to mass number } A) \\ <-1 & \text{for antinuclei.} \end{cases}$$

The conservation law is then

$$\Delta N = 0 \tag{1.8}$$

which means that the sum of baryonic numbers is not changed by any process. The conservation law (Equation (1.8)) explains the stability of protons: there exists no lighter baryon than the proton. Experiments (with a very large number of protons) have shown that if the proton decays – its lifetime must be longer than 10^{22} yr, that is 10^{12} times longer than the age of the universe.

1.1.7. LEPTONIC NUMBER

The leptonic number has been introduced for similar reasons. Leptons are light fermions and leptonic number l is defined

$$l \begin{cases} +1 & \text{for leptons (electron, muon, neutrino)} \\ 0 & \text{for non-leptons (baryons and bosons)} \\ -1 & \text{for antileptons (positron, positive muon, antineutrino)} \end{cases}$$

The conservation law for leptonic number is then expressed as

$$\Delta l = 0. \tag{1.9}$$

The sum of all the l before a reaction equals the sum of l's afterwards. For example, materialization of high energy photons γ

$$\gamma \rightarrow e^- + e^+ \tag{1.10}$$

conserves the leptonic number, because l of an electron (e^-) is plus one and of a positron (e^+) is minus one.

Experiments with Na I give the lower limit for lifetime of electrons: if they decay at all, then after more than 10^{17} yr.

1.1.8. ISOSPIN

The strong interaction of nucleons in a nucleus does not depened on electric charge. Proton–proton, neutron–neutron and neutron–proton interactions are all alike. There is not much difference between neutral and charged nucleons. The difference is expressed by the isospin.

Figure 1.3 shows that particles may be grouped into multiplets, such as p and n; Σ^+, Σ^0 and Σ^-; π^+, π^0 and π^-. Particles of the same multiplet have the same spin, the same baryonic number and approximately the same mass, but their electric charge is different. The multiplet can be considered as different states of the same particle. By similarity with optical multiplets a new quantum number I (isospin, isotopic spin, isobaric spin) for particle multiplets is introduced.

To determine isospin e.g., for nucleons we move the charge origin in Figure 1.3 to the middle, viz. to $+e/2$. Then a new charge is assigned to the neutron and proton, viz. $-e/2$ and $+e/2$, respectively, just as the Pauli spin has two projections $-\hbar/2$ and $+\hbar/2$. A multiplet with isotopic spin I has $(2I+1)$ different charge states. The nucleonic doublet with isospin $I=\frac{1}{2}$ is in fact one particle called a nucleon, which exists in two charge states viz. as proton and neutron. The proton has isospin state $+\frac{1}{2}$, while the neutron has isospin state $-\frac{1}{2}$. Another example is the pion, which may exist in three different charge states (pi plus, pi zero, pi minus) and therefore $I=1$. There is of course a fundamental difference between spin, which is a vector in ordinary space, and isospin, which is a vector in an artificial three-dimensional charge space. Spin characterizes angular momentum while isospin corresponds to electric charge.

1.1.9. STRANGENESS

Strangeness has been introduced to explain a strange behavior of hyperons and K mesons. These particles are produced by strong interactions and decay by weak interactions. The hyperons were always observed to be created with K mesons (K^+ or K^0 but never K^-). The creation in collisions of hadrons is very fast, which is characteristic for strong interactions. For example:

$$\begin{aligned} &\pi^+ + p \rightarrow \Sigma^+ + K^+ \\ &\pi^- + p \rightarrow \Lambda^0 + K^0 \\ &\pi^+ + p \rightarrow \Xi^0 + K^+ + K^+. \end{aligned} \tag{1.11}$$

Strangeness cannot be measured directly. It may be found for the multiplets in Figure 1.3. The charge center of the multiplet is shifted by a certain amount with respect to the charge center of the nucleon doublet or pion triplet. The strangeness S is then equal to the double shift. Thus for Λ^0 the charge shift is $-\frac{1}{2}$ so that its $S=-1$; also for Σ hyperons $S=-1$; for Ξ doublet the shift is -1 and $S=-2$ while the strangeness of the proton and neutron is zero. For K^+K^0 doublet the shift with respect to the pion triplet is $+\frac{1}{2}$ so that the strangeness of kaons is $+1$, while for pions $S=0$.

Particles with strangeness different from zero are called strange particles. They are created in a very short time ($\sim 10^{-23}$ s) and their strangeness is conserved

$$\Delta S = 0. \tag{1.12}$$

This may be seen in reactions (1.11), for example

$$\text{with } S \quad \left.\begin{aligned} &\pi^+ + p \rightarrow \Xi^0 + K^+ + K^+ \\ &0 + 0 = -2 + 1 + 1. \end{aligned}\right\} \tag{1.11a}$$

The reaction is allowed because strangeness is conserved. On the other hand

$$\text{with } S \quad \left.\begin{aligned} &\pi^+ + p \rightarrow \Sigma^+ + \pi^+ \\ &0 + 0 \neq -1 + 0 \end{aligned}\right\}$$

is forbidden because Equation (1.12) does not hold.

Decay of strange particles violates Equation (1.12) and is therefore very slow, with decay time $\geqslant 10^{-10}$ s, which is typical for weak interactions. To be specific:

$$\text{with } S \quad \left.\begin{aligned} &\Sigma^+ \rightarrow p + \pi^0 \\ &-1 \neq 0 + 0 \end{aligned}\right\} \tag{1.13}$$

where strangeness is not conserved. The decay occurs via weak interactions.

1.1.10. PARITY

Parity is another property of elementary particles which corresponds to mirror reflection of space coördinates. It is a symmetry property of a wave function. It may be either plus or minus if the wave function is unchanged by reflection or changed (i.e., even or odd). Parity is conserved in strong and electro-magnetic interactions and violated in weak interactions.

1.2. Antiparticles

It follows from the principles of relativity and quantum mechanics that to each particle there should exist an antiparticle with the same mass and the same spin. The other quantum numbers (electric charge, isospin, strangeness, baryonic number, leptonic number) have the same magnitude as for normal particles but the sign is reversed. The relation of particles and antiparticles is seen in Figure 1.3. It should be stressed that it is quite arbitrary to call electrons, protons, and neutrons particles rather than antiparticles; it is however more natural to consider ourselves (and the environment we live in) as consisting of matter rather than of antimatter.

For reasons of clarity, the matter of which our environment consists is called koinomatter, as opposed to antimatter, which consists of antiparticles.

The laws of conservation are valid for reactions involving particles and antiparticles. For example:

$$\begin{array}{ll} & \mathrm{p}+\mathrm{p}\rightarrow\mathrm{p}+\mathrm{n}+\mathrm{p}+\bar{\mathrm{p}}+\pi^{+} \\ \text{electric charge} & +1+1=+1+0+1-1+1 \\ \text{baryonic number} & +1+1=+1+1+1-1+0 \end{array} \tag{1.14}$$

where $\bar{\mathrm{p}}$ denotes antiproton.

Two processes have to be mentioned when talking about antimatter: annihilation (Figure 1.1) and pair production. A particle and its antiparticle annihilate in mutual collision and their energy is converted into photons or mesons. For example:

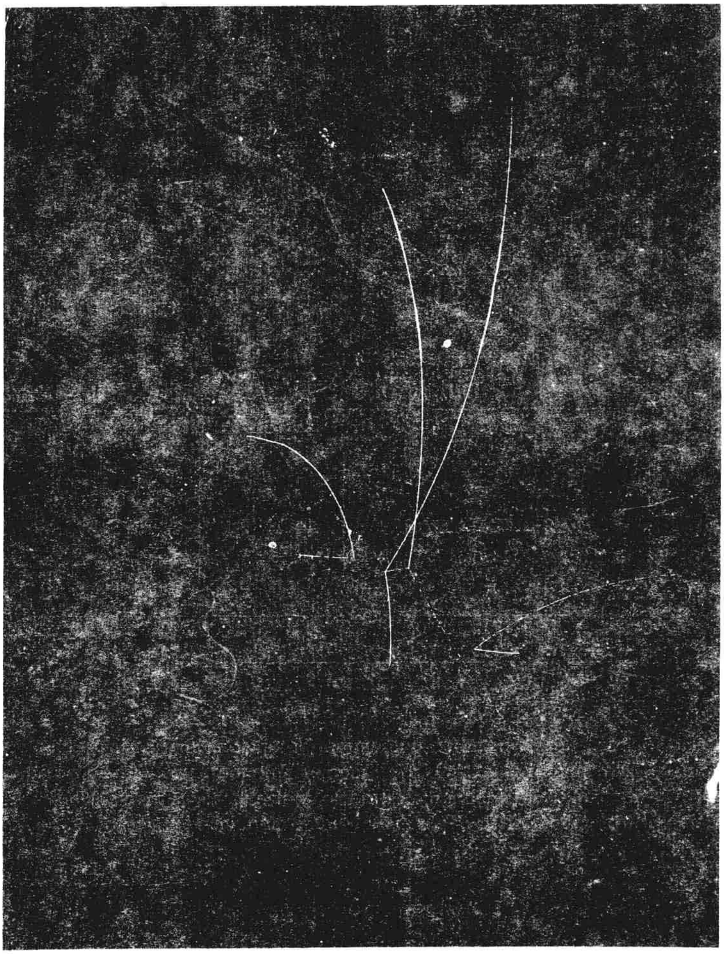
$$\mathrm{e}^{-}+\mathrm{e}^{+}\rightarrow 2\gamma \tag{1.15}$$

and

$$p+\bar{p}\rightarrow 2\gamma \tag{1.16}$$

with energy 0.5 MeV for each photon in Equation (1.15) and 938 MeV for each of the photons in Equation (1.16).

Pair production (materialization) is a reverse process to annihilation. It is the formation of a particle and its antiparticle from a photon with sufficiently high energy. The pair production occurs through electromagnetic interaction of the



Figs. 1.1a–b. An antiproton $\bar{p}$ enters from the top into a liquid hydrogen chamber (Saclay/École Polytechnique, Paris). The antiproton annihilates with a proton in point A. In the annihilation mesons K^0, K^- and π^+ as well as a π^0 are formed. The latter cannot be observed directly and is found by kinematic analysis of the event. The K^0 decays in B into π^+ and π^-, the π^+ decays in C, giving μ^+ and ν_μ (Equation (1.25)); the μ^+ decays at D into e^+, ν_e, $\bar{\nu}_\mu$ according to Equation (2.6). The K^- interacts in E, giving Λ^0 and π^0. The Λ^0 decays in F into a proton, which stops in G and a π^-. The π^0 is not seen since it is neutral and can leave no track. The π^+ produced in A scatters on a proton in H (CERN).

photon (or a high-energy particle) with the field of an atomic nucleus or other particle (Figure 1.2). Another way of pair creation is through the de-excitation of an excited nucleus (the so called internal pair production). The best known example of pair production is the creation of an electron–positron pair in the field of an atomic nucleus N:

$$\gamma + N \rightarrow N + e^- + e^+. \tag{1.17}$$

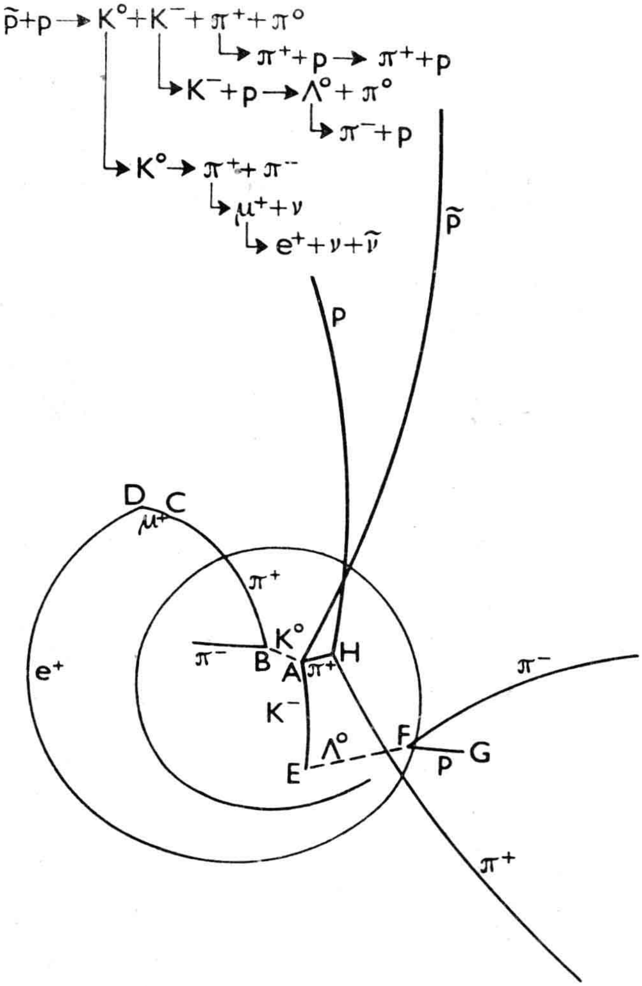


Fig. 1.1b.

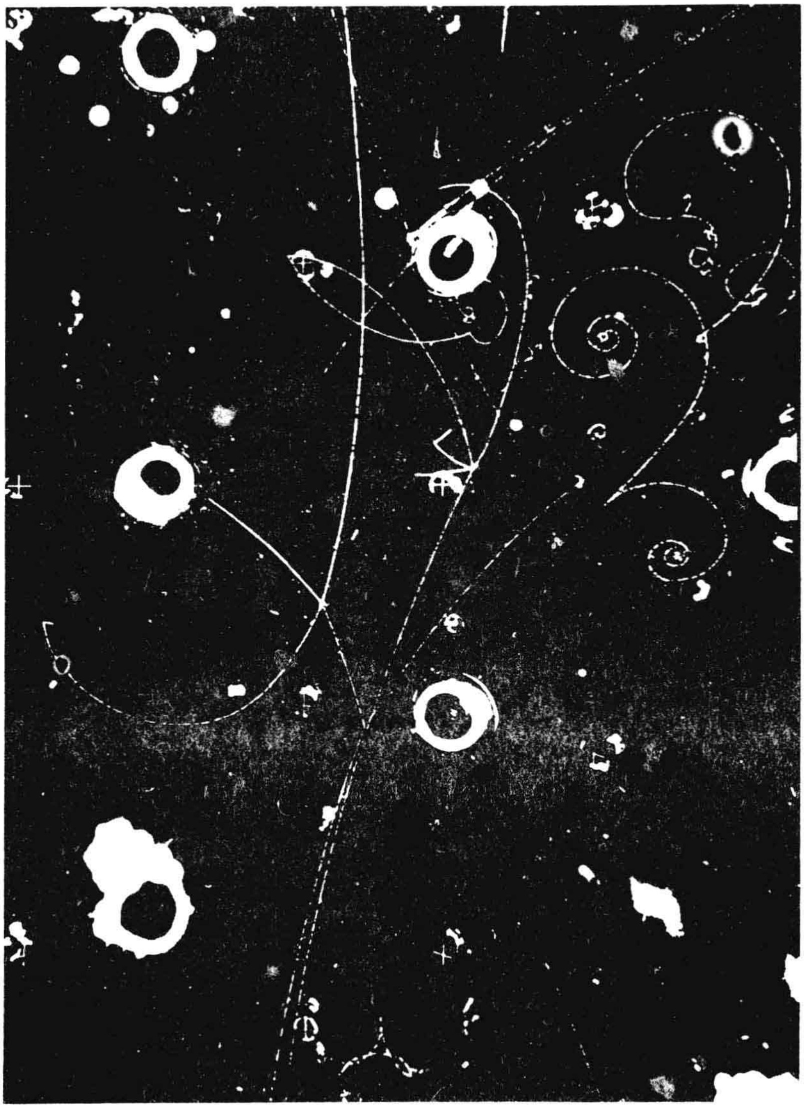
The photon energy must exceed the combined rest energies of the produced particles i.e. 1 MeV. By analogy

$$\gamma + \mathrm{p} \rightarrow \mathrm{n} + \pi^{+} \ (\gamma \text{ energy} > 140 \text{ MeV}) \tag{1.18}$$

$$\gamma + \mathrm{N} \rightarrow \mathrm{N} + \mathrm{p} + \bar{\mathrm{p}} \ (\gamma \text{ energy} \gtrsim 2 \text{ GeV}) \tag{1.19}$$

$$\gamma + \gamma \rightarrow \nu + \tilde{\nu}. \tag{1.20}$$

Antiparticles are produced in large particle accelerators and generally in any place where high energy particles occur, e.g., cosmic ray particles in the terrestrial atmosphere, in interstellar space, in the Crab nebula, etc. But one still does not know



Figs. 1.2a–b. Annihilation of an antiproton $\bar{p}$ arriving from below (track C) with a proton of the liquid hydrogen (point A). Five particles are produced by the annihilation reaction: π^+, π^-, π^0 and two gamma photons. The gamma photons have enough energy for electron–positron pair formation in points D. Another process occurs in point B, where a particle in the bubble chamber at E, collides with a hydrogen nucleus (CERN).

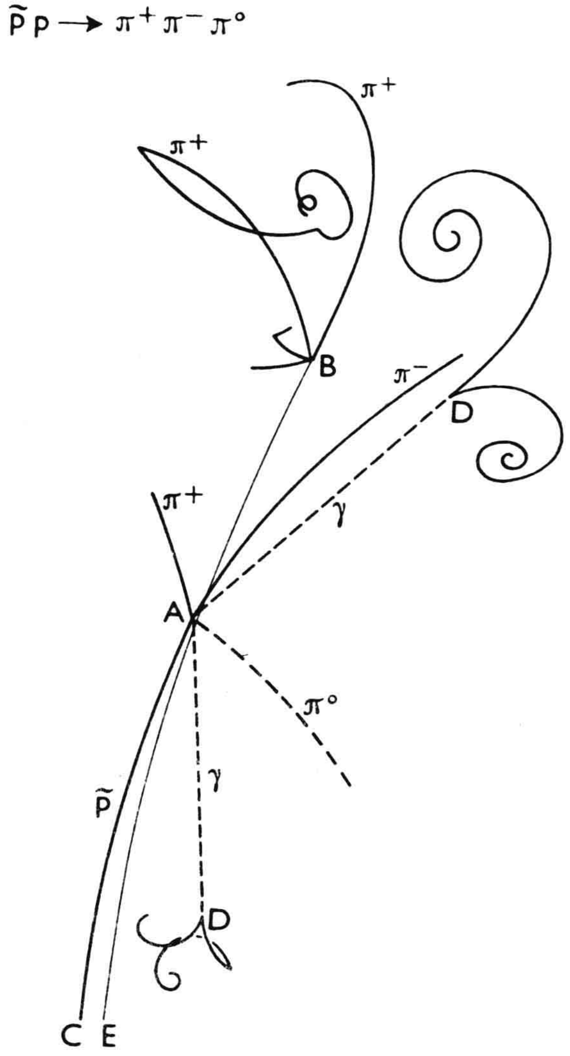


Fig. 1.2b.

whether antimatter exists in large quantities in our universe. Unfortunately a photon emitted by matter is the same as photon emitted by antimatter, so that by observing only electromagnetic radiation one cannot decide whether a star consists of normal matter (koinomatter) or antimatter. Neutrinos seem more promising in this respect: stars of koinomatter should be sources of neutrinos, while antistars are sources of antineutrinos. The sensitivity of present-day neutrino detectors is several orders of magnitude too low, however, to decide whether antimatter exists in large enough quantities to be important for the structure and evolution of the universe.