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Old and new exotic phenomena in the world of elementary particles

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Contents

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Abstract. This paper traces the history of elementary particle discoveries, beginning with the muon and ending with the t-quark and the τ-neutrino. Experimental work and basic theoretical concepts are reviewed. Recent neutrino oscillation research and attempts at finding exotic particles and creating artificial quark – gluon plasma are described. The physical beauty of experiments is emphasized and the elegance of both theoretical predictions and of the interpretation of discoveries is revealed. Possible research directions for the near future are discussed.

1. Introduction

"The scope of microphysics involves the most fundamental and essential, so to many people the most attractive, problems of physics"
V L Ginzburg

The words of the epigraph were written thirty years ago [1]. We ventured a presentation them here because they are most suitable for characterizing the goal set by us in writing this article: to give a popular account of how attractive and interesting microphysics is, i.e. the physics of elementary particles [1], in spite of its ultimately being fundamental and of principal character. After a lapse of ten years V L Ginzburg confirmed these words and added that "they were valid yesterday, are certainly correct today, and will be correct tomorrow" [3]. Fully sharing such a point of view, we have attempted to illustrate it in the present article by telling the story, full of riddles and sensations, of "yesterday's" discovery of elementary particles, by describing "today's" most recent exotic achievements in this field, and also by presenting a cautious prediction concerning possible discoveries of "tomorrow". In doing so we have also made use of another review by V L Ginzburg (see the Conclusions).

The present article is the second one touching exotics in microphysics in the broad sense. The first article that dealt with exotic processes in nuclear physics was published in *Physics – Uspekhi* last year [4]. It related half-forgotten nuclear-physics exotics such as, for instance, nuclear isomery or two- and three-neutron delayed radioactivity, very recent results relevant to new data on the double β-decay and cluster radioactivity, and also the sensational discoveries of the 114th, 116th and 118th elements [2]. But in that article it was not possible, without going beyond the chosen field (nuclear physics), to speak of exotics in the world of elementary particles. A sole exception was made for nucleons, since they 'pluralistically' represent both elementary particles and the simplest atomic nuclei. Meanwhile, elementary particle physics involves no less (or rather more) exotics than the physics of the atomic nucleus, which we shall try to prove in the present article. Here, not only particles that are actually termed *exotic* (see Section 10.3) are intended, but literally all elementary particles, since their discoveries revealed extremely unusual, surprising properties that often required many-year-long efforts of theorists and experimenters for their explanation.

[1] Somewhat earlier, in the fifties, V L Ginzburg also considered the scope of microphysics to include physics of the atom and of the atomic nucleus. For the authors of the present article, microphysics interpreted in this broad sense has always been and still remains attractive. One of us fully realized the attractiveness of microphysics 'to many' in 1969, when the first edition of his popular science book was published [2]. Besides the entire quite large edition (345,000 copies only in Russian) having been sold out, the attractiveness of microphysics 'to many' was also confirmed by numerous letters sent by readers of the book, who proposed projects, theories, particle classifications, etc. that were most often naive, but always full of lively interest in microphysics. By the way, such letters are still arriving. The last one (from Ukraine) came in March, 2001!!!

[2] We take the opportunity to express our sincere gratitude to all readers who sent comments on the article mentioned. We are particularly grateful to Corresponding Member of the RAS, V V Parkhomchuk, who not only wrote warm words to the authors of the article, but also brought to our attention one more exotic process in nuclear physics: the emergence of radioactivity in β-stable nuclides, when they are deprived of their electron shells.

Now, several words follow about the aforementioned microphysics being fundamental and of principal character. In spite of our article being at quite a popular level, meaning that it was not really intended for 'microphysicists' but for physicists 'in general' (so as to say, 'macrophysicists'), we were not able to totally avoid the elements of the theory and introducing radically new basic concepts and conservation laws which might not all be familiar to 'macrophysicists' (the baryon-number and lepton-number conservation laws, as well as the laws of conservation of strangeness, charm, beauty, isospin, of spatial, C- and CP-parities, etc.). In order to facilitate reading we introduce these new concepts gradually (one by one) as we proceed to describe the properties of one or another particle, to make sure that the reader, having come to the end of the article, will have learned to understand the 'bird's' language of 'microphysicists' and, at least to some extent, will have become familiar with modern experimental setups and methods of processing the data obtained from them. In any case, such a conscientious reader will be able, with an understanding of the meaning of all the symbols presented (Γ, B, L, S, I^G, J^P, u, d, s, c, b, t, etc.), to make use of the tables of the properties of elementary particles, which are regularly (every two years) published in physical journals and (in an abridged version) in the form of booklets.

And, finally, a few words concerning the special features of the article, but this time addressed to the 'microphysicists' (if, by chance, any of them happens to pick it up). Owing to the large number of particles considered ('from the muon to the gluon', and further to the t-quark and τ-neutrino), this article cannot naturally claim to be a theoretically rigorous exposition of the material presented. We have had to renounce dealing with many subtle theoretical issues, but in compensation we have tried to present what remained within the admissible volume in an informal manner and as interestingly as possible [3], thus attempting to underline in every possible way the surprising aspects of the predictions made, of discoveries and of their interpretations. We think that this approach makes the present article different from many other publications dealing with the same issue, which, although presenting an excellent and rigorous exposition of the actual material, do sometimes not succeed in demonstrating its physical beauty and elegance. We, the authors of this article, wanted to reveal in it the admiration (slightly tinted with 'white' envy) we felt every time we witnessed some outstanding discovery among those described here. If we succeeded, then the publication of yet one more article on elementary particles is justified.

Several words about the contents of the article: in it, we deal consistently with the prediction (when possible), the discovery (including a short description of the experiment and of the technique applied for processing the results), and investigation of the properties (with an introduction of the required new concepts) of muons, the τ-lepton, the three sorts of neutrinos, pions, antinucleons, the particles with strangeness, charm and beauty, and, also, the resonances. Two separate sections are devoted (at a very popular level) to considering the principal ideas of the physics of weak and electroweak interactions (and give an outline of the prediction and discovery of $W^{\pm}$- and Z^0-bosons) and of quantum

[3] To enliven the material presented we have supplied it, in certain places, with footnotes containing remarkable comments made by well-known physicists and, also, ourselves.

chromodynamics (including a short description of the discovery of quarks and gluons), and to the experimental confirmation of their actually having such unusual properties as color, flavor, confinement, etc. Of the most recent news, besides experimental confirmation of the τ-neutrino's existence, we shall speak of the latest searches for neutrino oscillations, and experimental attempts will be considered aimed at revealing exotic particles, at the creation and observation of quark – gluon plasma, and the first announcements about the discovery of the Higgs boson will be mentioned. The properties of particles discovered before the muon are considered known. Gravitational interaction between particles is not considered.

In the next to last section of the article we present the modern classification of elementary particles and single out those that are the 'most elementary' — fundamental ones and that are conventionally limited to (see, for example, Ref. [5]) 6 quarks, 6 leptons and 4 gauge bosons. In the Conclusions, a final analysis is presented, and a cautious prognosis for the future is given[4]. Taking into account the popular manner chosen for exposing the material, we hope the present article will be useful to those readers who are not specialists in elementary particle physics and who wish to become familiar with the history of its development and, partly, with the modern state of affairs of this science. On the other hand, it may also help specialists to recall the main facts, dates, names and principal works of outstanding physicists (for which they were awarded the Nobel Prize), as well as certain details of the experiments performed for the observation of $W^{\pm}$- and Z^0-bosons, the t-quark, the τ-neutrino, exotic particles and artificial quark – gluon plasma.

2. The status of elementary particle physics in the mid thirties. Yukawa's theory. Modern ideas of the nature of the strong interaction

By the middle of the 1930s, when, besides the particles discovered earlier: the electron e (J J Thomson, 1897), the photon γ (M Planck, 1900; A Einstein, 1905 and A Compton, 1922), and the proton p (E Rutherford, 1919), also observed had been the neutron n (J Chadwick, 1932) and the positron e^+ (P Dirac, 1928 and C Anderson, 1932), the existence of the neutrino had been hypothesized (W Pauli, 1930) and the first theory of β-decay elaborated (E Fermi, 1933)[5], it started to seem that a happy period of relative well-being had arrived for the physics of the atomic nucleus and elementary particle physics. The number of particles observed and predicted by that time was seemingly sufficient for the construction of a correct proton – neutron model of the atomic nucleus and for explaining its main properties (W Heisenberg and D D Ivanenko, 1932). True, the existence of the neutrino hypothesized by Pauli for explaining the continuous β-spectrum behavior had not been confirmed by direct experimental evidence[6], but it did seem quite convincing owing to numerous theoretical considerations and to indirect experiments (A I Leĭpunskiĭ, 1936; J Allen, 1942). Probably, the only serious thing that darkened the general harmony was the nature of nuclear forces. The problem of nuclear interactions became especially ponderable after the discovery of the neutron and the construction of the proton – neutron model of the atomic nucleus, in which the positively charged protons and chargeless neutrons were firmly held together inside the atomic nucleus. The question was: by what forces?

The initial period of interest in the problem of nuclear forces can be divided into three stages related to the names of three theoretical physicists: W Heisenberg, I E Tamm and H Yukawa[7]. Heisenberg thought (1933) that, by analogy with chemical exchange forces explained by an exchange of electrons, the nuclear interaction between a proton and a neutron should also exhibit an exchange character, although, instead of ordinary electrons, the interacting nucleons had to exchange certain hypothetical spinless electrons obeying the Bose statistics.

Heisenberg's idea of the exchange character of nuclear forces was further developed in 1934 by I E Tamm, who constructed the nuclear interaction potential assuming its origin to be the exchange of an electron and a neutrino (a peculiar Bose pair) between the proton and the neutron. However, Tamm himself showed that the internucleon interaction he constructed was significantly weaker than the experimental estimate for the nuclear forces. Roughly speaking, the failure of this theory could be explained by the electron having a very small mass with a respective interaction range that was too long.

The next step was taken in 1935 by H Yukawa, who showed that in the case of nuclear interaction the mass of the exchange particle had to be about 200 times greater than the electron mass. Yukawa modestly assumed his theory to be probably incorrect, since such particles had not been observed in nature. He was mistaken, however, only in harboring deep doubts but not in the main issue. A particle with approximately such a mass and with the appropriate properties was ultimately found (after a lapse of 12 years). Therefore, Yukawa's reasoning can be considered the prediction of the discovery of the nuclear quantum. Very roughly, his argumentation reduced to the following.

One of the principal tenets of quantum mechanics is the uncertainty relation

$$\Delta E \Delta t \simeq \hbar \tag{1}$$

($\hbar = 6.6 \times 10^{-16}$ eV s is the Planck constant), which indicates by what quantity ΔE the energy E of an isolated system can vary during the time interval Δt ('violation' of the law of conservation of energy during a short time Δt). As applied to the problem considered it can be interpreted as the origina-

[4] It is worthwhile to note that, while preparation of the manuscript of the article for publication was under way, certain predictions happened to be (at least, in part) realized and, thus, had to be transferred from the Conclusions into other sections.

[5] J J Thomson was awarded the Nobel Prize in physics in 1906 for discovering the electron; M Planck in 1918 for creating the theory of radiation; A Einstein in 1921 for creating the quantum theory of light; A Compton in 1927 for the theory of the effect named later after himself; E Rutherford in 1908 (the Nobel Prize in chemistry) for investigations into the transformation of elements and the chemistry of radioactive substances; J Chadwick in 1935 for discovering the neutron; P Dirac in 1933 for the creation of quantum mechanics; W Pauli in 1945 for formulating the principle named later after himself, and E Fermi in 1938 for discovering artificial β-radioactivity and creating the neutron slowing-down theory.

[6] As the legend goes, Pauli himself, who hypothesized the existence of the neutrino in nature, thought experimenters would never be able to observe it. Luckily, he was wrong, but it took a quarter of a century for the actual discovery of the neutrino to take place (see Section 3.5).

[7] W Heisenberg was awarded the Nobel Prize in physics in 1932 for creating the matrix version of quantum mechanics; H Yukawa in 1949 for prediction of the meson, and I E Tamm in 1958 for the theory of the Vavilov – Cherenkov effect.

tion (in a system of interacting nucleons) of an excess energy ΔE in the form of a particle of mass $m = \Delta E/c^2$ arising in the system for the time Δt. Considering $\Delta t = a/c$, where a is the exchange interaction radius, and c is its propagation velocity (the speed of light), we may write

$$m = \frac{\hbar}{ac} \,. \tag{2}$$

The mass of the exchange particle is inversely proportional to the interaction radius. The energy expression for mass is given by

$$\Delta E = mc^2 = \frac{\hbar c}{a} \,. \tag{3}$$

Setting $a = 2 \times 10^{-13}$ cm (the average distance between nucleons in the nucleus), we obtain

$$mc^2 = 100 \text{ MeV} \quad \text{or} \quad m \simeq 200 m_{\text{e}} \,,$$

since $m_{\text{e}}c^2 \simeq 0.5$ MeV.

The Yukawa particles that appear for the short time of nuclear interaction

$$\tau_{\text{nucl}} = \Delta t = \frac{a}{c} = \frac{2 \times 10^{-13} \text{ cm}}{3 \times 10^{10} \text{ cm s}^{-1}} \simeq 10^{-23} \text{ s} \tag{4}$$

are termed virtual. Such virtual (not real) particles continuously arising in the vicinity of a nucleon and being absorbed by it in a time Δt form something like a cloud ('fur coat') of radius a around it. Now, if two nucleons are at a distance of the order of a from each other, then they can exchange such particles, which actually represents the essence of the nuclear interaction.

There now remained little to do: one had to find these particles in nature, i.e. not in a virtual state, when they are fastened by a 'short leash' $a = 2 \times 10^{-13}$ cm long to the nucleons, but in a real free state, when they are capable of covering a significantly longer distance $l \gg a$ in a time[8] $\tau \gg \tau_{\text{nucl}}$. From the above it is clear that the internal quantum-mechanical 'supply' of energy ΔE cannot be used for releasing the particles from their nucleonic prison, since it is only sufficient for the length of the aforementioned 'leash'. Therefore, to resolve the problem one must add some additional energy to the system of interacting nucleons; as follows from the energy and momentum conservation laws, this added energy has to amount to about twice the energy expression for the mass of the nuclear quantum (i.e. to 200 MeV for a mass $m \simeq 200 m_{\text{e}}$, and 300 MeV for $m \simeq 300 m_{\text{e}}$). This energy can clearly be added to a system consisting of a pair of interacting nucleons in the form of the kinetic energy of one of them. And, since at the time described only outer space could be the source of such high-energy nucleons, the first experimental searches for the Yukawa nuclear quanta in nature were carried out with cosmic rays.

We shall present a detailed account of these experiments and the exotic results they yielded in subsequent sections, while now, somewhat anticipating events, we only notice that two stages were necessary for performing the task undertaken. At first, in 1936–1938, particles were observed in the cosmic rays that had the appropriate mass ($m \simeq 200 m_{\text{e}}$) and lifetime ($\tau \simeq 10^{-6}$ s) and that were subsequently called muons (μ). However, investigation of their properties revealed them not suitable to play the part of nuclear quanta. Only at the second stage of the search, in 1947, were the particles finally found that could serve as nuclear quanta. They turned out to be the π-mesons (pions, π) of mass $m_\pi \simeq 300 m_{\text{e}}$ and lifetime $\tau \simeq 10^{-8}$ s (see Section 3).

Anticipating events, it is necessary to say that, although the role played by π-mesons was extremely important for the initial description of the properties of nuclear forces (see Section 4.3) and the properties of π-mesons themselves are still being actively studied (see Section 4.4), modern ideas about the nature of the nuclear (strong) interaction have altered drastically. At present, the strong interaction is considered to be transferred by gluons, the source of which are color charges of the quarks that are constituents of the nucleons. Unlike π-mesons, both gluons and quarks do not exist in a free state (for details see Section 8.2).

3. Muons and pions (π-mesons). The six leptons

3.1 The discovery of muons. Their mass and lifetime. Three muon enigmas. The weak interaction of muons

The first evidence of the existence of muons (they used to be called mesotrons, μ-mesons or simply mesons, which meant a particle 'intermediate' in mass between the electron and the proton) was obtained in 1936 in studies of the absorption of cosmic rays passing through a layer of lead[9]. These experiments revealed cosmic rays to have a so-called hard component that, unlike the rapidly absorbed soft component consisting of electrons and photons, passed through tens of centimeters of lead practically without being absorbed. Such properties could be exhibited, for example, by protons of very high energies that are present in cosmic rays; however, subsequent experiments performed in 1938 by C Anderson and S Neddermeier with the aid of a Wilson cloud chamber placed in a magnetic field[10] also revealed negatively charged particles to be present in the hard component. The processing of their tracks photographed in the chamber made it possible to estimate the mass of these particles, which turned out to be approximately $200 m_{\text{e}}$. Thus the muons (μ^+ and μ^-) were observed for the first time.

The first experiments in which the lifetime of the muon was determined were quite ingenious. The idea consisted in comparing the muon flux intensities at the Earth's surface and at the top of a high mountain. The muon flux intensity should, naturally, be higher on the mountain, since some of the muons traveling downward from the top to the foot of the mountain are absorbed in the air column. However, it surprisingly turned out that, when at the top of the mountain an additional absorber equivalent in its stopping power to the aforementioned air column was put in the path of the muons, the intensity of muons that passed through the absorber

[8] Yukawa predicted that the nuclear quanta should have a finite lifetime $\tau \neq \infty$, i.e. be radioactive particles.

[9] The applications of lead in experiments by physicists studying cosmic rays were so wide and diverse that in a humorous poem they were said to work inside lead, behind lead, at lead, on lead, under lead, and above lead...

[10] This technique was applied in Russia by D V Skobel'tsyn for studying the properties of elementary particles. P L Kapitza was the first to place a Wilson cloud chamber in a magnetic field and to obtain curved tracks of α-particles. C Anderson was awarded the Nobel Prize in physics in 1936 for the discovery of the positron made in 1932; C T Wilson in 1927 for inventing the chamber named after him, and P L Kapitza in 1978 for fundamental research in the field of low-temperature physics.

remained higher than at the foot of the mountain as before. Thus, a series of exotic discoveries was initiated by studies of the muon properties.

In this case, the explanation of the effect observed seemed obvious, the more so as Yukawa had predicted nuclear quanta to be radioactive, and at the beginning muons were quite similar to them. The explanation consisted in that the muons traveling downward decayed according to the exponential law

$$N(t) = N_0 \exp(-\lambda t) = N_0 \exp\left(-\frac{H}{c\tau}\right), \tag{5}$$

where N_0 is the muon flux intensity at the top of the mountain (corrected for the additional absorption in the air column), N is the same quantity at the foot of the mountain, λ is the radioactive decay constant, $\tau = 1/\lambda$ is the muon lifetime, $t = H/v$ is the time of its travel, H is the height of the mountain, and v is the muon velocity which in the case of a muon with a high energy E approximately equals the speed of light c. Measurements carried out for muons of energy $E = 10^3$ MeV yielded $\tau \simeq 10^{-5}$ s. And, as we shall now see, this was the second exotic result of studies covering the physics of muons. The point is that the value of τ was obtained for a *moving* muon with a high energy E. But, in accordance with the special theory of relativity, the lifetime τ_0 of a muon *at rest* should be $E/m_\mu c^2$ times shorter:

$$\tau_0 = \tau \frac{m_\mu c^2}{E}, \tag{6}$$

which at $E = 10^3$ MeV and for $m_\mu c^2 = 10^2$ MeV ($200 m_e$) yields $\tau_0 = 10^{-6}$ s. Somewhat later this calculated value of τ_0 was confirmed by a direct measurement of the delay time between the decay of a stopped muon and the moment it came to rest. Thus, one of the first and most convincing proofs of the correctness of the inference from the special theory of relativity that time slows down in a moving reference system [11] was obtained during investigations into the radioactive decay of muons.

There also existed a third, probably the most surprising, exotics. The question was whether a muon could serve as a nuclear quantum? What was the intensity of its interaction with nuclei? This question could be answered if the lifetimes of positive and negative muons were measured separately in dense matter.

According to the Yukawa theory, if the negative muon is a nuclear quantum, then, upon landing in the vicinity of a nucleus it should very rapidly (in a nuclear time $\tau_{\text{nucl}} \simeq 10^{-23}$ s) be absorbed by the nucleus. Indeed, experiments performed making use of a magnetic field revealed negative muons moving in dense matter (lead) to exhibit a shorter lifetime than positive muons (7×10^{-8} s and 2.2×10^{-6} s, respectively), but it was far from being even comparable to nuclear times.

It is interesting to trace the fate of negative muons traveling in dense matter. At first, when a muon approaches a nucleus, it is captured onto one of the Bohr orbits that are similar to the electron orbits in an atom, but with radii being $m_\mu/m_e \simeq 200$ times smaller (a μ-atom). Then the muon undergoes transitions from one orbit to another, until it finally happens to be on the K-orbit that is the orbit closest to the nucleus.

By calculation it is readily shown that the radius of the muon K-orbit in a lead μ-atom turns out to be *smaller* than the radius of the nucleus itself, i.e. a muon captured into the K-orbit of a μ-atom already happens to be *inside the nucleus* and it lives there for 7×10^{-8} s, which is $7 \times 10^{-8}/10^{-23} = 10^{16}$ times greater than the nuclear time. The interaction between muons is weaker than the strong (nuclear) interaction by the same factor.

If the geometric cross section of the nucleus, $\pi R^2_{\text{nucl}} \simeq 10^{-24}$ cm^2, is taken to represent the scale of the strong interaction cross section, then the cross section σ of muon interaction with nuclei will be of the order of 10^{-40} cm^2. And this is a typical value for weak interaction cross sections.

Thus, in spite of the muon having an appropriate mass and lifetime (in vacuum), it cannot serve as a nuclear quantum. Moreover, since it does not undergo strong interaction, it cannot be produced in cosmic rays by the interaction between high-energy nucleons.

The only possibility for muons to be produced (with the exception of weak interaction that can only contribute to the production of a negligible fraction of the muons), as proposed by R Marshak and H Bethe [12], is the decay of other, heavier, nucleoactive (i.e. undergoing strong interaction) particles that may be produced by interacting cosmic nucleons. If their mass and lifetime do not differ too strongly from the values predicted by the Yukawa theory, then these particles are suitable for playing the part of nuclear quanta. Shortly afterward such particles were observed. They were termed π-mesons (pions).

3.2 Photoemulsion method. Emulsion chamber. The discovery of charged pions. Possible decay channels of pions and muons. The strong interaction of pions

Charged π-mesons (pions) were discovered in 1947 by S Powell [13] and his collaborators using the photoemulsion method [7]. As applied to investigation of the properties of elementary particles, this method was proposed and developed in Russia by L V Mysovskiĭ and A P Zhdanov together with their co-workers [8, 9]. Essentially, the modern version of this method consists in the utilization of thick (several hundred μm) layers of exceptionally sensitive photographic emulsion capable of registering relativistic single-charged elementary particles exhibiting minimum ionization losses. During the first years, glass thick-layer photographic plates were used for registering elementary particles; later, only emulsion layers (without glass) built up into thick (~ 10 cm) stacks (emulsion chambers, Fig. 1) were utilized. Such stacks were lifted by balloons up into the upper atmosphere, where they were exposed to cosmic rays. Then, a stack that came

[11] Heisenberg recalled [6] that the experimental proof of the lifetime dilation for rapidly moving muons saved relativity theory from persecution by the German government at the end of the thirties. At present, the effect of lifetime dilation for rapidly moving particles is utilized for creating hyperon beams. Thus, for example, at an energy of 600 GeV (attainable at the Tevatron of the Fermi Laboratory), the lifetime of the Σ^--hyperons increases from $\tau_0 = 1.5 \times 10^{-10}$ s up to $\tau = 7.5 \times 10^{-8}$ s (i.e. by a factor of 500!) so that the particles, even traveling at velocities close to the speed of light, can cover a distance of 22.5 m, which is quite sufficient for the formation of a beam of Σ^--hyperons.

[12] R Marshak is one of the creators of the universal theory of weak interactions (1957). In 1938, H Bethe discovered the proton–proton and carbon–nitrogen reaction cycles that are the source of solar energy (he was awarded the Nobel Prize in physics in 1967).

[13] S Powell was awarded the Nobel Prize in physics in 1950 for the discovery of π-mesons.

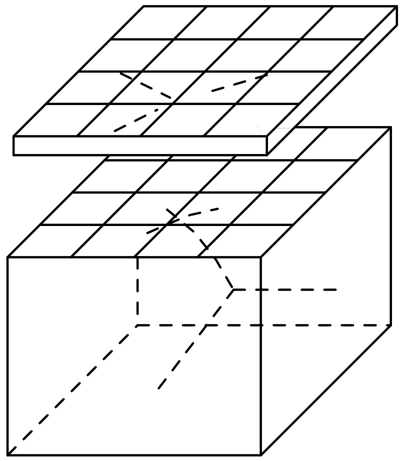

Figure 1. Layout of the photoemulsion chamber.

down to the Earth [14] was supplied (with the aid of X-rays or by an optical method) with a common coordinate grid. Afterwards the stack was taken apart into separate layers, which were developed and glued onto glass plates for subsequent scanning making use of a microscope of at least 200 – 500 times magnifying power.

The track of a charged particle in the photoemulsion film consists of a chain of black grains of metallic silver 0.5 μm in diameter with an average distance between them not exceeding 5 μm. The length of a track (range), the degree of its rectilinearity, the direction in which the density of grains changes along the range and certain other parameters make it possible to determine the charge, energy, velocity and mass of an elementary particle, as well as its direction of flight.

Tracks of π-mesons were observed during the scanning of nuclear photographic plates exposed to cosmic rays at the top of a high mountain. Such tracks were encountered in events of two totally different types. Events of the first type were represented by the track of a primary particle of mass $\sim 300m_e$, stopping and emitting a secondary particle of mass $\sim 200m_e$ and approximately the same range of 600 μm. At the end of its path this secondary particle also emits one charged particle of mass $\sim 1m_e$ with a range that differs from one decay event to another. The described chain of successive transformations of elementary particles was interpreted as the $(\pi^+ \to \mu^+ \to e^+)$-decay of a positively charged π-meson that, in spite of its nuclear activity, cannot be captured by the nucleus owing to Coulomb repulsion and that upon stopping emits a positively charged muon which in turn stops and emits a positron.

Since in all registered $(\pi \to \mu)$-decays the muon had the same range of ~ 600 μm, i.e. an energy of ~ 4 MeV, then together with the muon there should also, in accordance with the energy and momentum conservation laws, have been another particle emitted that had to be neutral (there being no second track) and light [since it took away an overwhelming part of the decay energy $(m_\pi - m_\mu - 4\ \text{MeV})$]. This particle could not be a γ-quantum, since no tracks from a conversion e^+e^--pair were observed in the vicinity of the $(\pi \to \mu)$-decay. Therefore, the conclusion was drawn that this particle had to be a neutrino, the existence of which was predicted by Pauli in 1930 for explaining the β-decay paradoxes:

$$\pi^+ \to \mu^+ + \nu\,. \tag{7}$$

A similar analysis of the second $(\mu^+ \to e^+)$-decay vertex led to the conclusion that a positron (the energy of which differed from decay to decay) was being emitted together with two other light neutral particles — a neutrino and an antineutrino:

$$\mu^+ \to e^+ + \nu + \tilde{\nu} \tag{8}$$

(the emission of a third neutrino contradicts the angular momentum conservation law, since all the particles participating in the scheme (8) have spin 1/2).

For more than a decade the decay schemes (7) and (8) gave rise to no doubt whatsoever. They seem quite plausible even now, since both the number of neutral particles and the fact that these particles are a neutrino and an antineutrino were guessed correctly. Nevertheless, in 1957 they were proved to be wrong (see Section 3.3).

Events of the second type were represented by the track of a particle of mass $m \approx 300m_e$, the stopping point of which was the vertex of a so-called star comprising several proton tracks. Such events were interpreted as the nuclear capture of a negatively charged π-meson, accompanied by the release of an energy $m_\pi c^2 \approx 150$ MeV at the expense of which the nuclear fission with the liberation of several protons occur (and neutrons leaving no tracks).

Later on, when the artificial production of π-mesons with the aid of proton accelerators was mastered (see Section 3.4) and it became possible to expose photoemulsion films to pure beams of π^--mesons (without any π^+ contamination), it turned out that among tens of thousands of nuclear capture events not even a single $(\pi^- \to \mu^-)$-decay was observed. Hence it follows that the lifetime of a π^--meson in dense matter before it is captured by the nucleus is at least $10^4 - 10^5$ times shorter than its lifetime with respect to the $(\pi^- \to \mu^-)$-decay in vacuum $(2.6 \times 10^{-8}$ s). Of the other estimates we present the mean range of a π-meson in the photoemulsion, $l \approx 25$ cm, from which it follows that the interaction cross section of a pion with a nucleus is equal to

$$\sigma = \frac{1}{n_{\text{nucl}}\, l} \approx 10^{-24}\ \text{cm}^2\,, \tag{9}$$

i.e. it equals the geometric cross section πR^2_{nucl} of the nucleus $(n_{\text{nucl}} \simeq 10^{22}\ \text{cm}^{-3}$ is the concentration of nuclei in the photoemulsion, $R_{\text{nucl}} \simeq 10^{-12}$ cm is the radius of a nucleus). And this means that a π-meson hitting a nucleus is sure to be captured. The average range of a π^--meson *in a nucleus* is then

$$l_{\text{nucl}} \simeq \frac{1}{n_N \sigma} = 10^{-14}\ \text{cm}$$

$(n_N = 10^{38}\ \text{cm}^{-3}$ is the concentration of nucleons in the nucleus), i.e. it is smaller than the nucleon radius $(0.8 \times 10^{-13}$ cm). And this requires the time

$$\Delta t = \frac{l_{\text{nucl}}}{c} \simeq 10^{-24}\ \text{s},$$

i.e. the nuclear time τ_{nucl}. Now, compare this result with the lifetime of a negative muon *inside* a lead *nucleus* $(\tau = 7 \times 10^{-8}$ s), during which it can cover, without being absorbed, a path in $l = c\tau_\mu \simeq 2 \times 10^3$ cm the *nuclear matter*, which is approximately equal to 10^{15} cross sections of the nucleus.

[14] To retrieve an intact stack was a difficult task, since individuals who found a stack often opened it and exposed it to light, in spite of a written notification. Moreover, the balloons were often carried abroad by the air flow.

3.3 Lepton number conservation laws. Corrected decay schemes of pions and muons

The photoemulsion method turned out to be very convenient and illustrative for a more profound study of the decay schemes of muons and pions, as compared to the one performed earlier: it made possible the substitution of correct schemes for the erroneous ones (7), (8). We mentioned above that the decay schemes (7) and (8) were quite verisimilar, since they apparently satisfied the necessary laws of conservation of energy, momentum, angular momentum and electric charge. Only one circumstance did not fit in: neither a single $\mu^+ \to e^+ + \gamma$ event, nor any three-particle decay

$$\mu^+ \to e^+ + e^+ + e^- \tag{10}$$

were found among the numerous muon decays observed, whereas both decay modes are allowed by all the aforementioned conservation laws, and they are very convenient for observation by the photoemulsion method: it is impossible to miss them during scanning.

The question arose as to why the muon cannot decay, according to scheme (10), only into electrons and positrons, without being accompanied by a neutrino and antineutrino, or into a positron and gamma quantum? In what do muons differ so much from electrons and positrons that such decays are forbidden? Indeed, these particles can all be either negatively or positively charged ($\mu^\pm$ and $e^\pm$); they interact weakly with nuclei in the same manner, which is manifested even in extremely subtle effects — in the violation of spatial parity (see Section 3.4); they have identical spins $J = 1/2$ and have magnetic moments that are similar in their formation structures:

$$\mu_e = \frac{e\hbar}{2m_e c}\,, \quad \mu_\mu = \frac{e\hbar}{2m_\mu c}\,. \tag{11}$$

The only thing in which the muon differs quite clearly from the electron is its mass ($m_\mu = 207 m_e$). But why is mass important here? Indeed, the mass only determines the direction of decay — from the heavy particle to the light one.

It turned out that the reason for no muon decays $\mu^+ \to e^+ + \gamma$ and $\mu \to 3e$ to exist actually consists in the character of the interaction. In spite of the fact that muons and electrons interact with nuclei in very similar manners (and this was subsequently demonstrated in the weak interaction theory), these interactions are manifested somewhat differently. In 1957 (already after Pauli's neutrino had been examined experimentally, see Section 3.5), the hypothesis was put forward (in Russia by M A Markov, and abroad by K Nishijima and E Schwinger [15]) that there exist two types of neutrinos — the Pauli electron neutrino (ν_e) and a new muon neutrino (ν_μ), each of which has its own antiparticle ($\tilde{\nu}_e$ and $\tilde{\nu}_\mu$). Electron neutrinos and antineutrinos accompany weak interaction processes involving electrons and positrons, while muon neutrinos and antineutrinos attend processes involving muons (μ^+ and μ^-). Therefore, the correct decay modes are the following

$$\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu\,, \tag{12}$$

$$\mu^- \to e^- + \tilde{\nu}_e + \nu_\mu\,. \tag{13}$$

In these decays muons pair with muon neutrinos (antineutrinos), and electrons (positrons) with electron neutrinos (antineutrinos); in both decay modes ν_e and $\tilde{\nu}_\mu$ (ν_μ and $\tilde{\nu}_e$) are not particle and antiparticle, since they pertain to different neutrino types, while the modes $\mu \to e + \gamma$ and $\mu \to 3e$ are not realized in nature because they involve neither one neutrino type nor the other.

Five years later the hypothesized existence of the muon neutrino was confirmed experimentally (see Section 3.5), and at present numerous weak processes of muon and electron types are known. Electrons (e^-, e^+), muons (μ^-, μ^+), and both types of neutrinos (ν_e, $\tilde{\nu}_e$, ν_μ and $\tilde{\nu}_\mu$) are all called leptons (meaning 'light').

In a somewhat formal (but quite convenient) way, the aforementioned peculiarity exhibited by the weak interaction is described by the introduction of laws of conservation of the electron and muon lepton numbers (charges) L_e and L_μ [16]. We stress that these are *different* charges that are conserved independently of each other, although numerically they are denoted identically. Thus, $L_e(e^-) = L_e(\nu_e) = +1$, $L_e(e^+) = L_e(\tilde{\nu}_e) = -1$, while L_e of all other particles (for example, the γ-quantum, the π-meson, the neutron and the proton), including μ^+, μ^-, ν_μ and $\tilde{\nu}_\mu$, are zero. Similarly, $L_\mu(\mu^-) = L_\mu(\nu_\mu) = +1$, $L_\mu(\mu^+) = L_\mu(\tilde{\nu}_\mu) = -1$, and $L_\mu(\gamma, \pi, n, p, e^+, e^-, \nu_e, \tilde{\nu}_e) = 0$. In the left- and right-hand parts of the correct μ^+-decay mode ($\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu$), the values of L_μ both equal -1, and the values of L_e are both equal to 0, i.e. both lepton numbers are conserved. As to the mode $\mu^+ \to e^+ + e^+ + e^-$, in its left-hand part $L_e = 0$ and $L_\mu = -1$, while in its right-hand part $L_e = -1$ and $L_\mu = 0$. The same discrepancy between the values of L_e and L_μ is observed in the ($\mu^+ \to e^+ + \gamma$)-decay mode. We have dealt with this issue in such detail, because we shall apply the notion of lepton charges more than once in subsequent sections of this article.

In conclusion of this subsection we draw attention to the simplicity of interpreting ($\pi \to \mu$)-decay modes with the aid of lepton numbers. Above we noted that the character of the observed π^+-meson decay events revealed these decays to involve the emission of a positive muon and a neutrino. From the preceding text, it should evidently be a muon neutrino:

$$\pi^+ \to \mu^+ + \nu_\mu\,, \tag{14}$$

since $L_\mu(\pi^+) = 0$, $L_\mu(\mu^+) = -1$ and $L_\mu(\nu_\mu) = +1$, whereas all three particles have L_e equal to zero. The decay scheme of negative π-mesons in vacuum (air), where they have no time to be captured by nuclei before decaying, is quite similar:

$$\pi^- \to \mu^- + \tilde{\nu}_\mu\,. \tag{15}$$

3.4 Spatial parity conservation law and the experimental proof of its violation in β- and (π → μ → e)-decays

One of the important conservation laws that is obeyed in strong and electromagnetic interactions is the law of conservation of spatial parity P. According to this law, the absolute value squared of the wave function describing the probability to find a particle at a given point (x, y, z) in space exhibits symmetry with respect to spatial inversion, i.e.

[15] E Schwinger together with R Feynman and S Tomanaga were awarded the Nobel Prize in physics in 1965 for the creation of relativistic quantum electrodynamics.

[16] The law of conservation of the electron lepton number L_e (being the only one before L_μ was introduced) was widely applied in interpretion of the β-decay.

satisfies the condition

$$\left|\psi(-x,-y,-z)\right|^2 = \left|\psi(x,y,z)\right|^2 . \qquad (16)$$

This result follows from the symmetry of the Hamiltonian of the Schrödinger equation. Taking into account the properties of complex functions with identical absolute values and the symmetry of functions $\psi(x,y,z)$ and $\psi(-x,-y,-z)$ with respect to spatial inversion, it follows from Eqn (16) that, first, the wave functions themselves must exhibit in this case either even or odd parity:

$$\psi(-x,-y,-z) = \pm\psi(x,y,z) , \qquad (17)$$

and, second, that the angular distribution of outgoing particles should be symmetric about the angles θ and $\pi - \theta$ (recall the relation between the orthogonal and spherical coordinate systems). Therefore, if the P-parity conservation law holds true, then the expansion of the angular distribution function in terms of $\cos\theta$ should contain no terms with odd powers of $\cos\theta$. This is confirmed by experimental studies of the angular distributions of α-particles and γ-quanta emitted in respective radioactive decays, and also of particles produced in nuclear reactions under the influence of strong and electromagnetic interactions. Figuratively, one can say that in the case of strong and electromagnetic interactions nature does not distinguish right from left.

In 1956, the theoretical physicists T Lee and Ch Yang proved the parity conservation law to be violated (see Section 6.1) in the weak interaction. In 1957 this was demonstrated for the β-decay by C Wu in an elegant experiment that was very difficult, since atomic nuclei had to be polarized, for which magnetic field strengths of $\sim 10^5$ G and extremely low temperatures ~ 0.01 K were required. The experiment revealed that polarized $^{60}_{29}$Co nuclei predominantly emit electrons in the direction opposite to the spins of the nuclei, i.e. that mirror symmetry does not exist in a β-decay, and that, consequently, the parity conservation law is violated [17].

According to the universal theory of weak interaction, the violation of parity conservation law must take place in any weak process, including, for example, the $(\pi \to \mu \to e)$-decay and the decays of strange particles (Section 6.5). In the $(\pi \to \mu \to e)$-decay, the violation of P-parity should result in asymmetry of the outgoing electrons (positrons) with respect to the muon spin. The photoemulsion method makes it possible to observe this effect in an experiment that is as elegant as the Wu experiment, but not quite so difficult. The point is that the muon emitted in the $(\pi \to \mu)$-decay is automatically produced in a polarized state. Schematically, this is shown in Fig. 2 where the thin arrows are directed along the muon and neutrino momenta, while the double arrows point along their helicities (the projections of spins onto the momenta). The momentum and angular momentum conservation laws, together with the fact that the spin of the π-meson equals zero (see Section 4.1) and that the neutrino's helicity is left-handed (Section 3.6), result in the positive muon produced in the π-meson decay also acquiring left-handed helicity.

That this proceeds automatically is, naturally, wonderful! But how can it be seen? Certainly, the spin cannot be

[17] We note that in another experiment performed with the β^+-radioactive isotope $^{58}_{29}$Co the positrons were mainly emitted along the spins of the nuclei.

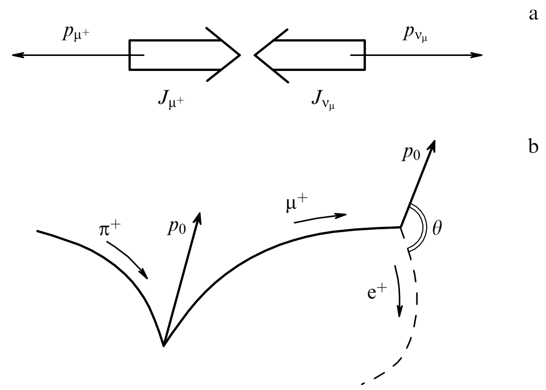

Figure 2. Properties of the $(\pi \to \mu \to e)$-decay: (a) polarization of muons in the $(\pi \to \mu)$-decay process, and (b) asymmetry of outgoing positrons in the $(\mu \to e)$-decay process.

seen in photoemulsion! The question then arises: how can one study the angular asymmetry of positrons relative to the muon spin that is not observable? Here is where the most interesting part starts. Indeed, the spin is not seen but we know how the spin of the μ^+ was directed when the $(\pi^+ \to \mu^+)$-decay occurred: against its momentum. And we also know that in the course of the muon slowing-down, when its momentum varies both in value and direction, the direction of the muon spin cannot change, since it is related to the orientation of its magnetic moment that can be altered only with the aid of a magnetic field, while no magnetic field was present in the experiment. Thus, if in the experiment an asymmetry of the outgoing positrons with respect to the muon momentum p_0 is observed *at the moment the muon is produced* (see Fig. 2b), this will be evidence of parity violation in the $(\mu \to e)$-decay. The experiment yielded the asymmetry:

$$dN \sim (1 - a\cos\theta) , \qquad (18)$$

where $a > 0$. Most of the positrons produced in the $(\mu^+ \to e^+)$-decay are directed against the initial muon momentum, i.e. along its spin (see Fig. 2a). This result fully coincides with the predictions of the universal theory of weak interactions (compare with the β^+-decay of $^{58}_{29}$Co).

3.5 Experimental confirmation of the existence of and the difference between the electron and muon neutrinos. Spark chamber

In this section we shall deal with two remarkable experiments that confirmed the existence of electron and muon neutrinos as well as the difference between them. The idea of the experiments is best understood if one takes advantage of the lepton charge conservation laws introduced above. In accordance with these laws, the $\beta^\pm$-decay of nuclei that reduces to the transformation of a proton (neutron) of the nucleus into a neutron (proton) proceeds as follows

$$p \to n + e^+ + \nu_e , \qquad (19)$$
$$n \to p + e^- + \tilde{\nu}_e , \qquad (20)$$

which satisfy the laws of conservation of both lepton and electric charges. Once again, we stress that in spite of the absence of an electric charge ν_e and $\tilde{\nu}_e$ differ from each other to quite the same extent as e^- and e^+ (they have different values of L_e). Therefore, they cannot be substituted for each other in schemes (19) and (20). Both aforementioned conservation laws, however, permit a particle to be transferred from the left-hand part of the decay scheme to the right-hand part and vice versa, with substitution of the antiparticle for the particle (the so-called algebra of particles and antiparticles). As a result, the $\beta^{\pm}$-decay scheme transforms into the scheme of inverse β-decay:

$$\tilde{\nu}_e + p \to n + e^+ , \tag{21}$$
$$\nu_e + n \to p + e^- . \tag{22}$$

The idea underlying the experimental proof of the existence of the electron neutrino (more correctly, antineutrino) is based on the application of scheme (21).

The experiment was conducted in 1953 by C Cowan and F Reines [10] who used the beam of electron antineutrinos emitted by a nuclear reactor as the $\tilde{\nu}_e$ source. The experimental setup is depicted in Fig. 3a. It consists of three large ($1.9 \times 1.3 \times 0.6$ m) detector tanks D_1, D_2, D_3 separated by two target tanks 7 cm thick each. The detector tanks were filled with a scintillating liquid and were viewed by 110 photomultipliers, while the target tanks were filled with water containing soluble cadmium salt. The setup was placed deep under ground in the vicinity of the reactor and was shielded against the γ-rays and neutrons from the reactor by lead and paraffin.

As follows from reaction (21), the interaction of a reactor antineutrino with a target proton must result in the production of a neutron and a positron. Collisions with nuclei slow the neutron down to the energy of thermal motion, upon which it undergoes diffusion and is ultimately absorbed by cadmium, which is accompanied by the emission of several γ-quanta with a total energy of up to 10 MeV that are registered by the coincidence circuit of detectors D_1 and D_2. The γ-quanta resulting from the annihilation of a positron with an atomic electron of the target ($E_{2\gamma} \cong 1$ MeV) are registered in a similar way. Owing to the time spent by the neutron during slowing-down and diffusion, the signal of its absorption in Cd arrives later than the annihilation signal. Moreover, they differ in amplitude. The amplitudes of the signals and the time delay between them were analyzed with the aid of an analyzer and a triple-beam oscilloscope (Fig. 3b). The exposure time of the setup amounted to 1400 hours, and the average registration rate was 2.88 ± 0.22 events per hour. Estimation of the interaction cross section for process (21) yielded $\sigma \simeq 10^{-43}$ cm^2. This result was confirmed by a series of control experiments. It is important to underline that, unlike previous indirect experiments in which the measured effect was due to neutrinos leaving the β-radioactive target studied, in the experiment performed by Reines and Cowan the direct interaction of *free* antineutrinos emitted by a *remote* source with protons of the target was registered. In 1995, F Reines was awarded the Nobel Prize in physics [11] (C L Cowan had already passed away by that time).

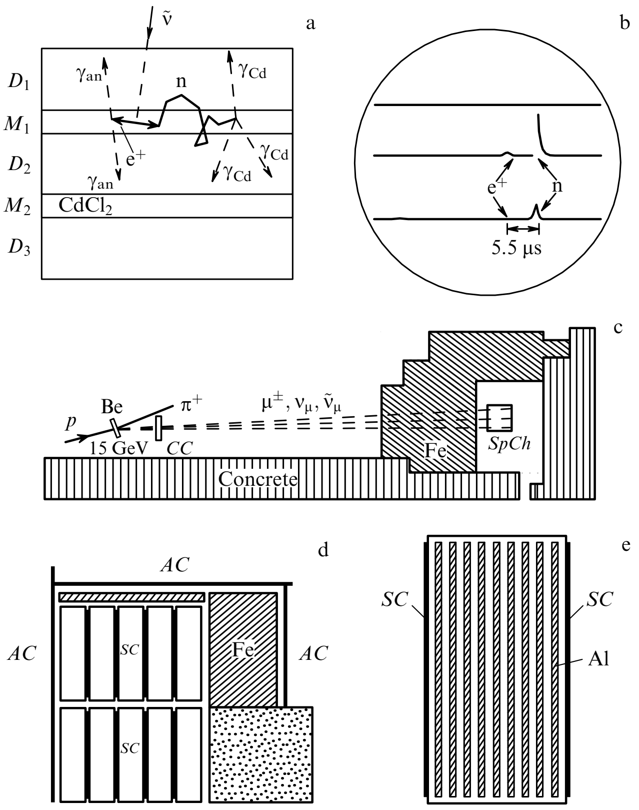

Figure 3. Layout of experiments for demonstrating the existence of ν_e and ν_μ: (a) layout of the experiment conducted by Reines and Cowan; (b) photograph of signals from positron annihilation and neutron capture in Cd; (c) layout of the experiment of Lederman et al.; (d) layout of spark chamber; (e) one of its sections.

The existence of the muon neutrino and its difference from the electron neutrino was experimentally demonstrated in 1962 in an experiment performed by L Lederman, M Schwartz, J Steinberger at the 30-GeV proton accelerator of Brookhaven (USA). The idea of the experiment consisted in investigating the interaction of nucleons with muon neutrinos ν_μ and antineutrinos $\tilde{\nu}_\mu$, which in the case of $\nu_\mu \neq \nu_e$ and $\tilde{\nu}_\mu \neq \tilde{\nu}_e$ should not proceed according to schemes (21) and (22) with the substitution of ν_μ for ν_e and of $\tilde{\nu}_\mu$ for $\tilde{\nu}_e$, but in accordance with the new schemes satisfying the law of conservation of muon lepton charge:

$$\nu_\mu + n \to \mu^- + p , \tag{23}$$
$$\tilde{\nu}_\mu + p \to \mu^+ + n . \tag{24}$$

The experimental layout is shown in Fig. 3c. The muon neutrinos ν_μ and antineutrinos $\tilde{\nu}_\mu$ originated in the decay processes (14) and (15) of $\pi^{\pm}$-mesons produced with an energy of ~ 15 GeV on the beryllium target of the accelerator. For the detection of processes (23) and (24), a large (10-ton) spark chamber (SpCh) was used, in which the tracks of charged particles were chains of sparks formed along the trajectories of particles in the gaps between the plates of the chamber, when high voltage (5 kV) was applied to them. Here, muon tracks could be distinguished from electron tracks from the structure of the spark chains.

The chamber consisted of 10 sections with 9 aluminium plates of dimensions $110 \times 110 \times 2.5$ cm, assembled with 1.0-cm gaps. The sections were separated from each other by flat scintillation counters (SC) operating in coincidence with a Cherenkov counter (CC) that registered the incident beam of $\pi^{\pm}$-mesons (see Figs 3d, e). The chamber was triggered (high voltage was applied to its plates) when the coincidence circuit produced a signal, i.e. only when an event of interest of type (23) or (25) occurred. For protection from fast $\pi^{\pm}$-mesons and muons, the chamber was placed inside a specially constructed housing of concrete, steel, lead, and paraffin, and it was also surrounded by a system of scintillation counters included in an anticoincidence circuit [18].

In all 350 hours of exposure were required for registering 60 events of types (23) and (24) differing drastically from the events of types (21), (22) in the structure of their spark chains. Thus, the experiment described yielded the proof that $\nu_\mu \neq \nu_e$ and $\tilde{\nu}_\mu \neq \tilde{\nu}_e$. An additional experiment [13] was later performed with an even heavier spark chamber (45 tons) in which events caused by a sole ν_μ (without any admixture of $\tilde{\nu}_\mu$) were studied, and they were shown to result only in the production of μ^- (without any admixture of μ^+), from which it follows that $\tilde{\nu}_\mu \neq \nu_\mu$.

3.6 Discovery of the τ-lepton and experimental proof of the existence of the τ-neutrino

In 1975–1978, M Pearl discovered the third sort of charged leptons [14], which was termed precisely the τ-lepton (from the first letter of the Greek word *τριτον* meaning 'third'). Its mass is $m_\tau = 1777 \pm 3$ MeV, which is somewhat too much (nearly $2m_p$) for a 'light' particle (lepton means light). The τ-lepton, however, is similar to the electron and muon in all its other properties. It constitutes a particle that has two charge states (τ^+ and τ^-); it has spin 1/2 and a lifetime $\tau_\tau \simeq 3 \times 10^{-13}$ s, and it decays via several decay channels with indispensable participation of the third sort of neutrino, the τ-neutrino ν_τ (and the τ-antineutrino $\tilde{\nu}_\tau$):

$$\tau^- \begin{array}{l} \nearrow \ \mu^- + \tilde{\nu}_\mu + \nu_\tau\,, \\ \rightarrow \ e^- + \tilde{\nu}_e + \nu_\tau\,, \\ \rightarrow \ \pi^- + \nu_\tau\,, \\ \searrow \ \rho^- + \nu_\tau\,, \end{array} \qquad \tau^+ \begin{array}{l} \nearrow \ \mu^+ + \nu_\mu + \tilde{\nu}_\tau\,, \\ \rightarrow \ e^+ + \nu_e + \tilde{\nu}_\tau\,, \\ \rightarrow \ \pi^+ + \tilde{\nu}_\tau\,, \\ \searrow \ \rho^+ + \tilde{\nu}_\tau\,. \end{array} \tag{25}$$

We note that the discovery of τ-leptons also involved certain exotics. True, this time it did not arise spontaneously, like in the cases considered above, but was conceived beforehand. The point is that the τ-lepton was sought in anomalous events such as

$$e^+ + e^- \to \mu^+ + e^- \quad (\text{or } \mu^- + e^+)\,, \tag{26}$$

which should apparently not exist, owing to violation of the laws of conservation of lepton numbers in expression (26). But let us follow the order of events in our story.

The τ-leptons were sought in experiments performed in the colliding e^+e^--beams of the storage ring SPEAR of the Stanford linear accelerator with the aid of a magnetic detector that included flat and cylindrical spark chambers as well as shower and Cherenkov counters. Such a detector allowed one to register e^+e^--annihilation processes in which at least two charged particles with quite long lifetimes were produced, for example, the following ones

$$e^+ + e^- \to \mu^+ + \mu^-\,, \qquad e^+ + e^- \to \pi^+ + \pi^-\,. \tag{27}$$

The production of τ-leptons by the following similar scheme

$$e^+ + e^- \to \tau^+ + \tau^- \tag{28}$$

could not be detected by the detector, since owing to their short lifetimes they decayed in the vicinity of the production point, even without reaching the experimental setup (Fig. 4).

[18] During an excursion to the ring of the Brookhaven accelerator that was under construction, the guide, in particular, told the participants of the 1960 International Conference on High-Energy Physics that the front wall of the housing was to be built making use of armored plates from obsolete battleships of the US Navy.

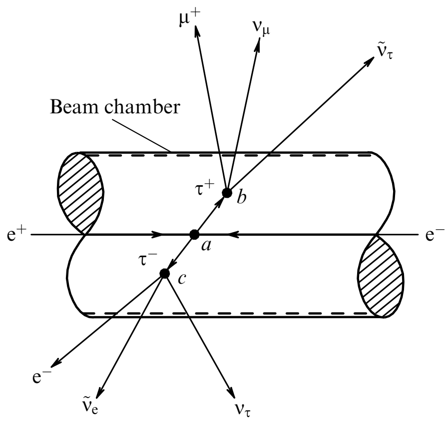

Figure 4. Scheme of production and decay of τ-leptons.

Therefore, the τ-lepton could only be detected by revealing its charged decay products. Here, it was necessary to choose such decay channels of the τ-leptons, in which particles were produced that were not encountered in other annihilation processes [for example, of type (27)]. This condition can be satisfied if the τ^+-lepton decays via the channel $\tau^+ \to \mu^+ + \nu_\mu + \tilde{\nu}_\tau$, and the τ^--lepton via the channel $\tau^- \to e^- + \tilde{\nu}_e + \nu_\tau$. Then the production and decay process of τ-leptons proceeding via the overall scheme

$$e^+ + e^- \to \tau^+ + \tau^- \to \mu^+ + \nu_\mu + \tilde{\nu}_\tau + e^- + \tilde{\nu}_e + \nu_\tau \tag{29}$$

will be perceived by the detector (which sees neither τ-leptons nor neutrinos) as 'anomalous' processes of type (26). A detailed analysis of these 'anomalous' processes first permitted the estimation of the τ-lepton mass (~ 1.8 GeV) and at a later time the establishment of the correct decay scheme (25).

Subsequent achievements in determining the properties of the new lepton were related to thorough investigations into the electron mode of this decay scheme, $\tau^- \to e^- + \tilde{\nu}_e + \nu_\tau$, in particular, into the electron spectrum, which showed the features of the $\tau^- \to e^-$ decay to be consistent with the universal theory of weak interaction and permitted the determination of the exact value of the τ-lepton mass, of its lifetime (the value of which agrees with the theoretical expectations for a particle with such a mass) and of its spin (1/2), and also the estimation of the τ-neutrino mass ($m_{\nu_\tau} < 35$ MeV). From the relationship between the decay widths of τ-leptons decaying via various channels it follows that the spin of ν_τ is 1/2.

In the light of the above it is natural to consider the τ-lepton to be analogous in properties to the other two charged leptons — the electron and the muon — and that like them it should be characterized by a new lepton number L_τ equal to $+1$ for τ^- and ν_τ, to -1 for τ^+ and $\tilde{\nu}_\tau$, and to zero for all other particles (including e^-, e^+, μ^-, μ^+, ν_e, $\tilde{\nu}_e$, ν_μ and $\tilde{\nu}_\mu$). And like the electron and the muon, the τ-lepton can be considered a pointlike particle with a radius $R < 10^{-16}$ cm.

With the discovery of the τ-lepton the total number of charged leptons and respective neutrinos (such pairs are termed generations) has risen up to three. And, while with the first generation it had long ago been clear as to 'why it exists' — the electron serves for the formation of the atomic electron shells, and the electron neutrino participates in the Bethe solar cycles, the discovery of the second generation (μ and ν_μ) quite drastically gave rise to the problem of the existence of the muon — nearly a 'copy' of the electron (with the exception of its mass), which was formulated as the question: what is the muon needed for? And now we have one more 'copy'! What for? At present theoreticians consider the answer to these questions to exist. But we shall present it to you after having dealt with two important issues: the violation of CP-invariance in the decays of K-mesons (see Section 6.7) and the existence of three quark generations (see Section 8.3).

And now we shall recount what information we succeeded in extracting from the Internet about an absolutely fantastic experiment concerning the issue under consideration. On 21.07.2000, an international collaboration comprising 54 physicists from the USA, Japan, Korea and Greece working at the Fermi Laboratory (Batavia, USA) announced they had obtained experimental proof of the existence of the tau-neutrino ν_τ that had been predicted long ago. The physicists observed 4 interactions of ν_τ with atomic nuclei (i.e. with the protons and neutrons of a nucleus) that proceeded via channels (23), (24) with the substitution of ν_τ, $\tilde{\nu}_\tau$, τ^-, τ^+ for ν_μ, $\tilde{\nu}_\mu$, μ^-, μ^+, respectively:

$$\nu_\tau + \mathrm{n} \to \tau^- + \mathrm{p}\,, \quad \tilde{\nu}_\tau + \mathrm{p} \to \tau^+ + \mathrm{n}\,. \tag{30}$$

The existence of ν_τ turned out to be proved only 38 years after the experiment that demonstrated the existence of ν_μ (1962) was performed, and 47 years later than when (1953) the first information was obtained on the existence of ν_e [19].

The work started in 1997, when at the Tevatron a neutrino beam of high intensity was obtained, which in the opinion of physicists contained ν_τ. The beam passed through the three-foot target of the detector DONUT (Direct Observation of the Nu Tau) consisting of alternating iron plates and layers of photoemulsion. One of the 10^{12} ν_τ interacted with the nuclei of iron and produced a τ-lepton that left a specific track ~ 1 mm long in the photoemulsion. It took the physicists three years to reveal these tracks and to identify them as tracks of τ-leptons and their decay products. We note that in the modern version of the photoemulsion method described in Section 3.2 scanning devices are used that are equipped with computer-controlled videocameras permitting one to obtain three-dimensional images of the particle tracks formed in the emulsion.

The electronic devices of the DONUT detector (with a total length of 50 feet!) recorded 6×10^6 potential interactions, the analysis of which permitted the researchers to single out about 1000 candidates for the events sought. And only four of them turned out to be interactions that proceeded along schemes (30). Regretfully, this is all we can say now about this superexotic experiment. No real publications with descriptions of the experimental setup and of the data processing are available yet, and what we have presented above is only based on the first announcement of the discovery made.

[19] As legend goes (extracted from the Internet and connected with the described discovery) the Nobel Prize winner in physics L Lederman said approximately the following: "When we discovered ν_μ, the number of different sorts of neutrinos rose from one to two. Now I learn there are three, so I predict popular indignation: why couldn't you fellows agree from the beginning on how many there would be, two or three!" Naturally, Lederman was joking, because we know quite well that the "fellows" had long ago agreed upon three types of neutrinos. It is another thing that it took a very long time for the third one to arrive.

3.7 What is known about ν_e, ν_μ and ν_τ today

To conclude the discussion of charged and neutral leptons, several words are due on what is known at present about the neutrinos of all the three generations. According to the most conventional point of view, which goes back to the Dirac theory and has not yet resulted in any contradiction with experiments, all the sorts of neutrinos (ν) and antineutrinos ($\tilde{\nu}$) have spin 1/2 and a mass very close (or simply equal) to zero. All the ν exhibit left-handed helicity, and all the $\tilde{\nu}$ right-handed. All ν and $\tilde{\nu}$ undergo only weak and gravitational interactions. The interaction cross section of ν_e with matter (nucleons) at $E_\nu \simeq 1$ MeV is approximately $10^{-43}\,\mathrm{cm}^2$, and it increases, first, quadratically and, then, linearly with energy and may amount to $0.7 \times 10^{-38}\,\mathrm{cm}^2$ at $E_\nu \simeq 1$ GeV. The electron neutrino is assumed to have a magnetic moment (which is necessary for one of the possible explanations of the deficit of solar neutrinos).

Modern experimental and theoretical estimates of the neutrino masses are the following: $m_{\nu_e} < 2.5$ eV (from the β-decay of tritium [15]); $m_{\nu_\mu} < 0.17$ MeV [from the $(\pi \to \mu)$-decay], and $m_{\nu_\tau} < 24$ MeV (from the decay of the τ-lepton). From astrophysical estimates one has $m_{\nu_e} + m_{\nu_\mu} + m_{\nu_\tau} < 40$ eV. Estimates based on another theoretical model (the so-called seesaw mechanism) yield: $m_{\nu_e} \leqslant 2 \times 10^{-4}$ eV, $m_{\nu_\mu} \leqslant 3 \times 10^{-3}$ eV, and $m_{\nu_\tau} \leqslant 10^{-1}$ eV.

If $m_\nu \neq 0$, neutrino oscillations can occur, which should result in neutrinos of one flavor transforming into neutrinos of another flavor. No reliable experimental observations have been made of either solar, or atmospheric, or reactor, or accelerator neutrino oscillations. Attempts are being made at resolving the problem of the electron neutrino mass being equal to or differing from zero with the aid of extremely difficult experiments (carried out deep under ground with the use of particularly sensitive devices) in search of neutrinoless double β-decay ($2\beta0\nu$), the observation of which will be evidence, according to the Majorana theory, that $m_{\nu_e} \neq 0$. In Majorana's theory, unlike Dirac's theory, the assumption is made that $\nu \equiv \tilde{\nu}$, i.e. the neutrino is considered a truly neutral particle which, however, can exist in two different (left-hand and right-hand) polarization states. The difference in polarization direction permits one to distinguish left neutrinos from right ones with the same certainty as the lepton charge permits us to distinguish Dirac neutrinos from antineutrinos. Thus, in spite of the lepton number in Majorana's theory not being conserved, it does not contradict experiment if its validity is proved. According to the most recent data, the best estimate for the lower half-life bound of the $2\beta0\nu$-process obtained by a Heidelberg–Moscow collaboration is $T_{1/2}(2\beta0\nu) > 5.7 \times 10^{25}$ a, which yields for the upper bound of the Majorana mass of the electron neutrino: $m_{\nu_e}^{(\mathrm{M})} \leqslant 0.2$ eV [16]. More details concerning the properties of neutrinos, the double β-decay, neutrino oscillations and other theoretical and experimental issues of neutrino physics can be found in reviews [17, 18].

4. The production of π-mesons in the laboratory and investigation of their properties and interactions

From the existence of strong nuclear absorption of π-mesons, mentioned in Section 3.2, follows the large probability of the inverse process — the production of π-mesons in nuclear interactions. In Section 2 we said that in nature π-mesons are produced precisely in such processes involving protons of sufficiently high energy. This means that π-mesons can be obtained artificially in laboratory conditions using proton (and neutron) beams, if their energy exceeds the production threshold of the π-meson.

The simplest $\pi^{\pm}$-meson production reactions satisfying the laws of conservation of energy, momentum, electric charge and baryon number (in our case — the number of nucleons, which was known to be conserved in all ordinary nuclear reactions and, also, in α- and β-decays) are the following:

$$n + p \to \pi^- + p + p, \qquad p + p \to \pi^+ + p + n\,. \tag{31}$$

The threshold of these reactions can be determined from the energy and momentum conservation laws and is $T^{\min} = 290$ MeV.

If as a target one does not make use of protons, i.e. of liquid or gaseous (at a high pressure) hydrogen, but of heavier elements (for instance, beryllium or copper), then owing to the Fermi motion of nucleons in the target nuclei the reaction threshold is reduced to about 200 MeV. In this case it becomes possible for $\pi^{\pm}$-meson production processes to occur not only on protons, but also on neutrons of the nuclear target:

$$p + n \to \pi^+ + n + n\,, \tag{32}$$
$$p + n \to \pi^- + p + p\,, \tag{33}$$
$$n + n \to \pi^- + p + n\,. \tag{34}$$

The $\pi^{\pm}$-mesons produced in reactions (31)–(34) are formed into beams with the aid of magnetic channels and are used for studying both the properties of $\pi^{\pm}$-mesons themselves and reactions of their interactions with nucleons and nuclei.

4.1 The mass, lifetime, spin and intrinsic parity of $\pi^{\pm}$-mesons. The CPT-theorem. The principle of detailed balance

First of all, the $\pi^{\pm}$-meson beams of high intensity were used for determining precise values of their masses and lifetimes, as well as the masses and lifetimes of muons:

$$m_{\pi^{\pm}} = 273.13 m_e\,, \quad \tau_{\pi^{\pm}} = 2.6 \times 10^{-8}\ \mathrm{s}\,, \tag{35}$$
$$m_{\mu^{\pm}} = 206.77 m_e\,, \quad \tau_{\mu^{\pm}} = 2.2 \times 10^{-6}\ \mathrm{s} \tag{36}$$

(the values presented are not the most precise ones).

It is obvious that both lifetimes are determined by the weak interaction, since they are quite large. As we saw in Section 3.2, and in accordance with our more detailed discussion in Section 3.3, no more rapid electromagnetic $\pi^{\pm}$-meson decay channels ($\pi^{\pm} \to \mu^{\pm} + \gamma$ and $\mu^{\pm} \to e^{\pm} + \gamma$) exist. Moreover, we note that like the electron and positron π^+ and π^- as well as μ^+ and μ^- are the particle and antiparticle of each other, so in accordance with the CPT-theorem [20] they have identical masses, spins and lifetimes.

Besides their mass and lifetime, $\pi^{\pm}$-meson beams were also used in determining other important parameters of these particles, such as, for example, their spin J and intrinsic parity P. From the structure of the $\pi^{\pm}$-meson production reactions (31)–(34), $\pi^{\pm}$-mesons clearly pertain to the class of bosons, i.e. their spin can only take an integer value (0, 1, 2, ... in units of $\hbar$), since the nucleons participating in the reactions have half-integer spin (1/2). The correct π-meson spin was chosen from this set of spin values on the basis of the detailed balance principle as applied to the two following mutually inverse reactions:

$$\pi^+ + {}^2_1\mathrm{H} \to p + p\,, \tag{37}$$
$$p + p \to \pi^+ + {}^2_1\mathrm{H}\,. \tag{38}$$

According to this principle, the two differential reaction cross sections

$$\frac{d\sigma(\pi^+\,{}^2_1\mathrm{H})}{d\omega} \quad \text{and} \quad \frac{d\sigma(pp)}{d\omega}$$

measured at the momenta p_{π^+} and p_p (in the center-of-mass system) of the π^+-meson and proton, respectively, and the spins of the proton ($J_p = 1/2$), deuteron ($J = 1$), and π^+-meson ($J_{\pi^+} = ?$) are related as follows

$$(2J_p + 1)^2 p_p^2 \, \frac{d\sigma_{pp}(\theta)}{d\omega} = (2J_{{}^2_1\mathrm{H}} + 1)(2J_\pi + 1)\, p_{\pi^+}^2 \, \frac{d\sigma_{\pi^+\,{}^2_1\mathrm{H}}(\theta)}{d\omega}\,, \tag{39}$$

where the only unknown quantity is the spin J_{π^+} of the π^+-meson. Measurements of the cross sections for the direct and inverse processes yielded the value $J_{\pi^+} = 0$ for the spin of the π^+-meson. The π^--meson, being the antiparticle of the π^+-meson, also has zero spin.

In Section 3.4 we saw that spatial parity is conserved in strong and electromagnetic interactions, which imposes certain restrictions (allowing some things and forbidding others) on the processes considered. Therefore, it is important to know how to determine the intrinsic parity of each individual particle participating in strong or electromagnetic processes, and, also, to apply the parity conservation law to processes of its interaction with other particles. We shall show how this is done by determining the intrinsic parity of the π-meson, as an example.

The following reaction was used for this purpose:

$$\pi^- + {}^2_1\mathrm{H} \to n + n \tag{40}$$

that proceeds under the action of slow π^--mesons, i.e. when $l_\pi = 0$. It hence follows that the total angular momenta of the $(\pi^- + {}^2_1\mathrm{H})$-system and of the pair of neutrons, as well as the mutual orbital angular momentum l_n of the neutrons, also equal unity. As to the parity P, using its property of multiplicativity we obtain for the $(\pi^- + {}^2_1\mathrm{H})$-system the following relations:

$$P(\pi^- + {}^2_1\mathrm{H}) = P_{\pi^-} P_{{}^2_1\mathrm{H}} (-1)^{l_\pi} = P_{\pi^-}\,, \tag{41}$$

where the factor $(-1)^{l_\pi}$ characterizes (the proof is provided by quantum mechanics) the parity of a wave function describing the relative motion of a pair of interacting particles (here, π^- and ${}^2_1\mathrm{H}$), and $P_{{}^2_1\mathrm{H}} = +1$, since both nucleons of the pair are in the s-state ($l = 0$).

Similarly, for the spatial parity of the neutron pair we have

$$P_{2n} = P_n^2 (-1)^{l_n} = -1\,. \tag{42}$$

[20] The Lüders–Pauli CPT-theorem (1955) establishes the invariance, under any interaction, of the product of three inversions: charge conjugation (C), spatial inversion (P), and time reversal (T). The CPT-theorem is based on Lorentz invariance and the known relationship between spin and statistics (particles with half-integer spin follow Fermi–Dirac statistics, and particles with integer spin — Bose–Einstein statistics), i.e. it holds true for all local theories (in which the causality principle is assumed to be satisfied).

And since, in accordance with the parity conservation law, both results obtained, Eqns (41) and (42), should be identical, we obtain for the π^--meson parity: $P_{\pi^-} = -1$. The π^+-meson, as the antiparticle of the π^--meson, has the same intrinsic parity, because both of them are bosons (the antiparticle of a fermion has the opposite parity). Particles with zero spin and negative intrinsic parity are termed pseudoscalars.

4.2 The π^0-meson and its properties: mass, lifetime, spin and C-parity

If one recalls Yukawa's reasoning concerning virtual π-mesons — the carriers of nuclear interaction, the existence, together with the π^+- and π^--mesons, of a neutral π-meson (π^0) is readily 'predicted'. Indeed, following Yukawa, the pn interaction can be conceived as the virtual (during a time interval $\Delta t \sim 10^{-23}$ s) transformation of a proton into an $n + \pi^+$-pair and subsequent capture of the π^+-meson by an adjacent neutron which transforms into a proton. In a similar manner, one can explain the np interaction by considering the neutron to be $p + \pi^-$ for a nuclear time and the adjacent proton to subsequently absorb the virtual π^--meson and to transform into a neutron. Thus, in both cases p and n as if change places, which in an illustrative manner manifests the exchange nuclear interaction between them. However, it is quite evident that the pp and nn interaction existing between like nucleons in nuclei cannot be explained with the aid of individual π^+- and π^--mesons (dealt with separately). For this purpose one needs the π^0-meson [21] with a mass approximately equal to the $\pi^\pm$-mass.

Naturally, such a 'prediction' does not seem very convincing, but the π^0-meson was nevertheless discovered during studies of peculiarities revealed in $\pi^\pm$-meson production by fast protons at accelerators. It was found that at proton energies exceeding the $\pi^\pm$ production threshold, an anomalously large number of γ-quanta with energies around 70 MeV are produced besides the pions, which resembles neither quantitatively nor qualitatively the bremsstrahlung allowed by the theory. The interpretation of this exotic phenomenon turned out to be quite simple. Besides reactions (31)–(34), in which π^+- and π^--mesons are produced, the interaction of protons and neutrons with nucleons of the accelerator target results in reactions in which π^0-mesons are produced that have approximately the same mass as $\pi^\pm$-mesons ($\sim$ 140 MeV):

$$p + p \to \pi^0 + p + p\,, \tag{43}$$

$$n + p \to \pi^0 + n + p\,, \tag{44}$$

$$p + n \to \pi^0 + p + n\,, \tag{45}$$

$$n + n \to \pi^0 + n + n\,. \tag{46}$$

The π^0-mesons produced decay via the electromagnetic scheme into two γ-quanta:

$$\pi^0 \to 2\gamma \tag{47}$$

each one of which possesses an energy 140 : 2 = 70 MeV.

Later on, this interpretation of the described experiment was confirmed by other experiments that permitted the estimation of the mass of the π^0-meson ($264 m_e$) and its lifetime (0.84×10^{-16} s). The π^0-meson is a truly neutral particle, i.e. it is identical to its antiparticle. Such particles are said to have a definite charge parity C equal either to $+1$ or to -1. The reasoning that resulted in the concept of C-parity is close to that we used in introducing the concept of spatial parity (P) in Section 3.4.

The antiparticle of the π^0-meson, coinciding with the π^0-meson itself, signifies in the language of quantum mechanics that the operation of charge conjugation $\widehat{C}$ does not alter the absolute value squared of the π^0-meson's wave function:

$$\widehat{C}\,|\Psi_{\pi^0}|^2 = |\Psi_{\pi^0}|^2\,, \tag{48}$$

whence follows that the wave function itself satisfies the following condition

$$\widehat{C}\,\Psi_{\pi^0} = \pm \Psi_{\pi^0}\,, \tag{49}$$

i.e. it is characterized either by positive or negative C-parity. It is not difficult to understand that the π^0-meson's C-parity is positive ($C_{\pi^0} = +1$). This is clear from the following reasoning. Among the particles known to us there exists one more truly neutral particle — the γ-quantum. It possesses negative C-parity because all the vectors of the electromagnetic field (including the γ-quantum) change sign when the sign inversion of the electric charge takes place:

$$\widehat{C}\,\Psi_\gamma = -\Psi_\gamma\,, \quad \text{i.e.} \quad C_\gamma = -1\,. \tag{50}$$

It is also clear that the C-parity is multiplicative (like P-parity), meaning that

$$\widehat{C}\Psi_{n\gamma} = (-1)^n \Psi_\gamma \quad \text{or} \quad C_{n\gamma} = (-1)^n\,. \tag{51}$$

And since the π^0-meson decays into 2γ, its C-parity is positive ($C_{\pi^0} = +1$). C-parity is conserved in strong and electromagnetic interactions. The C-parity conservation law forbids, for instance, the decay of a π^0-meson into three γ-quanta, but allows it to decay into 4 quanta (with a much smaller probability than into 2). Besides the π^0-meson and the γ-quantum, several other truly neutral particles are also known, and we shall consider some of them later. These are the η-, η'-, ρ^0-, ω-, φ-, $\eta_c(1s)$-, J/ψ- and Υ-mesons, some of which [η, η', $\eta_c(1s)$] have positive C-parity, while the others (ρ^0, ω, φ, J/ψ, Υ) possess negative C-parity. The concept of C-parity can also be introduced, besides truly neutral elementary particles, for a charged particle–antiparticle pair, such as, for instance, a ($\pi^+\pi^-$)-meson pair. In this case, the C-parity of the ($\pi^+\pi^-$)-pair equals $(-1)^l$, where l is the angular momentum.

4.3 Isotopic invariance of the strong interaction. Isotopic multiplets. G-parity

A remarkable property of the strong nuclear interaction is its charge independence, according to which the strong interactions (without due account of the electromagnetic interaction) of any two nucleons (n–p, p–p, n–n) of the same energy and being in the same space and spin states are identical. In nuclear physics this follows, for example, from comparison of the properties of mirror nuclei (in which all the protons are replaced by neutrons and vice versa), in elementary particle physics — from direct comparison of the results of investigations into np, pp and nn scattering. In both cases the properties of the systems compared turn out to be identical for strong nuclear interaction, if one discards the contribution of diverse electromagnetic interactions that

[21] With the aid of the neutral pair of ($\pi^+ + \pi^-$)-mesons one can explain the exchange interaction between like nucleons but then in accordance with Eqn (2), owing to the doubled mass of the π-meson pair, the radius of nuclear forces will turn out to be two times smaller.

varies from case to case owing to the electric charges differing from each other.

The strong nuclear properties of the proton and the neutron being identical is described by the introduction of a special quantum-mechanical vector of isotopic spin (isospin) I, the numerical value of which is considered the same for both nucleons and equal to 1/2 ($I_p = I_n = 1/2$). According to quantum-mechanical rules, when $I = 1/2$, the vector I has $2I + 1 = 2$ projections, one of which ($I_\xi = +1/2$) characterizes the proton, and the other one, $I_\xi = -1/2$, characterizes the neutron. In this case, the proton and neutron are said to form an isotopic doublet (isodoublet) of particles.

In the language of isospin, the charge independence of nuclear interaction is termed isotopic invariance, which is manifested by the strong interaction being independent of the isospin projection, i.e. of the rotation of the isospin vector in theoretical isotopic space. By analogy with invariance of the laws of mechanics in a mechanical system with respect to rotation in an ordinary space, which results in the conservation of angular momentum, from the invariance of strong interaction with respect to rotation of the isospin vector in isospace follows the isotopic spin conservation law in the strong nuclear interaction.

The independence of strong interaction on the isospin projection does not mean that it is independent of the isospin vector itself. On the contrary: thus, for example, the n – p system comprising two nucleons with $I = 1/2$ each can exhibit a total isospin vector equal to zero ($I_\xi = 0$) or to unity ($I_\xi = -1, 0, +1$), and from experiment it is known that different strong interactions correspond to these two possibilities. This is particularly clear in the case of a neutron interacting with a proton at low energies: the (p – n)-system with $I = 0$ forms a bound state — a deuteron nucleus, and when $I = 1$, $I_\xi = 0$ — an unbound state equivalent in its properties to two other states with $I = 1$: the (p – p)-system ($I = 1$, $I_\xi = +1$), and the (n – n)-system ($I = 1$, $I_\xi = -1$). Below we shall also encounter other examples revealing the dependence of the character of strong interaction on isotopic spin (see Section 4.4).

The law of conservation of isospin is violated in the electromagnetic interaction, which is manifested (besides the obvious difference in charges and magnetic moments) in a certain difference between the neutron and proton masses and in the neutron having a finite lifetime as compared to the proton [22].

All three π-mesons, like the two nucleons, are close to each other in properties. Their masses are nearly the same. They all interact strongly with nuclei and nucleons in both the production and absorption processes. Finally, from the above discussion we have seen that they can be considered quanta of the nuclear interaction. All the above made it possible, in its time, to put forward the hypothesis that the main properties of strong nuclear interaction should be manifested not only in the properties of nucleons, but also in the properties of π-mesons, the behavior of which should also obey isotopic invariance. But, since there exist three π-mesons differing in electric charges, they should be characterized by isospin $I = 1$ having $2I + 1 = 3$ projections I_ξ. The projection $I_\xi = +1$ corresponds to the π^+-meson, $I_\xi = 0$ to the π^0-meson, and $I_\xi = -1$ to the π^--meson. Thus, unlike the nucleon isodoublet, π-mesons form an isotriplet of particles with similar nuclear (strong) properties.

The experimentally confirmed hypothesis (see Section 4.4) of the existence of isotopic invariance in the properties of π-mesons permits us, first, to assert that the neutral π-meson, like the π^+- and π^--mesons, is a pseudoscalar, meaning that it has zero spin and negative intrinsic parity [23], and, second, to introduce a new quantum number G and the corresponding conservation law for all three π-mesons. Such a conclusion becomes obvious if the π-meson is subjected to the combined transformation $\widehat{G} = \widehat{C}\widehat{I}_\xi$ consisting of rotation $\widehat{I}_\xi$ in isotopic space and charge conjugation $\widehat{C}$. Since each operation transforms π^+ into π^- and vice versa, while the π^0-meson is a truly neutral particle, then both operations together leave the π-meson intact, which, by analogy with the P- and C-parities introduced above, signifies that the wave function of π-mesons and the π-mesons themselves exhibit certain G-parities:

$$\widehat{G}\Psi_\pi = \pm\Psi_\pi\,, \qquad G_\pi = \pm 1\,. \tag{52}$$

With the aid of additional reasoning (going beyond the framework of the popular style of exposition adopted in this article) it is possible to show that π-mesons have negative G-parity:

$$G_\pi = -1\,. \tag{53}$$

Thus, the complete set of quantum numbers of the $\pi^\pm$-mesons looks as follows: $I^G(J^P) = 1^-(0^-)$, and for the π^0-meson (which also exhibits C-parity) it is $I^G(J^{PC}) = 1^-(0^{-+})$

It is quite obvious that like the $\widehat{P}$- and $\widehat{C}$-transformations considered above $\widehat{G}$ also presents a multiplicative operation, from which it follows that the G-parity of several (n) π-mesons is

$$G(n\pi) = (-1)^n\,. \tag{54}$$

Relation (54) permits the determination of the G-parity of unstable particles decaying into π-mesons by strong interaction. Thus, for example, the G-parity of the ρ-meson that decays into two π-mesons is positive: $G_\rho = +1$, and of the ω-meson decaying into three π-mesons — negative: $G_\omega = -1$. The G-parity is conserved only in strong interactions, since isotopic invariance was allowed for in conceiving this concept.

We have already mentioned that electromagnetic interaction violates isotopic invariance, which results in the removal of degeneracy within the isotriplet of π-mesons. For this reason, like in the case of nucleons, differences arise between the masses, lifetimes and decay schemes of π-mesons with different electric charges [24]. We notice that electromagnetic interaction does not violate the law of conservation of the isotopic spin projection, which is actually a consequence of

[22] Somewhat anticipating our discussion (see Section 8.1) we note that in quantum chromodynamics the mass differences between p and n, $\pi^\pm$- and π^0-mesons (and, also, of other particles composing any isomultiplets) is explained by the difference in masses between u- and d-quarks composing these particles.

[23] The negative intrinsic parity of the π^0-meson is also confirmed by the reaction $\pi^- + {}^2_1\mathrm{H} \to \mathrm{n} + \mathrm{n} + \pi^0$, differing from reaction (40) in the production of an additional π^0-meson, not being observed in the s-channel for $l_{\pi^-} = 0$. If the π^0-meson had positive parity, this reaction would be allowed [19].

[24] The identity of the mass and lifetime and the charge conjugation of the decay schemes of π^+- and π^--mesons are explained by their being a particle and antiparticle.

the electric charge and baryon number conservation laws obeyed in any (including strong and electromagnetic) interactions, and the existence of the following obvious relationship

$$Z = I_\xi + \frac{B}{2} \tag{55}$$

that holds true both for nucleons and for π-mesons. From Eqn (55) it follows that the average charge for any multiplet (the nucleon doublet and the pion triplet) is equal to

$$\bar{Z} = \frac{B}{2} \,. \tag{56}$$

4.4 Experimental check of the hypothesis of isotopic invariance in pion–nucleon interactions. Pion–nucleon resonances

For experimental confirmation of the hypothesized existence of isotopic invariance of strong interactions with the participation of π-mesons, the reactions of π-meson production in nucleon–nucleon interactions and π-meson scattering by nucleons were analyzed.

All the above-mentioned π-meson production reactions (31)–(34) and (41)–(44) can briefly by written as

$$\underbrace{\mathrm{N}+\mathrm{N}}_{I_1=0.1} \to \underbrace{\pi}_{I_\pi=1} + \underbrace{\mathrm{N}+\mathrm{N}}_{I_2=0.1} \,, \tag{57}$$

where N is a nucleon (p or n), and π signifies π^+-, π^0- or π^--mesons. In accordance with the rules for treating quantum-mechanical vectors, each of the nucleon pairs can have a total isospin equal to zero or unity, so that from the viewpoint of the isospin conservation law only three different varieties of reaction (57) are possible; we shall characterize them by their cross sections σ_{I_1, I_2}. These reactions correspond to transitions of nucleon pairs from the state $I_1 = 0$ to the states with $I_2 = 1$ ($\sigma_{0,1}$); $I_1 = 1$ to $I_2 = 0$ ($\sigma_{1,0}$), and $I_1 = 1$ to $I_2 = 1$ ($\sigma_{1,1}$). The fourth version ($I_1 = 0$, $I_2 = 0$) is obviously forbidden by the isospin conservation law, since the π-meson isospin $I_\pi = 1$. The existence of only three isotopically different π-meson production schemes means that if the hypothesis of isotopic invariance of pion–nucleon interaction holds true, then the cross sections of all the π-meson production reactions considered above, independently of their charges and of the sort of nucleons, must be expressed in terms of the three above-introduced cross sections $\sigma_{0,1}$, $\sigma_{1,0}$ and $\sigma_{1,1}$ (it is clear, for example, that the cross sections of the reaction $\mathrm{p} + \mathrm{p} \to \pi^0 + \mathrm{p} + \mathrm{p}$ and, also, of the reaction $\mathrm{n} + \mathrm{n} \to \pi^0 + \mathrm{n} + \mathrm{n}$ have to simply equal $\sigma_{1,1}$). Experimental data confirm this conclusion.

One can arrive at a similar inference by considering the π-meson scattering from nucleons via the reaction scheme

$$\underbrace{\pi}_{I_{\pi_1}=1} + \underbrace{\mathrm{N}}_{I_{\mathrm{N}_1}=1/2} \to \underbrace{\pi}_{I_{\pi_2}=1} + \underbrace{\mathrm{N}}_{I_{\mathrm{N}_2}=1/2} \,. \tag{58}$$

In this case, the (π–N)-system can have isospin $I = I_\pi + I_\mathrm{N} = 1/2;\ 3/2$ and, consequently, if the isospin conservation law is valid, it should undergo transition (in scattering) either from the state with $I_1 = 1/2$ to the state with $I_2 = 1/2$ ($\sigma_{1/2}$) or from the state with $I_1 = 3/2$ to the state with $I_2 = 3/2$ ($\sigma_{3/2}$).

Meanwhile, it is possible to list over ten concrete processes of πN scattering [$\pi^+\mathrm{p} \to \pi^+\mathrm{p}$ (σ_1); $\pi^-\mathrm{p} \to \pi^-\mathrm{p}$ (σ_2); $\pi^-\mathrm{p} \to \pi^0\mathrm{n}$ (σ_3) and so on]. And, indeed, the cross sections of all these processes can be successfully expressed in terms of $\sigma_{1/2}$ and $\sigma_{3/2}$. Thus, for example, one obtains

$$\sigma_1 = \sigma_{3/2} \,, \qquad \sigma_2 + \sigma_3 = \frac{\sigma_{3/2} + 2\sigma_{1/2}}{3} \tag{59}$$

and, on the contrary:

$$\sigma_{1/2} = \frac{3(\sigma_2 + \sigma_3) - \sigma_1}{2} \,, \qquad \sigma_{3/2} = \sigma_1 \,. \tag{60}$$

Figure 5 shows the dependences of $\sigma_{1/2}$ and $\sigma_{3/2}$ versus the π-meson energy and, also, the experimental cross sections for $\pi^+\mathrm{p}$ and $\pi^-\mathrm{p}$ scattering. From the figure one can see that $\sigma_{3/2}$ is dominant within the energy range $T_\pi = 100-300$ MeV, where $\sigma_{1/2}$ is small and, contrariwise, when $T_\pi \simeq 1$ GeV, $\sigma_{1/2}$ becomes dominant; if $T_\pi > 2$ GeV, one finds $\sigma_{1/2} \simeq \sigma_{3/2}$. This result proves the existence of a strong dependence of the πp interaction on isotopic spin in the energy range $T_\pi < 1$ GeV, which smooths out at higher energies. As to the experimentally determined cross sections for $\pi^+\mathrm{p}$ and $\pi^-\mathrm{p}$ scattering, from Fig. 5 it is seen that the first one (coinciding with $\sigma_{3/2}$) passes through maxima at $T_\pi = 190$ and 1300 MeV, while the second has maxima at $T_\pi = 190$, 600 and 900 MeV. These broad maxima in the π-meson scattering cross sections on protons are called pion–nucleon resonances, while the first of them (at $T_\pi = 190$ MeV) is termed the Δ-isobar. The resonance at $T_\pi = 190$ MeV was first observed in 1952 by E Fermi.

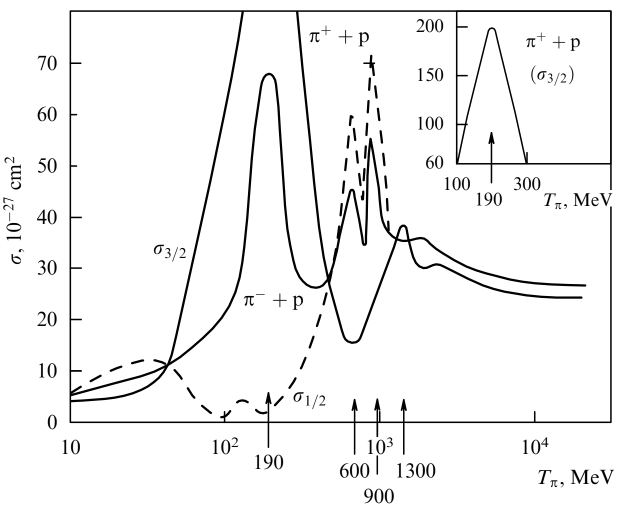

Figure 5. Experimental values of π^+p- and π^-p-scattering cross sections versus π-meson energy.

4.5 Unstable particles. Properties of a Δ-isobar. Pion–pion interaction

Besides a resonance energy, pion–nucleon resonances are also characterized by other parameters that are typical of ordinary stable and metastable elementary particles. These are mass, baryon number, isospin, electric charge, ordinary spin, lifetime and others. We shall illustrate this taking advantage of the Δ-isobar, the production and decay schemes of which are depicted in Fig. 5. Its baryon number equals unity ($B_\mathrm{p} = +1$ and $B_\pi = 0$), and the following expression is naturally considered as mass:

$$m_\Delta = m_\mathrm{N} + m_\pi + T'_\mathrm{res} = 1230-1234 \quad \mathrm{MeV} \,, \tag{61}$$

where m_N is the nucleon (p or n) mass, m_π is the π-meson ($\pi^\pm$ or π^0) mass, T'_res is the resonance energy (~ 155 MeV) in the c.m.s.. The Δ-isobar has isospin 3/2, meaning that it is encountered in four close in mass charge states (Δ^{++}, Δ^{+}, Δ^{0} and Δ^{-}) that decay by the schemes

$$\Delta^{++} \to \mathrm{p} + \pi^{+}\,, \qquad \Delta^{+} \begin{array}{l} \nearrow\ \mathrm{p} + \pi^{0}\,, \\ \searrow\ \mathrm{n} + \pi^{+}\,, \end{array}$$
$$\Delta^{0} \begin{array}{l} \nearrow\ \mathrm{p} + \pi^{-}\,, \\ \searrow\ \mathrm{n} + \pi^{0}\,, \end{array} \qquad \Delta^{-} \to \mathrm{n} + \pi^{-}\,. \tag{62}$$

The values of an ordinary spin ($J = 3/2$) and intrinsic parity ($P = +1$) were determined from the analysis of decay schemes. The lifetime of the Δ-isobar is evaluated from the width of the resonance ($\Gamma \simeq 100$ MeV) and amounts to $\tau \simeq \hbar/\Gamma \simeq 10^{-23}$ s, i.e. it is a *nuclear* time and corresponds to the decay proceeding via strong interaction.

Thus, the Δ-isobar (and other pion – nucleon resonances as well) can indeed be characterized by the complete set of quantum numbers, which is used in describing ordinary elementary particles. The only exception is the unusually short (nuclear) lifetime. In this connection, the Δ-isobar and other pion – nucleon resonances are conventionally considered to compose a new class of *unstable* elementary particles decaying via strong interaction schemes, i.e. with conservation of isotopic spin. To confirm this definition, we note that the properties of πN-resonances as *particles* are manifested as cojoint production reactions with ordinary particles, for example:

$$\pi^{+} + \mathrm{p} \to \Delta^{++} + \pi^{0}\,, \tag{63}$$
$$\pi^{+} + \mathrm{p} \to \Delta^{++} + \pi^{+} + \pi^{-}\,. \tag{64}$$

In this case it turns out that for analyzing these reactions one can invoke the usual kinematics, i.e. assign the Δ-isobar certain values of a momentum and kinetic energy. True, one must bear in mind here that the Δ^{++}-isobar (and any other unstable particle) cannot be identified by a sole event, since it actually represents a resonance distribution of many πN systems with a large width Γ.

At present, not only the properties of a free Δ-isobar, but also of the Δ-isobar produced within atomic nuclei, have been studied comprehensively. The present-day state of this topic is dealt with in the review [20].

Besides πN-resonances, unstable particles are also encountered in other combinations of strongly interacting particles, for instance, in the form of 2π- or 3π-resonances (ρ- and ω-mesons, respectively), and, also, in combinations of π-mesons with strange particles — with K-mesons and hyperons (see Section 6).

In conclusion of this section we note that the investigation of the interaction between two pions is not restricted to the examination of 2π-resonances [for example, the ρ-resonance with a mass of 770 MeV and quantum numbers $I^{G}(J^{PC}) = 1^{+}(1^{--})$, and the f^{0}-resonance with a mass of 980 MeV and $I^{G}(J^{PC}) = 0^{+}(0^{++})$], but represents an important separate chapter in the physics of strong interactions. This is due to the π-meson being the quantum of strong interaction which is characterized by a constant of the order of unity (we recall that the constant of electromagnetic interaction, also quite intense and responsible for the stability of atoms and molecules, equals only $\alpha = 1/137$). Therefore, there exists a strong pion – pion interaction between the nuclear quanta themselves, which is not only manifested in the existence of unstable particles such as the 2π-resonance, but makes a noticeable contribution to practically all strong processes at arbitrary energies. The ππ interaction cannot naturally be studied directly as the scattering of a π-meson by a π-meson, because no pion target exists (even in the form of colliding pion beams). In this connection, the ππ interaction is only studied by indirect methods, for example, by the investigation of a reaction such as $\pi + \mathrm{N} \to \pi + \pi + \mathrm{N}$ or a rare K-meson decay channel of the type $\mathrm{K}^{+}_{e4} \to \pi^{+} + \pi^{-} + e^{+} + \nu_{e}$. The present-day state of the issue of the ππ interaction is dealt with, for example, in the review [21].

5. Antinucleons

5.1 Prediction and discovery of the first antiparticles

We started our article by describing the discovery of muons, considering that everything discovered before them was well known. This was, naturally, a correct decision because the famous discoveries of the neutron and the positron made in 1932, four years before muons were detected, have been known to everyone since their school years. But we, nevertheless, will have to recall the history of how the positron was discovered, since this is necessary for presenting the material of this section. Rather than 1932, we will mention 1928, when the positron's existence was predicted theoretically. We refer to the relativistic quantum-mechanical equation for the electron, proposed that year by P Dirac [22]. We recall that the exotic peculiarity of the Dirac equation lies in the fact that it predicts the existence of two regions of electron energy E for a given momentum p:

$$E = \pm\sqrt{m_{\mathrm{e}}^{2}c^{4} + p^{2}c^{2}}\,, \tag{65}$$

which are separated by the energy gap $2m_{\mathrm{e}}c^{2}$. So, from the equation followed the existence of an electron possessing negative energy values $E \leqslant -mc^{2}$ and, thus, the negative mass $m_{\mathrm{e}} < 0$, which seemed quite strange. However, it was not possible to simply discard the 'negative' solution, since it followed quite legitimately from the *exact* equation that yields correct solutions for other properties of the electron: for example, it results automatically in true values for the spin and the magnetic moment (for which a value disagreeing with the experimental finding was obtained before Dirac).

Dirac found an absolutely brilliant way out from this seemingly hopeless situation. He assumed negative energy levels to actually exist, but to be all occupied by unusual electrons of mass $m < 0$ and energy $E < 0$, owing to which they are imperceptible, although the total negative electric charge, mass and energy of these electrons are infinitely large.

This invisible background of occupied levels can be revealed only if a 'hole' is formed in it, i.e. if one of the unusual electrons with a negative energy, mass and electric charge is extracted from it with the aid, for instance, of a γ-quantum with $E > 2m_{\mathrm{e}}c^{2}$ and transferred to the region of $E \geqslant m_{\mathrm{e}}c^{2}$. Then, this electron becomes normal, meaning it will have $m_{\mathrm{e}} > 0$ and $E > 0$, but will retain its negative charge, while the hitherto invisible background of electrons with $m < 0$, $E < 0$ and $Z = -1$ will manifest itself as a 'hole' with opposite parameters: $m > 0$, $E > 0$ and $Z = +1$, i.e. as the *antiparticle* of the electron — the positron.

Clearly, the inverse annihilation process, i.e. the transition of a single normal electron from the region of $E > m_{\mathrm{e}}c^{2}$ to a 'hole' in the background, accompanied by the release of the energy $E > 2m_e c^2$ in the form of the emission of two γ-quanta, is also possible. The law of conservation of the lepton number L_e, considered in Section 3.3, is obeyed in both the processes.

As pointed out above, four years later the positron was observed by C Anderson in cosmic rays [23], and one year later both the processes predicted by Dirac — e^+e^--pair production and its subsequent annihilation upon the encounter between the electron and the positron — were observed in laboratory conditions by F Joliot-Curie [25]. Later on, as we mentioned in Section 2, the antiparticles were also found for other particles — muons and pions. Moreover, it follows from studies of the properties of electron and muon neutrinos that they also have antiparticles with opposite lepton numbers L_e and L_μ. But all these particles pertained to the classes of leptons and mesons, i.e. they had baryon number $B = 0$. The question arises as to what is the situation with the antiparticles of baryons?

5.2 The antiproton and antineutron. Scintillation and Cherenkov counters. Annihilation

According to the CPT-theorem (see Section 4.1), an antiparticle must exist for each particle, including the proton and neutron that have baryon number $B = 1$, and not only the electric charges and magnetic moments of their antiparticles must have opposite values, but also their baryon numbers ($Z_{\tilde{p}} = -1$, $\mu_{\tilde{p}} = -\mu_p$, $\mu_{\tilde{n}} = -\mu_n$, $B_{\tilde{p}} = B_{\tilde{n}} = -1$). Therefore, the simplest reactions in which an antinucleon can be produced are the following:

$$\mathrm{N} + \mathrm{N} \to 3\mathrm{N} + \widetilde{\mathrm{N}} \quad \text{and} \quad \pi + \mathrm{N} \to 2\mathrm{N} + \widetilde{\mathrm{N}} \tag{66}$$

with the thresholds $T_{\min}^{\mathrm{N+N}} = 5.6$ GeV and $T_{\min}^{\mathrm{N}+\pi} = 3.6$ GeV. If, instead of a nucleon, an atomic nucleus serves as a target, then owing to the Fermi motion of the nucleons in the nucleus both thresholds drop down to 4.3 and 2.85 GeV, respectively.

Interestingly enough, it was mostly theoreticians who believed in the existence of antinucleons, while certain experimenters considered it necessary to wait for the results of experiments [26]. Nevertheless, the next in energy proton accelerator — the bevatron — was constructed, so as to achieve an energy of the proton beam (6.3 GeV) sufficient for the production of antinucleons.

In our previous review [4] in the section devoted to the simplest antinuclei we presented a detailed discussion of the two remarkable experiments performed by O Chamberlain, E Segre et al. [25] and by B Cork et al. [26], in which antiprotons and antineutrons were produced artificially at the accelerator [27]. Therefore, to avoid unnecessary repetitions, here we shall only briefly recall the layouts of installations at which artificial antiprotons and antineutrons were first produced, and in the main we shall deal with the description of new accelerators with antiproton beams and the peculiarities in the properties and interactions of antinucleons as the first antiparticles with a baryon number differing from zero and equal to $B = -1$. We shall further see that, besides antinucleons, there exist many other antibaryons — these are antihyperons within the class of strange particles (so as to say, 'antistrange' antibaryons; see Section 6.4). Similarly, there exist antibaryons with 'anticharm' (see Section 8.4.1) and 'antibeauty' (see Section 8.4.2). All of them, like the antinucleons, have $B = -1$ and opposite values of electric charges and quantum numbers characterizing the flavors of the corresponding particles (the strangeness S, charm c and beauty b).

The layout of the experimental setup with which antiprotons were first obtained in 1953 is shown in Fig. 6a. Here, p is the proton beam of the bevatron with an energy 4.3–6.2 GeV, T is the copper target, $M1$ and $M2$ are the deflecting magnets which together with the focusing lenses $L1$ and $L2$ compose the magnetic channel that is set to transmit negative particles of momentum 1.19 GeV/c. The identification of antiprotons among the enormous amount of π^--mesons ($N_{\tilde{p}} : N_{\pi^-} = 1 : 6 \times 10^4$) was performed on the basis of the flight time ($\tau_{\tilde{p}} = 51 \times 10^{-9}$ s, $\tau_{\pi^-} = 40 \times 10^{-9}$ s) measured with the aid of scintillation counters $SC1$ and $SC2$ situated at a distance of 12 m from each other, and of two Cherenkov counters $CC1$ and $CC2$. The counter $CC1$ served for cutting off beam π^--mesons (with $\beta > 0.99$) and scattered π^--mesons (with $\beta > 0.79$) ($\beta = v/c$, where v is the particle velocity, and c is the speed of light in vacuum), and the counter $CC2$ was set to register antiprotons with β within the limits 0.75–0.78. A total of 60 antiprotons were recorded in this experiment.

Somewhat later, at the largest accelerators of that period (in Brookhaven, Serpukhov, Batavia and Geneva) antiproton

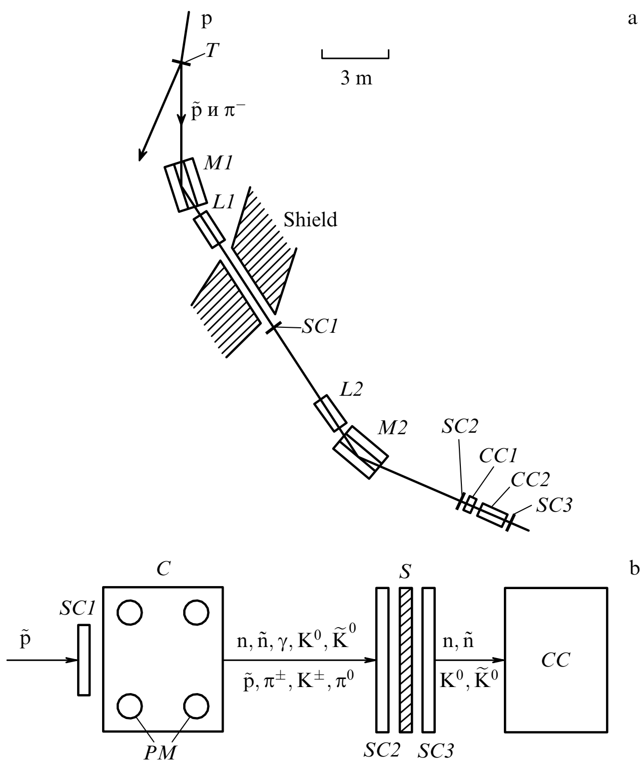

Figure 6. Layouts of experiments for studying antinucleon production: (a) antiproton production: p — proton beam, T — copper target, $\tilde{p}$ and π^- — produced antiprotons and π^--mesons, $M1$ and $M2$ — deflecting magnets, $L1$ and $L2$ — focusing magnetic lenses, $SC1$–$SC3$ — scintillation counters, $CC1$ and $CC2$ — Cherenkov counters; (b) antineutron production: $\tilde{p}$ — antiproton beam, $SC1$–$SC3$ — scintillation counters, C — converter, PM — photomultipliers, S — lead shield, CC — Cherenkov counter.

[25] In 1935, F Joliot-Curie and I Joliot-Curie were awarded the Nobel Prize in chemistry for the discovery of artificial radioactivity.

[26] The Nobel Prize laureate L Alvarez (one of the most prominent specialists in the field of elementary particle physics) recalls [24, 39] how two outstanding physicists — an experimenter and a theorist — even made a bet for 500 dollars (which, as noted by Alvarez, was quite a large sum, given the salaries received by scientists at the time) regarding this matter.

[27] In 1959, O Chamberlain and E Segre were awarded the Nobel Prize in physics for the discovery of the antiproton.

beams were formed, and in 1978 at CERN an essentially new result in antiproton physics was achieved — a successful experiment was carried out for long-term storage of antiprotons in a magnetic ring. In 1981, this achievement permitted the researchers to put two accelerators with colliding proton – antiproton beams into operation: $p\tilde{p}$ and $Sp\tilde{p}S$ colliders with energies of 2×31.4 GeV and 2×270 GeV (later on, 2×310 GeV), respectively, of which the second accelerator was constructed especially 'for the discovery' of $W^{\pm}$- and Z^0-bosons (see Sections 9.4 and 9.5). Somewhat later (in 1987) in the USA (Batavia), the tevatron (from the word teraelectron-volt: 1 TeV= 10^{12} eV) — a $p\tilde{p}$ collider with an energy of 2×1 TeV — was put into operation (the t-quark was discovered at this accelerator in 1994; see Section 8.4.3). In the region of relatively low energies, new possibilities for studies with antiprotons arose in 1983, when the antiproton complex LEAR (Low-Energy Antiproton Ring) was commissioned at CERN; from the very beginning LEAR provided a pure (without any admixture of other particles) monoenergetic antiproton beam of a momentum of 0.06 – 2 GeV/c ($\Delta p/p = 10^{-4}$), the intensity of which (upon reconstruction in 1988) reached the value $3 \times 10^6\ \tilde{p}\,s^{-1}$. The antiproton beams of the accelerators listed, of the $p\tilde{p}$ colliders and of the LEAR complex were used for studying the properties and interactions of antiprotons (see the next section).

The layout of the experimental setup with the aid of which the first antineutrons were obtained in 1956 is shown in Fig. 6b. Here, $\tilde{p}$ is the antiproton beam of the bevatron, *SC1 – SC2* are the scintillation counters, *C* is the converter (scanned by 4 photomultipliers) in which the antineutrons $\tilde{n}$ were produced in charge exchange processes involving antiprotons:

$$\tilde{p} + p \to \tilde{n} + n, \quad \tilde{p} + n \to \tilde{n} + n + \pi^- . \tag{67}$$

In this case, the antiprotons release a small (< 50 MeV) ionization energy in the converter *C*. On the other hand, the antiproton may pass through the converter *C* without undergoing any interaction but spending only 50 MeV (exactly) on ionization, or undergoing (this is what happens most often) annihilation with the encountered nucleons of the converter material and releasing an enormous amount of annihilation energy $E \simeq 2m_N c^2$ that is consumed in the production of particles of lesser masses (mainly π- and K-mesons as well as γ-quanta). As a result, at the exit from the converter there turns out to be a very large number of charged and neutral particles: $\tilde{n}$, $\tilde{p}$, n, $\pi^{\pm}$, π^0, $K^{\pm}$, K^0, $\widetilde{K}^0$, γ (see Fig. 6b). The identification of antineutrons was done in two stages. At the first stage, the system of two scintillation counters *SC2* and *SC3* (included in the anticoincidence circuit) separated by a lead shield discarded all the charged particles, γ-quanta and π^0-mesons (that rapidly decayed into two γ-quanta). At the second stage, after the passage of particles of four sorts through the counter *SC3* (n, $\tilde{n}$, K^0, $\widetilde{K}^0$), the antineutrons $\tilde{n}$ were singled out by a powerful annihilation flash in the Cherenkov counter *CC* (scanned by 16 photomultipliers), the recorded energy spectrum of which extended up to 1.5 GeV. Comparison of this spectrum (with its low-energy part corrected for the background from the energy release due to K^0- and $\widetilde{K}^0$-mesons) with the antiproton spectrum (measured in the same Cherenkov counter *CC* after removal of counters *CC2* and *CC3* and of the lead shield) revealed their total identity. The described scheme for the identification of antineutrons permitted the obtaining of $0.003\tilde{n}$ per antiproton.

5.3 The properties and interactions of antinucleons. The Pomeranchuk theorem

In accordance with the CPT-theorem, the antinucleon has precisely the same mass, spin, lifetime and conjugate decay scheme as the nucleon corresponding to it. Thus, the antiproton should be stable, while the antineutron decays by the scheme

$$\tilde{n} \to \tilde{p} + e^+ + \nu_e \tag{68}$$

with the same half-life as the neutron. We shall only note that the above is true only when certain conditions are satisfied (see below).

Like the proton and neutron, the antiproton and antineutron form an isotopic doublet of antinucleons with identical nuclear properties. This isodoublet is characterized, like the nucleon isodoublet, by isospin $I = 1/2$, but with opposite projection values ($I_{\xi}^{(\tilde{p})} = -1/2$, $I_{\xi}^{(\tilde{n})} = +1/2$), for which relations (55) and (56), earlier established for nucleons, obviously hold true. The magnetic moments of antinucleons also have the same absolute values but opposite signs as compared with the magnetic moments of the respective nucleons. This assertion, like other ones, of the CPT-theorem was tested experimentally soon after the discovery of antinucleons and was fully confirmed. The intrinsic parity of antinucleons is negative ($P_{\tilde{N}} = -1$).

The above-mentioned assertion that the lifetimes of the antiproton and antineutron are equal to the lifetimes of the proton and neutron holds true only for vacuum (in outer space or special devices continuously pumped out for storing antinucleons — storage rings similar to the LEAR complex described above). Under ordinary conditions, antinucleons perish rapidly, since encounters with nucleons of surrounding matter give rise to annihilation processes that result in the nucleon – antinucleon pair with $B_N + B_{\tilde{N}} = 0$ transforming into several lighter particles with zero baryon number. In 95% of cases these particles are π-mesons (about 5 π-mesons at low energies and approximately 30 π-mesons at energies of 2×270 GeV), while in 5% — K-mesons. Very rarely $N\widetilde{N}$ annihilation results in the production of γ-quanta.

The annihilation cross section (150 mb) at low energies (~ 50 MeV) exceeds the elastic scattering cross section (75 mb) by a factor of approximately two and amounts to 2/3 of the total cross section (225 mb). The relative role of the annihilation process drops as the antiproton energy increases, and at an energy of $\sim 10^3$ GeV the total $\tilde{p}p$-interaction cross section decreases and becomes equal to the total pp-interaction cross section ($\sigma_{\tilde{p}p}^{tot} \simeq \sigma_{pp}^{tot} \simeq 42$ mb), thus confirming the Pomeranchuk theorem [28]. A further increase of energy is accompanied by an increase of both the cross sections, too (see Fig. 7).

6. Strange particles. The Wilson cloud chamber and the bubble chamber

From previous sections we saw that all the elementary particles hitherto considered turned out to be carriers of many unusual, at first sight, properties, for the explanation

[28] According to the Pomeranchuk theorem, the total interaction cross sections of particles and antiparticles with one and the same arbitrary target (for example, with nucleons) should be identical at energies tending toward infinity [27].

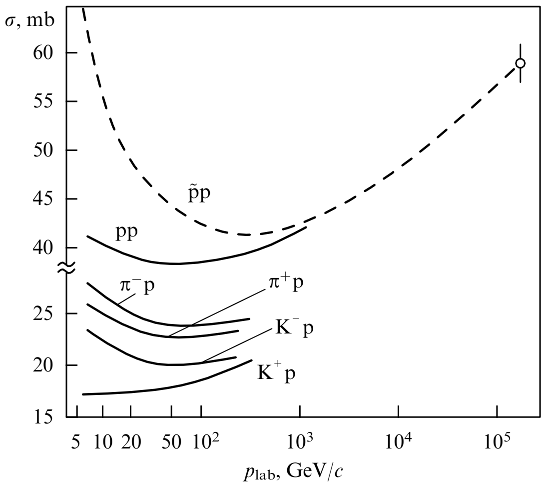

Figure 7. Comparison of cross sections for pp and $\tilde{\rm p}$p interactions (and also for π^-p and π^+p, and K$^-$p and K$^+$p).

of which many years of joint efforts were required of theoretical physicists who proposed introducing new concepts, quantum numbers and conservation laws and of experimental physicists who performed most complicated experiments to confirm the novel theoretical ideas. But perhaps none of these particles can be compared favorably with the *strange* particles discovered late in the 1940s and in early 1950, which were termed so on account of the many amazing properties peculiar to them.

Strange particles were discovered and studied with the aid of three track techniques: photoemulsions, Wilson cloud chambers and bubble chambers. The photoemulsion method was described in Section 3.2. Operation of the Wilson cloud chamber, mentioned in Section 3.1, is based on the property of oversaturated vapor to condense into extremely small liquid droplets along the trajectory of a charged particle, and of the bubble chamber — on the property of overheated liquid to form vapor bubbles in the path of a charged particle. Hydrogen, helium, propane, freon and xenon can all serve as the working liquid in bubble chambers. Both the Wilson cloud chamber and the bubble chamber are used together with a magnetic field. Events recorded by both types of chambers are photographed on a film which is subsequently processed using special semiautomatic (and sometimes totally automatic) scanning devices. Owing to the joint application of the three mentioned methods, studies were carried out of the meson type strange particles called K-mesons, and of the baryon type strange particles called hyperons.

6.1 K-mesons and the $(\theta - \tau)$-problem. Theoretical discovery of the violation of the spatial parity conservation law in weak interactions

The first particle of the new sort was observed with the aid of the photoemulsion method. The recorded events consisted of a primary track left by a singly charged particle with a mass of the order of $1000 m_{\rm e}$ and of three secondary tracks, from the character of which it was established that they were left by three π-mesons ($2\pi^+$ and π^-) and that there should be no fourth (neutral) particle. From the sum of kinetic energies and masses of the three π-mesons it was possible to determine the exact mass of the primary particle ($965 m_{\rm e}$) which, at the beginning, was termed a τ-meson [29] ($B_\tau = 3B_\pi = 0$):

$$\tau^+ \to \pi^+ + \pi^+ + \pi^- \,. \tag{69}$$

Besides photoemulsion, τ-mesons were also recorded in the Wilson cloud chamber, where τ^--mesons were observed together with the τ^+-mesons, and their estimated lifetimes came to

$$\tau_{\tau^-} \simeq \tau_{\tau^+} \simeq 10^{-8}\ \text{s}\,.$$

After the $\tau^\pm$-mesons, the $\theta^\pm$- and θ^0-mesons with the following decay schemes were observed:

$$\theta^\pm \to \pi^\pm + \pi^0 \,, \tag{70}$$

$$\theta^0 \to \pi^+ + \pi^- \,, \tag{71}$$

as well as some other particles, and in all cases the masses of the primary particles turned out to be practically the same ($965 - 970 m_{\rm e}$), and their lifetimes close to each other ($\sim 10^{-8}$ s for the charged, and 10^{-10} s for the neutral particles). This was surprising, but not too much, since such coincidences could readily be explained by the observation of decays of one and the same particle via different channels, i.e. by $\theta = \tau$. However, if this assumption is correct, then the θ- and τ-mesons should not only have identical masses and lifetimes, but other parameters as well, for example, spin and intrinsic parity.

In Section 4.1 we related how the spin and parity of π-mesons were determined. About the same thing can also be done in this case, *if one considers parity to be conserved in decays of the* θ- *and* τ-*mesons, when determining it*. These arguments (we do not present them here for a reason which will soon become clear) yielded quite an unusual result. The spins of both the θ- and the τ-mesons are identical, $J = 0$, but they have different parities: $P_\theta = +1$, while $P_\tau = -1$. Meanwhile, the difference in masses between the θ- and the τ-mesons no longer exceeded 0.1% by this time, i.e. it was very difficult to doubt that $\theta \equiv \tau$. The situation seemed so hopeless that it was termed the $(\theta - \tau)$- problem.

The solution to this problem was found in 1956 by the theoretical physicists T Lee and C Yang, who assumed $\theta \equiv \tau$, but that *parity is not conserved* in their decay (it is for this reason that we did not present arguments based on the parity conservation law). It is often said that everything of genius is simple. The solution to the $(\theta - \tau)$-problem was of genius, but not simple. The point is that the decay of the K-meson (thus called were θ, τ and other particles of close properties) is a slow process (taking about $10^{-10} - 10^{-8}$ s), i.e. it proceeds through the weak interaction, and the weak interaction, as we have already pointed out, is universal. Therefore, the violation of the parity conservation law should occur not only in the K-decay but also in any other weak process, including the β-decay of nuclei, the first theory of which was constructed by Fermi under the assumption of *parity conservation* and which has been confirmed by numerous experiments.

Thus, to actually resolve the $(\theta - \tau)$-problem, Lee and Yang had to create a new theory of the β-decay, in which:

[29] The τ-meson has, naturally, nothing in common with the heavy τ-lepton described in Section 3.6 and discovered significantly later than the τ-meson, when it already became clear that the latter did not exist as an independent particle and the letter "τ" was freed.

(a) the parity conservation law did not have to be obeyed; (b) all the experimentally confirmed consequences of the old theory had to remain valid, and (c) there arose new consequences that had to be tested experimentally. In Section 3.4 we anticipated our story and have already dealt with two such consequences — the Wu experiment with polarized Co, and the observation of parity violation in the $(\pi \to \mu + e)$-decay. These and other experiments confirmed Lee and Yang's guess of genius that the parity is not conserved in weak interactions as well as the correctness of the new theory they constructed for the β-decay [28] [30].

6.2 Hyperons

Coincidently with the detection of K-mesons, a heavy neutral metastable particle was observed in cosmic rays (subsequently called the Λ-hyperon), exhibiting baryon number $B = 1$ and the following decay schemes:

$$\Lambda \begin{array}{l} \nearrow \ \mathrm{p} + \pi^- \quad (\sim 2/3)\,, \\ \searrow \ \mathrm{n} + \pi^0 \quad (\sim 1/3)\,. \end{array} \tag{72}$$

It should be emphasized that the second decay scheme was studied using a xenon bubble chamber that permitted recording of π^0-mesons by the e^+e^--pairs resulting from conversion of the γ-quanta produced in the $(\pi^0 \to 2\gamma)$-decay. The mass of the Λ-hyperon, $m_\Lambda = 2183 m_e$, and its lifetime $\tau_\Lambda = 2.6 \times 10^{-10}$ s.

Several years later, charged $\Sigma^\pm$-hyperons decaying via the channels that follow were observed both at accelerators and in cosmic rays:

$$\Sigma^+ \begin{array}{l} \nearrow \ \mathrm{p} + \pi^0 \\ \searrow \ \mathrm{n} + \pi^+ \end{array} \quad (m_{\Sigma^+} = 2327\, m_e\,, \quad \tau_{\Sigma^+} = 0.8 \times 10^{-10}\ \mathrm{s})\,, \tag{73}$$

$$\Sigma^- \to \mathrm{n} + \pi^- \ (m_{\Sigma^-} = 2343\, m_e\,, \quad \tau_{\Sigma^-} = 1.5 \times 10^{-10}\ \mathrm{s})\,. \tag{74}$$

Notice that the difference in masses and lifetimes between the Σ^+- and Σ^--hyperons are consistent with the CPT-theorem because, as we will learn later, Σ^+ and Σ^- are not particle and antiparticle of each other.

In those years, the Σ^0-hyperon was also discovered that decayed by the electromagnetic scheme

$$\Sigma^0 \to \Lambda^0 + \gamma \tag{75}$$

and had a mass $m_{\Sigma^0} = 2334 m_e$ and lifetime $\tau_{\Sigma^0} \simeq 10^{-19}$ s, as well as two cascade hyperons decaying via two stages:

$$\Xi^- \to \Lambda + \pi^-\,, \qquad \Lambda \to \mathrm{N} + \pi\,, \tag{76}$$

$$\Xi^0 \to \Lambda + \pi^0\,, \qquad \Lambda \to \mathrm{N} + \pi\,, \tag{77}$$

and having the respective masses and lifetimes: $m_{\Xi^-} = 2586 m_e$, $\tau_{\Xi^-} = 1.6 \times 10^{-10}$ s, and $m_{\Xi^0} = 2573 m_e$, $\tau_{\Xi^0} = 2.9 \times 10^{-10}$ s.

Finally, the heaviest negatively charged hyperon with a mass of $3273 m_e$ and lifetime of 0.8×10^{-10} s, termed the Ω^--hyperon, was observed at the beginning of 1964 in a two-meter hydrogen bubble chamber. The decay scheme of the Ω^--hyperon is even more complicated than that of the Ξ-hyperons:

$$\Omega^- \begin{array}{l} \nearrow \ \Xi^- + \pi^0\,, \\ \longrightarrow \ \Xi^0 + \pi^-\,, \\ \searrow \ \Lambda \ + \mathrm{K}^- \end{array} \tag{78}$$

with subsequent decays of the Ξ^--, Ξ^0-, Λ-, K^-- and π^0-particles. Since the conditions in which the Ω^--hyperon was observed were quite special (all its parameters were predicted theoretically), we shall deal with it in greater detail in Section 7.3.

6.3 The astonishing properties of strange particles

We have already become familiar with one of the unexpected properties of K-mesons [the $(\theta - \tau)$-problem] and seen in what drastic consequences its explanation resulted. But that was only the beginning! As a matter of fact, strange particles possess very many unusual properties and they all require explanation, too. Firstly, K-mesons and hyperons, on the one hand, behave like nuclear-active particles, since their production cross sections are large ($\sim 1\%$ of the geometric cross section), and, on the other hand, like nuclear-passive particles, since they decay via *weak* interaction (in $10^{-10} - 10^{-8}$ s) into *nuclear-active* particles $(\mathrm{K} \to \pi + \pi + \pi$, $\Lambda \to \mathrm{N} + \pi$, and so on). Secondly, the K-mesons and hyperons originating in NN and πN interactions are never produced singly, but in pairs or triplets, and in certain combinations such as, for example:

$$\pi^- + \mathrm{p} \to \Lambda + \mathrm{K}^0\,, \tag{79}$$

$$\pi^- + \mathrm{p} \to \Sigma^- + \mathrm{K}^+ \tag{80}$$

or

$$\pi^+ + \mathrm{p} \to \Xi^0 + \mathrm{K}^+ + \mathrm{K}^+\,, \tag{81}$$

while the following reactions (in which, like in the preceding ones, the charge and baryon number conservation laws are obeyed) have never been observed:

$$\pi^\pm + \mathrm{p} \not\to \mathrm{K}^\pm + \mathrm{p}\,, \tag{82}$$

or

$$\mathrm{p} + \mathrm{p} \not\to \Sigma^+ + \Sigma^+\,, \tag{83}$$

and also

$$\pi^- + \mathrm{p} \not\to \Sigma^+ + \mathrm{K}^- \tag{84}$$

(which seems particularly strange, since the apparently symmetric reaction (80) proceeds with a high probability).

Thirdly, still another asymmetry was noticed in the properties of K^+- and K^--mesons. For interaction energies of 1 – 2 GeV, 100 times more of the former are produced than of the latter, with K^+-mesons being produced in pairs together with both K^--mesons and hyperons, while K^--mesons only in pairs together with K^+-mesons. Another feature peculiar to K^--mesons (not possessed by K^+-mesons) consists in their capability of producing hyperons in reactions with nucleons:

$$\mathrm{K}^- + \mathrm{p} \begin{array}{l} \nearrow \ \Sigma^- + \pi^+\,, \\ \searrow \ \Sigma^+ + \pi^- \end{array} \tag{85}$$

[30] The year after the discovery in 1956 of the violation of the parity conservation law in weak interactions, Lee and Yang were awarded the 1957 Nobel Prize in physics. This was probably one of the most rapidly awarded prizes for a theoretical discovery.

Table 1.

Particle	K^+	K^-	K^0	$\widetilde{K}^0$	Λ	$\Sigma^+, \Sigma^0, \Sigma^-$	Ξ^0, Ξ^-	Ω^-	$\widetilde{\Lambda}$	$\widetilde{\Sigma}^-, \widetilde{\Sigma}^0, \widetilde{\Sigma}^+$	$\widetilde{\Xi}^0, \widetilde{\Xi}^+$	$\widetilde{\Omega}^+$
S	+1	−1	+1	−1	−1	−1	−2	−3	+1	+1	+2	+3

unlike K^+-mesons, for which the seemingly similar reaction

$$K^+ + p \not\to \Sigma^+ + \pi^+ \qquad (86)$$

is not possible.

Such are the strangenesses! One can really lose one's head! But these strangenesses have been explained, and once again by theoreticians.

6.4 The classification of strange particles. Hyperons and antihyperons. K^0- and $\widetilde{K}^0$-mesons. The strangeness conservation law

To be brief to the utmost, the explanation consists in the existence of a certain new conservation law which allows some processes to proceed and forbids others. Recall the situation with the decay schemes of pions and muons and with the two sorts of neutrinos and antineutrinos. At the time, everything was cleared up by the introduction of the lepton numbers L_e and L_μ and by formulating the respective conservation laws for them. Now, a successful explanation was provided by the introduction of a new quantum number — strangeness (S), and the law of conservation of strangeness. In detail, what actually happened is the following.

In 1953–1954, the American and Japanese theoreticians M Gell-Mann and K Nishijima proposed to extend the principle of isotopic invariance to K-mesons and hyperons by introducing (by analogy with nucleons and π-mesons) the concepts of isotopic spin and isotopic multiplets. Then, relationship (55) introduced for nucleons and π-mesons is replaced by the more general expression

$$Z = I_\xi + \frac{B+S}{2} = I_\xi + \frac{Y}{2}\,, \qquad (87)$$

where Z, I_ξ and B retain their previous values, $Y = B + S$ is termed a hypercharge, while the strangeness S may take (for different particles) the following values:

$$S = 0,\ \pm1,\ \pm2,\ \pm3, \qquad (88)$$

with the value $S = 0$ corresponding to ordinary (not strange) particles — the nucleons and π-mesons, when expression (87) transforms into Eqn (55). From relation (87) one can see that the average charge of an isotopic multiplet of strange particles is

$$\bar{Z} = \frac{B+S}{2} = \frac{Y}{2}\,. \qquad (89)$$

In accordance with the generalization of the isotopic invariance hypothesis to strange particles, expression (87) can also be considered [like Eqn (55)] valid for strong and electromagnetic interactions, i.e. the *strangeness S* can be considered *conserved* in these interactions.

The strangeness conservation law permits us to explain all the aforementioned unusual properties of strange particles. This will readily become clear to us upon making a classification of K-mesons and hyperons by their isospin and strangeness. We shall start with the hyperons. The Λ-hyperon is a neutral singlet with $I = 0$ and $Z = 0$. Consequently, in accordance with relation (89), $\bar{Z} = (B+S)/2 = 0$ and $S_\Lambda = -B_\Lambda = -1$. The Σ-hyperons form an isotriplet (Σ^+, Σ^0, Σ^-) with $I = 1$ and $\bar{Z} = 0$, i.e. all three particles have $S = -1$. The Ξ-hyperon is a doublet (Ξ^- and Ξ^0) with $I = 1/2$ and $\bar{Z} = (-1+0)/2 = -1/2$, from which the value of $S_\Xi = 2\bar{Z} - B = -2$ is obtained for S. The Ω^--hyperon makes up a negatively charged singlet with $I = 0$ and $Z = \bar{Z} = -1$, from which it follows that $S_{\Omega^-} = -3$. For antihyperons, from the same formula (89) one obtains opposite values of strangeness ($S_{\widetilde{\Lambda}} = S_{\widetilde{\Sigma}} = +1$, $S_{\widetilde{\Xi}} = +2$, $S_{\widetilde{\Omega}^+} = +3$), as one should in the case of the appropriate antiparticles.

In classifying K-mesons with $B = 0$ it would seem natural to consider the observed K^+-, K^-- and K^0-particles an isotopic triplet with $I = 1$ and $\bar{Z} = 0$. But from formula (89) it would then follow that the strange particles have $S = 0$! Thus arose one more puzzle. But we will resolve it in a relatively easy way by analyzing the properties of K^+-, K^-- and K^0-mesons (when we dealt with this issue for the first time, we knew less than now and it was more difficult to find the solution). From the masses and lifetimes of the K^+- and K^--mesons being identical it follows that they are particle and antiparticle with opposite strangenesses, the values of which are not yet known to us [31]. But what can be said about K^0? If it is not a member of the isotriplet, then why is its mass close to the $K^\pm$ mass? And why has only one K^0 been found? The point is that it cannot be a truly neutral particle, because in this case all its quantum numbers, including strangeness, would be equal to zero. This means that there should be two particles: K^0 and $\widetilde{K}^0$ with opposite S. Thus, there exists a total of four K-mesons (K^+, K^-, K^0 and $\widetilde{K}^0$). So, maybe, in this case they form an isoquartet with $I = 3/2$? No, because in this case it also turns out that $S = 0$. Therefore, there remains only a single possibility for explaining why the masses of charged and neutral K-mesons are close to each other: they form two isodoublets with identical isospins $I = 1/2$, but with different strangenesses S. One of these isodoublets contains the K^+- and K^0-mesons, for which $\bar{Z} = S/2 = +1/2$, i.e. $S = +1$, while the other comprises the K^- and $\widetilde{K}^0$ with $\bar{Z} = S/2 = -1/2$, i.e. with $S = -1$. The projections of isospin I of these particles, in accordance with formula (87), will be $I_\xi(K^+) = I_\xi(\widetilde{K}^0) = +1/2$ and $I_\xi(K^-) = I_\xi(K^0) = -1/2$. That the signs of I_ξ and Z are the same for charged K-mesons is not an exception but a general rule for all isotopic multiplets (nucleon, pion and K-meson, as well as Σ- and Ξ-hyperon multiplets). The sign of the isotopic spin projection of a charged particle coincides with the sign of its electric charge (this facilitates memorization).

Thus, strange particles and antiparticles have the values of strangeness that are compiled in Table 1.

[31] Formally, if one considers K^+- and K^--mesons as isosinglets with $\bar{Z} = Z = +1$ and $\bar{Z} = Z = -1$, respectively, one can obtain the strangeness values $S = +2$ and $S = -2$ for them, but this does not resolve our problem concerning the reason for the similarity between K^+-, K^-- and K^0-mesons. We note that somewhat later (when K-mesons had already been shown to form two isodoublets with $S = \pm1$) searches started for a particle with $S = +2$ and $\bar{Z} = +1$, which was assumed to comprise an independent isosinglet (the so-called D-meson), but they came to nothing [see, for example, paper [29] whose authors attempted to discover the D-meson in the K^+-meson beam of the LVE JINR (Dubna) collider].

And now look how elegant and simple the explanation is for all the astonishing properties of strange particles mentioned above. In strong interactions strangeness is conserved. Therefore, pairs and triplets of strange particles can be produced in NN and πN interactions ($S_{NN} = S_{\pi N} = 0$) with total strangeness $S = 0$ [reactions (79)–(81)], and cannot if it is nonzero [reactions (82)–(84)]. Even four strange particles can be produced in NN interactions for the same reason:

$$\begin{aligned} &\mathrm{p}+\mathrm{p}\to \mathrm{K}^+ + \Sigma^- + \mathrm{K}^+ + \Sigma^+\,, \\ S:\;& 0+0=+1\quad -1\quad +1\quad -1\,, \end{aligned} \tag{90}$$

and in the $\mathrm{K}^-\mathrm{p}$ interaction — one strange particle:

$$\begin{aligned} &\mathrm{K}^- + \mathrm{p} \;\to \Sigma^- + \pi^+\,, \\ S:&-1\;+0=-1\;\;+0\,, \end{aligned} \tag{91}$$

or three strange particles:

$$\begin{aligned} &\mathrm{K}^- + \mathrm{p} \;\to\; \Omega^- + \mathrm{K}^+ + \mathrm{K}^0\,, \\ S:&-1\quad +0=\;-3\quad +1\quad +1\,. \end{aligned} \tag{92}$$

But, on the other hand, the reaction 'symmetric' to that in Eqn (91) is impossible:

$$\begin{aligned} &\mathrm{K}^+ + \mathrm{p} \not\to \Sigma^+ + \pi^+\,, \\ S:&+1\quad +0\neq -1\quad +0\,. \end{aligned} \tag{93}$$

Application of the strangeness conservation law is just as simple as in the case of antihyperon production reactions. The following antihyperon production reactions were observed, for example:

$$\begin{aligned} &\mathrm{N}+\mathrm{N}\to\Lambda+\widetilde{\Lambda}+\mathrm{N}+\mathrm{N}\,, \\ S:&\,0\;+0=-1+1\;+0\;+0\,, \end{aligned} \tag{94}$$

$$\begin{aligned} &\tilde{\mathrm{p}}+\mathrm{p}\to\widetilde{\Lambda}+\Lambda\,, \\ S:&\,0+0=+1-1\,, \end{aligned} \tag{95}$$

$$\begin{aligned} &\pi^- + \mathrm{p}\;\to\;\widetilde{\Lambda}+\Lambda+\mathrm{n}\,, \\ S:&\,0\quad +0=+1\;-1\;+0\,, \end{aligned} \tag{96}$$

$$\begin{aligned} &\widetilde{\mathrm{p}}+\mathrm{p}\;\to\;\widetilde{\Xi}^+ + \Xi^-\,, \\ S:&\,0+0=+2\quad -2\,, \end{aligned} \tag{97}$$

$$\begin{aligned} &\mathrm{K}^+ + \mathrm{d}\;\to\;\widetilde{\Omega}^+ + \Lambda+\Lambda+\mathrm{p}+\pi^+ + \pi^-\,, \\ S:&+1\quad +0=+3\quad -1\;-1+0+0\quad +0\,. \end{aligned} \tag{98}$$

Thus, we have succeeded in explaining all the strangenesses of strange particles, with the exception of one — why was only one neutral K-meson with a strangeness $S = +1$ observed [in reaction (79)]? Where is the second one — $\widetilde{\mathrm{K}}^0$ with $S = -1$? This issue will be raised in Section 6.6.

6.5 Decays of strange particles and strange resonances

If you compare the decay schemes of strange particles, you will notice something common to all of them. They are all characterized by a decay time $\tau \simeq 10^{-10} - 10^{-8}$ s, i.e. the decays proceed via weak interaction, in which the strangeness is not conserved. And, indeed, whatever decay scheme of those considered ($\mathrm{K}^+ \to \pi^+ + \pi^0$, $\Lambda \to \mathrm{p} + \pi^-$, $\Xi^- \to \Lambda + \pi^-$, $\Omega^- \to \Xi^- + \pi^0$) one examines, the strangeness is seen to change by unity: $\Delta S = \pm 1$.

According to the universal theory of weak interaction, the law of conservation of spatial parity should be violated in the weak decays of strange particles. As we saw in Section 6.1, such a violation was practically postulated for K-mesons. As to hyperons, special experiments were carried out for them. Thus, for example, the violation of the parity conservation law was recorded in 1957 in an investigation of the angular distribution of the Λ-hyperon decay products in a hydrogen bubble chamber. Similar results were also obtained for other hyperons. The only exception is the Σ^0-hyperon that decays via the electromagnetic scheme ($\Sigma^0 \to \Lambda + \gamma$), i.e. without any change of strangeness and, therefore, rapidly ($\tau_{\Sigma^0} \simeq 10^{-19}$ s).

Even more rapid (in a nuclear time $\tau_{\mathrm{nucl}} \simeq 10^{-23}$ s) are the decays of strange resonances, i.e. of unstable particles that are similar to the pion–nucleon and pion–pion resonances dealt with above (see Sections 4.4 and 4.5) and differ from them only in that they are not composed of ordinary particles (nucleons and π-mesons) but of strange particles (K-mesons and hyperons). The best known strange meson resonance is the K^*_{892}-resonance that decays into K- and π-mesons with $\Delta S = 0$. This resonance, like the K-meson, is encountered in the form of two isotopic doublets K^{*+}_{892} and K^{*0}_{892} with $S = +1$ and K^{*-}_{892} and $\widetilde{\mathrm{K}}^{*0}_{892}$ with $S = -1$. Of the hyperon strange resonances we shall mention only two: Σ_{1325} with $S = -1$ that decays into a Λ-hyperon and a π-meson, and Ξ_{1530} with $S = -2$ that decays into a Ξ-hyperon and a π-meson. In both cases the strangeness is conserved ($\Delta S = 0$). We shall deal with all these resonances in greater detail in Section 7.

6.6 New puzzles of neutral K-mesons. K^0_1- and K^0_2-mesons. CP-invariance. The regeneration of K-mesons

In Section 6.4 we arrived at the conclusion that there should exist two neutral K-mesons in nature — K^0 and $\widetilde{\mathrm{K}}^0$. But only one strange neutral θ^0-particle decaying by the scheme $\theta^0 \to \pi^+ + \pi^-$ was examined experimentally. The question arises, which should the θ^0-particle be associated with — the K^0- or the $\widetilde{\mathrm{K}}^0$-meson? The answer was apparently obtained when θ^0 was observed to be produced in the reaction

$$\pi^- + \mathrm{p} \to \Lambda + \theta^0, \tag{99}$$

i.e. to have $S = +1$ (since $S_\Lambda = -1$). Does this mean that $\theta^0 \equiv \mathrm{K}^0$? It turns out no! When a large statistics was accumulated in reaction (99), it was found that the decays such as $\theta^0 \to \pi^+ + \pi^-$ were observed only in 50% of the events. This cannot be explained by the existence of two decay channels for $\theta^0 \equiv \mathrm{K}^0$ — a fast one, which is observed, and a slow one, which is not seen (in this case, the percentage would be nearly 100%). Thus, it turns out that although a K^0-meson is produced in reaction (99), it cannot decay into a $\pi^+\pi^-$-pair. What, then, decays and what happens with the K^0-meson produced, if it does not decay? Moreover, the old question remains unsolved concerning the $\widetilde{\mathrm{K}}^0$-meson, which according to the classification of strange particles should exist, but has not been observed in nature. More riddles!

And again the solution was found by theoreticians — M Gell-Mann, A Pais and O Piccioni, who put forward the assumption that the K^0- and $\widetilde{\mathrm{K}}^0$-mesons are two versions of a special 'mixture' (1 : 1) of two other neutral particles, namely, the K^0_1- and K^0_2-mesons having differing lifetimes, different decay schemes and slightly differing masses. In their turn, the K^0_1- and K^0_2-mesons can also be represented as two different versions of a 50% 'mixture' composed of K^0- and $\widetilde{\mathrm{K}}^0$-mesons.

Neither K_1^0 nor K_2^0 have definite strangeness, i.e. they cannot originate by scheme (99), but are allowed to decay and, indeed, do decay via different schemes with strongly differing times:

$$K_1^0 \to 2\pi \quad (\tau_{K_1^0} = 0.9 \times 10^{-10}\ \text{s})\,, \tag{100}$$

$$K_2^0 \to 3\pi \quad (\tau_{K_2^0} = 5.2 \times 10^{-8}\ \text{s})\,. \tag{101}$$

We apologize to the reader for not being able to present this most beautiful idea in detail, owing to the chosen popular style of exposing the material. We will only hint that the word 'mixture' actually means four combinations of wave functions of the form

$$\psi_{K^0} = \frac{\psi_{K_1^0} + \psi_{K_2^0}}{\sqrt{2}}\,, \qquad \psi_{\tilde{K}^0} = \frac{\psi_{K_2^0} - \psi_{K_1^0}}{\sqrt{2}}\,, \tag{102}$$

$$\psi_{K_1^0} = \frac{\psi_{K^0} - \psi_{\tilde{K}^0}}{\sqrt{2}}\,, \qquad \psi_{K_2^0} = \frac{\psi_{K^0} + \psi_{\tilde{K}^0}}{\sqrt{2}}\,, \tag{103}$$

where ψ_{K^0} and $\psi_{\tilde{K}^0}$ possess a certain strangeness ($S = +1$ and $S = -1$, respectively), while $\psi_{K_1^0}$ and $\psi_{K_1^0}$ exhibit a certain combined CP-parity ($CP_{K_1^0} = +1$, $CP_{K_2^0} = -1$) which, unlike the (individual) C- and P-parities violated in weak interactions, is conserved in them up to at least an accuracy of 99% (this is an experimental fact). Therefore, the K_1^0-meson can decay into 2π-mesons which also have $CP_{2\pi} = +1$, while the K_2^0-meson can decay into 3π-mesons that have $CP_{3\pi} = -1$. But, as follows from formula (103), neither K_1^0 nor K_2^0 exhibit definite strangeness, and for this reason cannot be produced directly in strong interactions such as reaction (99).

Experiments have confirmed that everything proceeds exactly like we have narrated. K_1^0 represents those 50% decays of the type $\theta^0 \to \pi^+ + \pi^-$, which were observed near the K^0-meson production point in reaction (99), while $K_2^0 \to 3\pi$ decays were seen later with the aid of a Wilson chamber situated far from the production point of the K^0-mesons (at a distance corresponding to their long lifetime).

An additional confirmation of the validity of the described scheme for the existence and the interrelationship of the four neutral K-mesons (K^0, $\tilde{K}^0$, K_1^0 and K_2^0) is presented by one more remarkable quantum-mechanical phenomenon predicted by Pais and Piccioni and termed the regeneration of neutral K-mesons. Imagine you are irradiating a totally evacuated chamber with a thin partition P that can be established at different distances (P_1 and P_2) from the front wall of the chamber with π^--mesons (Fig. 8a). Then in accordance with our previous reasoning the reaction $\pi^- + p \to \Lambda + K^0$ will result in the production of K^0-mesons in P_1, while no $\tilde{K}^0$-mesons will be produced (until the energy of the π^--mesons becomes sufficient for the reaction $\pi^- + p \to n + K^0 + \tilde{K}^0$ to take place). The composition of the originating K^0-mesons (which is a 50% 'mixture' of K_1^0- and K_2^0-mesons) will change (owing to the fast K_1^0-decay) as they propagate through the chamber and will become enriched with the long-lived component K_2^0, so that only this component will reach the partition P_2. But K_2^0 is a 50% 'mixture' of K^0 and $\tilde{K}^0$, i.e. a $\tilde{K}^0$-meson will appear in the beam, which could not originate within the partition P_1. Their appearance is confirmed experimentally by the production of hyperons resulting from the interaction of the $\tilde{K}^0$-meson with the material of P_2 by the scheme

$$\tilde{K}^0 + p \to \Lambda + \pi^+\,. \tag{104}$$

If the partition P_2 is sufficiently thick, then all the $\tilde{K}^0$-mesons will ultimately be absorbed, and only the single K^0-compo-

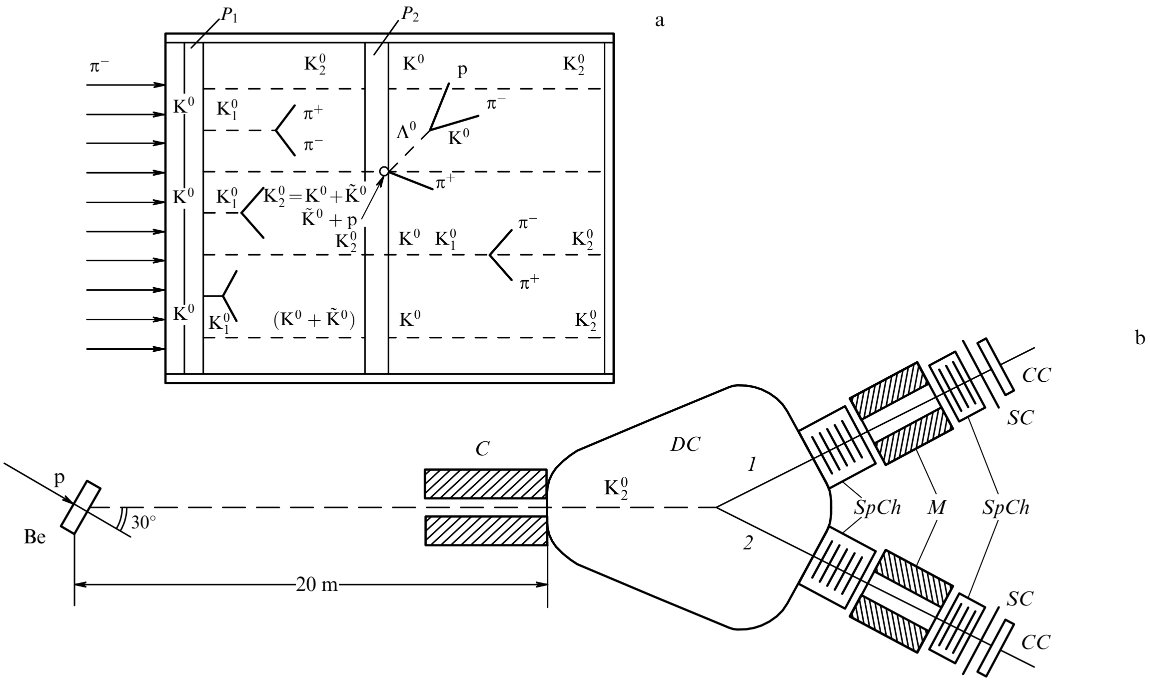

Figure 8. Experimental test of the accuracy with which CP-parity is conserved in neutral K-meson decays; (a) layout for observation of neutral K-meson regeneration (partial CP-parity conservation): π^- — incident π^--meson beam, P_1 and P_2 — two positions of the thin partition in the totally evacuated chamber, K^0, $\tilde{K}^0$, K_1^0, K_2^0 — neutral K-mesons, Λ^0 — Λ-hyperon, p — proton, π^+ and π^- — $\pi^\pm$-mesons (for details see text), and (b) layout of the experiment for demonstration of CP-parity violation in the K_2^0-decay: p — 30-GeV proton beam, Be — beryllium target, *C* — collimator, *DC* — decay chamber, K_2^0 — trajectory of K_2^0-mesons, *1*, *2* — kinematically possible decay trajectories of the K_2^0-meson via the scheme $K_2^0 \to \pi^+ + \pi^-$, *SpCh* — spark chamber, *M* — magnet, *SC* — scintillation counter, *CC* — Cherenkov counter.

nent that originated anew (truly, only 25% of the amount of K^0 in P_1) will be left in the beam. The K_1^0-component, which is manifested in the $K_1^0 \to \pi^+ + \pi^-$-decays, will also be revived together with the K^0. Such a process of some kind of 'pumping back and forth' of K^0 into $\widetilde{K}^0$ and back and the revival of the decayed K_1^0 was termed the regeneration of neutral K-mesons. We note that all the above was confirmed experimentally with an accuracy up to 99.5%. Consequently, it is with such an accuracy that one can be confident that the CP-invariance conservation law is obeyed in weak interactions and, in particular, that CP-parity is conserved in the decays of neutral K-mesons.

6.7 Violation of CP-invariance in the K_2^0-decay. K_S^0- and K_L^0-mesons

Above, we especially stressed the 99.5% accuracy of the experimental tests of CP-invariance conservation, because at the subsequent 1964 Conference in High-Energy Physics, V Fitch, J Cronin and others presented their work in which a 0.2% *violation* of CP-parity in the decay of K_2^0-mesons was revealed. The experiment essentially consisted in observation of the decay $K_2^0 \to \pi^+ + \pi^-$ forbidden by CP-parity. The experimental layout is shown in Fig. 8b. The K_2^0-meson decay was studied in a decay chamber (*DC*) situated at a distance of 20 m from the target of the accelerator, i.e. in the region where the K_1^0-component of the combination of K^0- and $\widetilde{K}^0$-mesons originating in the target had totally decayed. The rare ($K_2^0 \to \pi^+ + \pi^-$)-decay events, forbidden by CP-parity, were identified by the very definite kinematics of a two-particle decay and the effective mass of the two pions, which coincided with the K_1^0-meson mass measured when it underwent regeneration from K_2^0 in a specially performed experiment (for details see, for example, Refs [30, 31]).

In the experiment, a total of 45 events of the K_2^0-meson decay into a $\pi^+\pi^-$-pair were recorded, 10 of which originated owing to the regeneration of K_1^0-mesons in the helium that filled the chamber volume. The remaining 35 events yielded the following ratio of forbidden to allowed decay numbers:

$$\frac{K_2^0 \to 2\pi}{K_2^0 \to \text{anything}} \simeq 2 \times 10^{-3}\,. \tag{105}$$

Thus, instead of the K_2^0-meson with $CP = -1$, one should consider a composition of the K_2^0-meson and a small 'admixture' of the K_1^0-meson possessing $CP = +1$ to be the long-lived state of the neutral K-meson, K_L^0 ($\tau \simeq 5 \times 10^{-8}$ s):

$$K_L^0 = K_2^0 + \varepsilon K_1^0\,. \tag{106}$$

Similarly, the short-lived neutral K-meson, K_S^0 ($\tau = 0.9 \times 10^{-10}$ s), should now be represented as a composition of K_1^0 with a small K_2^0 admixture:

$$K_S^0 = K_1^0 + \varepsilon K_2^0\,. \tag{107}$$

The main result (105) obtained in the experiment of Fitch and Cronin was tested in a series of control experiments. Thus, for example, a totally evacuated chamber in which the regeneration of K-mesons is impossible was used instead of the chamber filled with helium. The corrected result confirmed the small ($\sim 0.1\%$) violation of CP-parity in the decay of neutral K-mesons. And although 0.1% is very little, the law of conservation of CP-parity has passed from the category of exact conservation laws to the category of approximate laws.

Besides the decays of K-mesons, several attempts were also made to reveal CP-parity violation in other decay processes (see review by M V Danilov [32]) and in the properties of the neutron as well (searches for the electric dipole moment of the neutron, see Ref. [33]).

The importance of studying the problem of CP-invariance violation is, in particular, related (in the opinion of many physicists) to the fact that it has played an important part in the formation of the early Universe (see Section 10.1).

In 1980, Fitch and Cronin were awarded the Nobel Prize in physics for the discovery of nonconservation of combined parity in the K_2^0-decay [34, 35].

7. Hadron systematics

7.1 The concept of unitary symmetry

After the discovery of strange particles — the metastable K-mesons and hyperons and the unstable strange resonances, the total number of strongly interacting particles, which all together (including the nucleons, pions and ordinary non-strange resonances) are termed hadrons [32], became so large that the time had arrived for their classification by some common characteristics, which would allow one to identify the groups of particles with more or less close parameters, the principal one of which is mass. We saw above that particles with identical isospin (a pair of nucleons, a triplet of pions and others) have close masses but, firstly, these groups are not very numerous and, secondly, totally different (in mass, too) particles (for example, pions and Σ-hyperons) may possess the same isospin. Strangeness is also not suitable for this role, since particles with the same strangeness differ very significantly in mass (from 140 to 1232 MeV for $S = 0$, and from 500 to 1200 MeV for $S = \pm 1$). We will arrive at the same conclusion, if we try to combine particles into groups with the same baryon number B or the same intrinsic parity P. In both cases only two large groups of absolutely different particles will be created. The same result will be achieved if the particles are divided into groups with half-integer and integer spins (fermions and bosons). Thus, none of the characteristics mentioned above will separately resolve the issue. However, if one simultaneously takes advantage of the latter three characteristics (B, P and J), without paying attention to the differences in I and S, a remarkable result is achieved.

Figures 9a–d show four groups of particles with all the particles of a given group having the same values of B, P and J. These groups are two meson ($B = 0$) nonets containing 9 particles each with the spin and parity equal to $J^P = 0^-$ in one case, and to $J^P = 1^-$ in the other; a baryon ($B = 1$) octet consisting of 8 baryons with $J^P = 1/2^+$, and a baryon decouplet containing 10 baryons with $J^P = 3/2^+$. From the figures one can see that, if the particles are arranged along the S- and I_ξ-axes, they form regular symmetric (with respect to rotation through 120°) figures — three hexagons and one triangle. In this case, the masses of the particles in each of the four figures are relatively close to each other. If one examines this closeness of masses with more attention, one will notice the particularly small difference in masses between the members of isotopic multiplets situated on lines parallel to the I_ξ-axis. At the time described, this result was explained by

[32] The term 'hadron' translated from Greek means 'large', 'massive'.

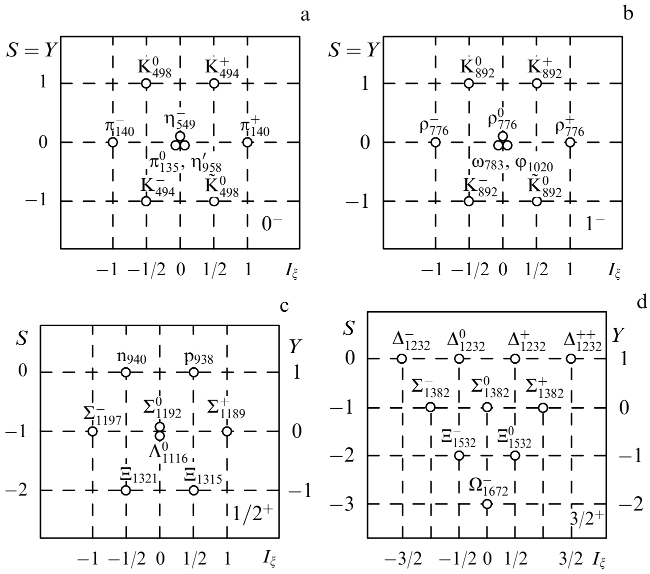

Figure 9. Three-quark unitary multiplets: (a) pseudoscalar meson nonet 0^-; (b) vector meson nonet 1^-; (c) baryon octet $1/2^+$, and (d) baryon decouplet $3/2^+$.

the relative weakness of the electromagnetic interaction as compared with the strong interaction. Somewhat later (after the creation of quantum chromodynamics), the difference in masses between the members of isotopic multiplets started to be explained by the small difference between the masses of the u- and d-quarks entering into their composition (for details see Section 8.1).

The aforementioned symmetry with respect to rotation through 120° consists in that multiplets comprising 1, 2, 3, 4 and 5 particles can be traced along the diagonal lines of the discussed figures, like the multiplets arranged along the horizontal lines. In this case, however, the splitting of mass is related to the strangeness, instead of the projection of isospin, and the scale of this splitting is significantly larger, since it is determined by the peculiarities of strong interaction for differing values of isospin I and strangeness S (by the greater mass of the s-quark as compared to the masses of u- and d-quarks).

The complete set of particles composing each of the four figures in Fig. 9 was called a unitary multiplet [33] which, for visual demonstration, can be represented as the double splitting of a single particle along the S- and I_ξ-axes. For example, the baryon octet $1/2^+$ in Fig. 9c can be represented as the splitting of a particle with the parameters $B = 1$, $J^P = 1/2^+$ and $M \simeq 1200$ MeV along the S-axis (the scale of splitting, $\Delta m \simeq 10 - 20\%$) and the I_ξ-axis ($\Delta m \simeq 1\%$). We draw the attention of the reader to the fact that the above-described symmetry in Figs 9a–d and its interpretation presented only serve as a certain illustrative explanation of the strong interaction symmetry (more general and less precise than the isotopic invariance) existing in nature, which was termed *unitary symmetry*.

[33] Unitary multiplets were previously called supermultiplets. Now this word signifies a family of particles uniting equal numbers of fermions and bosons (for instance, the photon and the photino) within the framework of the theory of supersymmetry [36]. See Conclusions for more details.

7.2 SU(3)-symmetry. The eight-fold way

In the 1960s, several theoretical models of unitary symmetry were developed, in which attempts were made to explain the composition and properties of particles belonging to unitary multiplets. The best results were achieved with the so-called SU(3)-symmetry proposed independently by M Gell-Mann [37] and Y Neeman [38] in 1961. The mathematical basis of SU(3)-symmetry is the theory of special unitary and unimodular SU(n)-groups. When $n = 2$, this theory provides a description of isotopic invariance, and when $n = 3$ of a wider unitary symmetry. The simplest representation of the SU(2)-group is (after the scalar) an isotopic doublet of particles differing in their charges. The simplest representation of the SU(3)-group is (again, after the scalar) an unitary triplet, the members of which differ, besides charge, in strangeness, too. Meson unitary multiplets in SU(3)-symmetry are obtained as the combination of a triplet and 'antitriplet':

$$3 \times \tilde{3} = 1 + 8\,, \tag{108}$$

and baryon multiplets by combining three triplets:

$$3 \times 3 \times 3 = 1 + 8 + 8 + 10\,. \tag{109}$$

Above we have seen that these predictions are well illustrated by Figs 9a–d which depict the two meson nonets 0^- and 1^- found in nature and representing the combination of a unitary octet and a unitary singlet ($1+8=9$) that by chance have identical spin and parity, and a baryon octet $1/2^+$ and decouplet $3/2^+$. However, no unitary triplet was found in nature, so Gell-Mann proposed the so-called *eight-fold way* (octet geometry) in which the unitary multiplets encountered in nature are obtained by combining an octet of baryons with an octet of antibaryons:

$$8 \times \tilde{8} = 1 + 8 + 8 + 10 + 10 + 27\,. \tag{110}$$

Anticipating, we note that the unitary triplet of particles was ultimately identified (as you will see somewhat later, the word 'discovered' is not quite suitable), however, the particles composing it exhibit such unusual properties that a special discussion is required for their description (see Section 8).

7.3 Prediction and discovery of the Ω^--hyperon

The most important advantage of SU(3)-symmetry is its prognostic power. It is necessary to note that the first hexagonal diagram for the baryon octet $1/2^+$ was obtained by Gell-Mann and Neeman at the beginning of 1961. At the time, only 7 of the 9 pseudoscalar (0^-)-mesons were known, while of the 9 vector (1^-)-mesons none were known. But in half a year both the nonets had been filled with the predicted particles. However, the most remarkable confirmation of SU(3)-symmetry being valid was the consistent decoding of the triangular diagram depicted in Fig. 9d, which resulted in the brilliant prediction of the Ω^--hyperon's existence in nature and in its subsequent discovery.

In the autumn of 1962, by the time the next International Conference in High-Energy Physics was held, 9 of the particles (excluding the lowest one) composing the $3/2^+$ decouplet (Fig. 9d) were known. Then the Ξ_{1532}-resonance was revealed just before the conference opened, and it turned out to occupy precisely the place forecast in Fig. 9d by the theory of SU(3)-symmetry which, in particular, predicted the mean masses of isomultiplets to be equidistant from each other. After this discovery, 9 particles of the decouplet were arranged along the S- and I_ξ-axes in such an expressive manner that the position and properties of the tenth particle were determined quite unambiguously [34].

L Alvarez, who was present at the conference (and was awarded the Nobel Prize in physics in 1968 for the construction of hydrogen bubble chambers of very large dimensions and for the discovery, with their aid, of a number of particles composing unitary multiplets) recalls in his memoirs [24, 39] that this prediction was the most significant event at the International Conference, since it was "*admission of the actual existence of a working theory in elementary particle physics*", from which it followed that "*to calculate the mass and strangeness of the last member of the decouplet — the particle* Ω^- *— had become a task of simple arithmetic*".

And, indeed, from examination of Fig. 9d one can see that the particles situated on the three upper horizontal lines (corresponding to the values of $S = 0$, -1 and -2) are separated from each other by the mass difference $\Delta m \simeq 150$ MeV, from which it follows that the mass of the Ω-hyperon should be ~ 1680 MeV, and its strangeness $S = -3$. But, in addition to the above, we also note that (1) from the position of the Ω-hyperon on the diagonal with negatively charged particles it follows that its charge is also negative, (2) the Ω^--hyperon cannot decay via strong interaction (with strangeness conservation) into $\Xi + \mathrm{K}$, since $m_{\Omega^-} < m_\Xi + m_\mathrm{K}$. Consequently, it should decay via the weak interaction (with $\Delta S = 1$) by the schemes $\Omega^- \to \Xi + \pi$ or $\Omega^- \to \Lambda + \mathrm{K}^-$ in $\tau \simeq 10^{-10}$ s, and (3) the Ω^--hyperon as a member of the decouplet should, naturally, have $B = 1$ and $J^P = 3/2^+$, and as an isotopic singlet — the isospin $I = 0$. As you can see, Alvarez was right: we indeed have "simple arithmetic".

The Ω^--hyperon was registered at the Brookhaven accelerator in the two-meter bubble chamber exposed to a K^--meson beam with a momentum of 5 GeV/c [40]. The production and decay schemes of the Ω^--hyperon are shown in Fig. 10. The Ω^--hyperon is produced in the following reaction proceeding with strangeness conservation:

$$\begin{aligned} &\mathrm{K}^- + \mathrm{p} \;\to \Omega^- + \mathrm{K}^+ + \mathrm{K}^0\,, \\ &S:\; -1 \quad +0 = -3 \quad +1 \quad +1\,, \end{aligned} \tag{111}$$

and decays via the scheme

$$\Omega^- \begin{cases} \nearrow \pi^- \\ \searrow \Xi^0 \begin{cases} \nearrow \pi^0 \begin{cases} \nearrow \gamma \to \mathrm{e}^+ + \mathrm{e}^-\,, \\ \searrow \gamma \to \mathrm{e}^+ + \mathrm{e}^-\,, \end{cases} \\ \searrow \Lambda \;\to\; \mathrm{p} + \pi^-\,, \end{cases} \end{cases} \tag{112}$$

the first ($\Omega^- \to \pi^- + \Xi^0$) and second ($\Xi^0 \to \pi^0 + \Lambda$) stages and partly the third ($\Lambda \to \mathrm{p} + \pi^-$) stage of which proceeded with a change of strangeness by $\Delta S = 1$, i.e. via weak interaction. The second part of the third decay stage ($\pi^0 \to 2\gamma$) proceeds via electromagnetic interaction, i.e. rapidly (in $\tau \simeq 10^{-16}$ s). The tracks of all the charged particles are shown in the figure by solid lines, while those of neutral particles (with the exception of the π^0-meson that has a negligible range) by dotted lines. In the case of the neutral particles Ξ^0, Λ, K^0 and π^0, the scheme of the event was used for calculating their masses that coincided with the tabular values, thus confirming that the recorded event was decoded correctly. The mass and lifetime of the Ω^--hyperon turned out to be close to the predicted values:

$$\begin{aligned} m_{\Omega^-} &= 1672.5 \pm 0.29 \ \mathrm{MeV}\,, \\ \tau &= (0.822 \pm 0.012) \times 10^{-10} \ \mathrm{s} \end{aligned} \tag{113}$$

(the values presented are current).

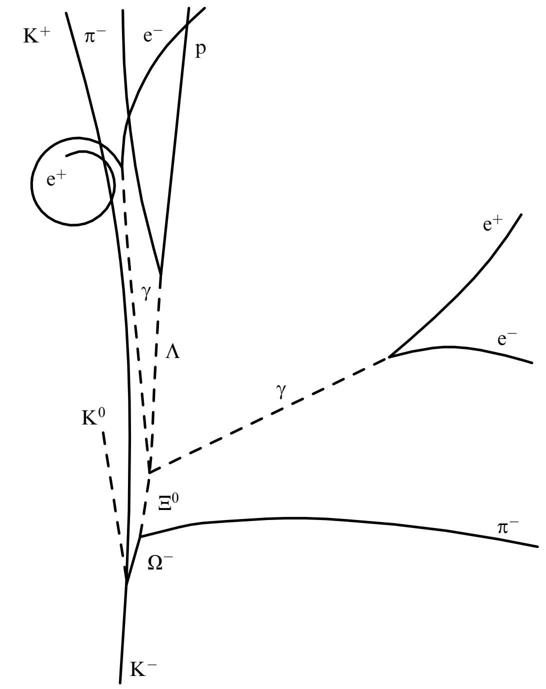

Figure 10. Production and decay schemes of the Ω^--hyperon.

8. The quark model and the concept of quantum chromodynamics (QCD)

8.1 u(up)-, d(down)-, s(strange)-quarks as composite parts of mesons and baryons. Searching for quarks in nature

We said above that the simplest representation of the SU(3)-group (after a scalar) is the triplet which must include a particle of strangeness differing from zero. The existence of such a triplet follows from the regularities established by the theory, interrelating various (1, 3, 8, 10) representations of the SU(3)-group. However, when trying to identify these representations with observed particles, it turned out that there existed no suitable triplet of particles in nature. The attempt, made by S Sakata, to choose the p, n and Λ-particles as this triplet has only led to a partial success — only meson octets were constructed unambiguously.

Total success was achieved when Gell-Mann [41] and Zweig [42] independently and simultaneously (in 1964) proposed something, at first sight, totally improbable: the existence in nature of particles with a *fractional* baryon number and charge, owing to which (as it was assumed at the time) they have not been observed in nature (actually, as we shall see below, the reason was different). Gell-Mann

[34] Legend has it that when one of the speakers of the conference drew a scheme with 9 particles of the decouplet, Gell-Mann, who was in the hall, shouted from his chair: "Draw the tenth particle!".

termed these particles quarks [35], and Zweig called them aces. Table 2 presents the old and new notation and terms for quarks, as well as their quantum numbers. At the beginning, the notation chosen for quarks was q_p, q_n and q_Λ, by analogy with the particle notation used by Sakata in creating his model. All the quantum numbers of quarks (with the exception of B, Z and m) also coincide with the quantum numbers of the corresponding particles. The new names [u(up), d(down), s(strange)] stress the orientation of isospin in the u- and d-quarks (up, i.e. $I_\xi = +1/2$, of the u-quark, and down, i.e. $I_\xi = -1/2$, of the d-quark) as well as the nonzero strangeness of the s-quark.

Table 2.

Name and notation of quarks: old	new	J	B	Z	S	I	I_ξ	m, MeV
q_p	u-up	1/2	1/3	+2/3	0	1/2	+1/2	~4
q_n	d-down	1/2	1/3	−1/3	0	1/2	−1/2	~7
q_Λ	s-strange	1/2	1/3	−1/3	−1	0	0	~150

It is readily seen that in spite of B and Z having fractional values the quarks satisfy the same formula (87) which was obtained for the elementary particles, i.e. $Z = I_\xi + (B+S)/2 = I_\xi + Y/2$ as before.

Baryons are constructed from the quarks according to the scheme qqq, while mesons according to $q\tilde{q}$. It is easy to verify that the proposed three quarks are sufficient for constructing any one of the aforementioned strongly interacting particles. Thus, for example, to obtain the Δ^{++}-resonance it is necessary to make use of the combination uuu involving the 'up' spin values, which will yield the entire set of quantum numbers for this particle ($B=1$, $Z=+2$, $I=3/2$, $J=3/2$, $P=+1$, $S=0$). In a similar manner, the proton is obtained as the combination of two u-quarks and one d-quark (p = uud), and the neutron as n = udd, $\Sigma^+ = \mathrm{uus}$, $\Sigma^0 = \mathrm{uds}$, $\Sigma^- = \mathrm{dds}$, $\Xi^0 = \mathrm{uss}$, $\Xi^- = \mathrm{dss}$, $\Omega^- = \mathrm{sss}$. As to the mesons, they have the following composition: $\pi^+ = \mathrm{u}\tilde{\mathrm{d}}$, $\pi^- = \mathrm{d}\tilde{\mathrm{u}}$, $K^+ = \mathrm{u}\tilde{\mathrm{s}}$, $K^- = \mathrm{s}\tilde{\mathrm{u}}$, $K^0 = \mathrm{d}\tilde{\mathrm{s}}$, $\tilde{K}^0 = \mathrm{s}\tilde{\mathrm{d}}$. Here, the somewhat differing masses of particles pertaining to a given multiplet (for example, of p and n, Σ^+, Σ^0 and Σ^- or K^+ and K^0) are explained by the small mass difference between the u- and d-quarks serving as constituents of these particles in various amounts and combinations. Notice that the masses of particles and antiparticles (π^+ and π^-, K^+ and K^-, K^0 and $\tilde{K}^0$) turn out to be identical (like they should according to the CPT-theorem mentioned in Section 4.1), because the corresponding quarks and antiquarks have equal masses ($m_u = m_{\tilde{u}}$, $m_d = m_{\tilde{d}}$, $m_s = m_{\tilde{s}}$). In those cases, when different particles (for instance, p and Δ^+) are represented by the same quark triplet (uud), these quarks form various combinations in accordance with the values of an ordinary spin and isotopic spin (1/2 and 1/2 for p, and 3/2 and 3/2 for Δ^+). Similarly, different neutral mesons can be represented as various compositions of the neutral quark states $\mathrm{u}\tilde{\mathrm{u}}$, $\mathrm{d}\tilde{\mathrm{d}}$, and $\mathrm{s}\tilde{\mathrm{s}}$. The structure of a composition is determined by the properties of the respective neutral mesons. Thus, the π^0-meson that has isospin $I=1$ is represented by the composition

$$\frac{\mathrm{u}\tilde{\mathrm{u}} - \mathrm{d}\tilde{\mathrm{d}}}{\sqrt{2}}\,, \tag{114}$$

and the η-meson — a member of the unitary octet with $I=0$ and a mass close to that of the K-meson — by the composition

$$\frac{\mathrm{u}\tilde{\mathrm{u}} + \mathrm{d}\tilde{\mathrm{d}} - 2\mathrm{s}\tilde{\mathrm{s}}}{\sqrt{6}}\,, \tag{115}$$

and, finally, the η'-meson belonging to another unitary multiplet, namely, to the unitary singlet with a mass noticeably larger than those of the members of the octet, by the fully symmetric composition

$$\frac{\mathrm{u}\tilde{\mathrm{u}} + \mathrm{d}\tilde{\mathrm{d}} + \mathrm{s}\tilde{\mathrm{s}}}{\sqrt{3}}\,. \tag{116}$$

As we can see, the three-quark model overcame in a very natural manner the main difficulty of the SU(3)-symmetry — the absence of a unitary triplet in the particle systematics, while all the achievements of the 'eight-fold way' were conserved. However, a new obstacle arose and, as it subsequently turned out, a very very serious one, since the initial idea that quarks were not observed in nature owing to their unusual properties (fractional charges and baryon numbers) was not confirmed by subsequent searches carried out with account of these features. Quarks were sought in cosmic rays, attempts were made to obtain them on accelerators (up to proton energies of 500 GeV, at which particles with masses up to $15m_p$ can be produced), the composition of meteorites was analyzed (quarks were expected to accumulate in them during their long time of motion in outer space, since there was *nothing they could decay into* because of Z and B being fractional). But all was in vain, and finally physicists arrived at the conclusion that free-state quarks do not exist in nature. The consistent development of this point of view led to a drastic change in the understanding of the nature of strong interaction, the new essence of which is described in quantum chromodynamics (QCD).

8.2 Elementary ideas of QCD. The color and flavor of quarks. Gluons. Confinement and asymptotic freedom. Jets

Very roughly, the idea of QCD essentially reduces to each one of the known sorts (flavors) of quarks (u, d, s, ...) existing in the form of three varieties: u_r, u_y, u_b, etc., where the letters r, y, b stand for a new quark quantum number — color [36] (r — red, y — yellow, b — blue). Originally, the concept of color was introduced for removing the contradiction with the Pauli principle, which arises when a baryon includes two or even three identical quarks (p = uud, $\Delta^{++} = \mathrm{uuu}$, $\Omega^- = \mathrm{sss}$). For this not to happen, quarks composing a baryon were considered to have different colors ($\mathrm{p} = \mathrm{u^r u^y d^b}$, $\Delta^{++} = \mathrm{u^r u^y u^b}$, and so on). Later on, however, the concept

[35] As legend goes Gell-Mann took the exotic name for his three particles from the novel *Finnegans Wake* by the avant-garde Irish writer J Joyce, the main character of which has visions of nightmarish birds racing around with triple mysterious cries of "quark, quark, quark". A description of the quark model 'for pedestrians' can be found in an article by Ya B Zel'dovich [43].

[36] Naturally, the idea of 'color' in QCD has nothing in common with an ordinary color but, as we shall soon see, this term is very convenient owing to the possibility of introducing the concept of a complementary color — anticolor and others.

of color acquired a new more important meaning. Color is a specific charge and the source of quanta of the strong interaction — gluons, similar to the electric charge which is the source of quanta of the electromagnetic interaction — photons. Here, the red, yellow and blue colors taken together compensate each other and form white color (w) that does not exhibit the properties of a charge ($\mathrm{r}+\mathrm{y}+\mathrm{b}=\mathrm{w}$). The quark – gluon interaction is 'confined' inside the baryon and is in no way manifested when its interaction with other hadrons is examined. The concrete structure of a baryon depends on the flavors of its constituent quarks: $\mathrm{p} = \mathrm{u^r u^y d^b}$, $\mathrm{u^y u^b d^r}$, and so on. Antibaryons and mesons are constructed in a similar way. They are also white — colorless. An antibaryon consists of three antiquarks with different 'anticolors' $\tilde{\mathrm{r}}$, $\tilde{\mathrm{y}}$, $\tilde{\mathrm{b}}$ (i.e. colors complementary to the given color up to white), which altogether are just as colorless as the sum of the main colors ($\tilde{\mathrm{r}}+\tilde{\mathrm{y}}+\tilde{\mathrm{b}}=\mathrm{r}+\mathrm{y}+\mathrm{b}=\mathrm{w}$). Thus, for example, antibaryons are written as combinations of the form: $\tilde{\mathrm{p}} = \tilde{\mathrm{u}}^{\tilde{\mathrm{r}}}\tilde{\mathrm{u}}^{\tilde{\mathrm{y}}}\tilde{\mathrm{d}}^{\tilde{\mathrm{b}}}$, $\tilde{\mathrm{u}}^{\tilde{\mathrm{y}}}\tilde{\mathrm{u}}^{\tilde{\mathrm{b}}}\tilde{\mathrm{d}}^{\tilde{\mathrm{r}}}$, and so on. A meson consists of three quark – antiquark pairs with mutually complementary colors, for instance, $\pi^+ = \mathrm{u^r}\tilde{\mathrm{d}}^{\tilde{\mathrm{r}}} + \mathrm{u^y}\tilde{\mathrm{d}}^{\tilde{\mathrm{y}}} + \mathrm{u^b}\tilde{\mathrm{d}}^{\tilde{\mathrm{b}}}$, and so on.

We shall now examine more comprehensively the properties of gluons (from the word glue) that realize the interaction between quarks ('glueing' them together into colorless hadrons). In a certain sense the gluon is similar to the photon. Both of them serve, as we have already pointed out, as carriers of an interaction: one — of the electromagnetic interaction, and the other — of the strong interaction, and both of them have the same quantum numbers ($m=0, Z=0, J^P=1^-$). There exist, however, three essential differences. The first consists in that the photon exists in a free state and travels in space with the speed of light, while the gluon, as we mentioned above, is confined in hadrons. The second consists in that the photon participates in a long-range interaction (like it should with a quantum of $m=0$), while the gluon, *in spite of its* $m=0$, takes part in forming the short-range strong interaction, the quantum of which is required to exhibit $m \neq 0$. We shall explain how this obstacle can be overcome toward the end of this section, while now we will deal with the third feature distinguishing the gluon from the photon. It consists in that photons are electrically neutral, while gluons, like the quarks, possess color charges themselves and, consequently, are capable of emitting (and even with higher intensity than quarks) new gluons that in turn can also emit gluons, and so on. Thus, the gluon field increases with the distance from a quark, which means that as the distance between quarks increases the actual interaction between them is also enhanced. This results in the quarks and gluons being 'confined' inside a hadron and not being capable of leaving it. At the same time, owing to the property of antiscreening (see Section 10), at very small distances ($\ll 10^{-13}$ cm) quarks inside a hadron behave like free particles, i.e. their interaction is apparently 'weak' with a constant of the order of $0.16 \ll 1$, which permits us to apply the perturbation theory in calculations. Such behavior of quarks at very small distances is known as *asymptotic freedom*.

Owing to the variegation in color of quarks entering into a hadron, the gluons that stick them together must be characterized by two colors. To 'glue' the red, yellow and blue quarks of a baryon together, two-colored gluons are required of the form $\mathrm{r}\tilde{\mathrm{y}}$, $\mathrm{r}\tilde{\mathrm{b}}$, $\mathrm{y}\tilde{\mathrm{r}}$, $\mathrm{y}\tilde{\mathrm{b}}$, $\mathrm{b}\tilde{\mathrm{r}}$, $\mathrm{b}\tilde{\mathrm{y}}$. For example, the interaction between a red quark and a blue quark proceeds as follows: the red quark emits a $\mathrm{r}\tilde{\mathrm{b}}$-gluon and loses the red and antiblue colors (i.e. it actually *loses* its red color but, in turn, *acquires* blue color). In a similar manner, when the blue quark absorbs the $\mathrm{r}\tilde{\mathrm{b}}$-gluon, it acquires red and antiblue colors, of which the second is mutually compensated for with the initial blue color of the quark, resulting in the quark becoming red. Thus, the interaction between quarks terminates in their exchanging colors. Antiquarks in antibaryons interact similarly.

The interaction between quarks and antiquarks in mesons is realized with the aid of colorless gluons of the form $\mathrm{r}\tilde{\mathrm{r}}$, $\mathrm{y}\tilde{\mathrm{y}}$, $\mathrm{b}\tilde{\mathrm{b}}$, which, however, do not act individually but in the form of combinations

$$\frac{\mathrm{r}\tilde{\mathrm{r}} - \mathrm{y}\tilde{\mathrm{y}}}{\sqrt{2}}\,, \tag{117}$$

$$\frac{\mathrm{r}\tilde{\mathrm{r}} + \mathrm{y}\tilde{\mathrm{y}} - \mathrm{b}\tilde{\mathrm{b}}}{\sqrt{6}} \tag{118}$$

with a structure following from the theory of color $\mathrm{SU(3)_c}$-symmetry [compare with formulae (114), (115) describing quark SU(3)-compositions employed for constructing neutral mesons]. Besides the listed $\mathrm{SU(3)_c}$-octet of gluons, there exists one more 'truly white' gluon of the form

$$\frac{\mathrm{r}\tilde{\mathrm{r}} + \mathrm{y}\tilde{\mathrm{y}} + \mathrm{b}\tilde{\mathrm{b}}}{\sqrt{6}}\,, \tag{119}$$

which is similar in composition to the η'-meson [compare with formula (116)].

Thus, to conclude the elementary description of QCD fundamentals, we once more stress that together with color quarks and two-color gluons there exist colorless hadrons, the colors of which do not 'peep out' as those of quarks or gluons, since both the former and the latter are confined inside the hadron (to be true, the total color of gluons is, obviously, also white). It is impossible to reveal the strong quark – gluon interaction 'outside' the hadron. Considering the interaction of hadrons, we think it proceeds approximately like those presented in the section on the Yukawa theory, i.e. via the exchange of π-mesons or, possibly, of certain other particles with $m \neq 0$. It is therefore natural for hadrons, unlike quarks, to be encountered in a free state and, if they are bound, like, for instance, nucleons in a nucleus, then in this case they can be freed by introducing an amount of energy into the nucleus exceeding the binding energy of the nucleon.

The properties of quarks and gluons were most clearly revealed in studies of quark – antiquark pair production in the process of $\mathrm{e^+e^-}$-annihilation at a total energy of $E_{\mathrm{e^+e^-}} \geqslant 7$ GeV with subsequent quark *hadronization* into colorless thin ($p_\perp \ll p_\parallel$) *hadron jets* traveling in the direction of the quark separation (see schematic Fig. 11):

$$\mathrm{e^+} + \mathrm{e^-} \to \gamma + \gamma \to \mathrm{q} + \tilde{\mathrm{q}} \to \text{hadron}\,. \tag{120}$$

At a higher $\mathrm{e^+e^-}$-annihilation energy (~ 10 GeV), one of the quarks (or very rarely, both) can emit a soft gluon escaping in the same direction as the quark, which results in a certain swelling of the respective jet, and the swelling increases with energy. A 'thick' hadron – gluon jet can be distinguished from a 'thin' purely hadron jet by this characteristic, but the observation of such events is, however, difficult owing to their poor separability. Purely gluon jets, first observed in 1979 with the aid of the PETRA installation that permitted the production of hard (32 GeV in the center-of-mass system) $\mathrm{e^+e^-}$ colliding beams, look much more convincing. At such a

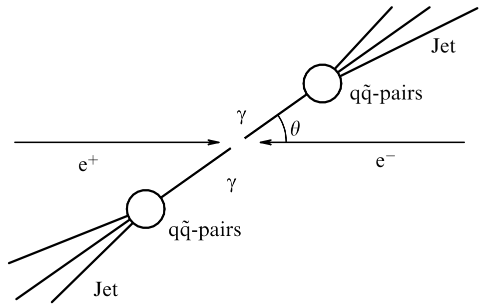

Figure 11. Scheme of jet production.

high energy, the hadronization of quarks is not only accompanied by two-jet events, but also by a significant amount (7 – 10%) of three-jet events in which the third jet is formed by a gluon emitted at a large angle with respect to the line along which the quarks are scattered. This jet starts swelling with energy earlier than the hadron jet, and its swelling is stronger.

We now go back to the issue of apparent contradiction between the zero mass of the gluon and its function of the quantum of strong interaction, which requires $m \neq 0$. In other words, how does QCD explain the nuclear forces between the nucleons in a nucleus, and how does ordinary hadron interaction, for example, the reactions $\pi N \to \pi\pi N$, proceed from the standpoint of QCD? Where does the additional $q\tilde{q}$-pair required for producing a virtual pion in the first case and the real pion in the second, come from? Let us first consider the second question. Very approximately, it proceeds as follows. The influence of the energy introduced by the incident pion results in one of the nucleon constituent quarks undergoing a strong displacement, which leads to its interaction with the other quarks of the nucleon increasing drastically. If the energy of this interaction exceeds the value required for producing a quark – antiquark pair, then the newly produced quark will substitute the one displaced in the nucleon, while the latter will combine with the produced antiquark and form a new real pion. And all this will take place without any quark being freed, so the reaction will only culminate in our observing an additional free 'white' pion.

About the same kind of picture can be imagined of the nature of nuclear forces between the nucleons in a nucleus. In this case only one of the quarks composing the nucleon is shifted by the 'internal reserve of energy' that arises for a short period of time Δt in accordance with the uncertainty relation. Further, everything proceeds as in the previous case, but the $q\tilde{q}$-pairs and the pion produced will only be virtual, since no energy is received from outside. It is this pion that serves as the quantum with $m \neq 0$, which we mentioned in Section 2. Thus, the strong nuclear interaction remains short-ranged, in spite of the zero gluon mass.

8.3 Experimental confirmation of the existence of quarks, gluons, and color charge

We mentioned above that quarks have not been observed in nature, since owing to the peculiar features of the interaction between themselves they cannot exist in a free state. At present, however, specialists in elementary particle physics do not doubt either the existence of quarks, or the existence of gluons, or the existence of color charges. And this confidence is not only shared by theoreticians who are fully sure of their rightness, but also by experimenters who have confirmed it by experiments. Here are some of the experimental facts.

(1) Experimental studies of deep-inelastic scattering of electrons by protons have revealed large-angle deflections pointing to the existence of pointlike objects inside the proton, i.e. to the nucleon's quark structure (recall Rutherford's experiments in which he discovered the atomic nucleus by observing large-angle scattering of α-particles by atoms).

(2) From experimental investigations of nucleon – nucleon (NN), antinucleon – nucleon ($\tilde{N}N$), and pion – nucleon (πN) interactions it is known that the total cross sections of these processes satisfy the following relations

$$\frac{\sigma_{NN} + \sigma_{\tilde{N}N}}{\sigma_{\pi N}} = 3\,, \qquad \frac{\sigma_{NN}}{\sigma_{\pi N}} = \frac{3}{2}\,. \tag{121}$$

These relations are readily obtained, if one recalls that in accordance with the quark model one obtains

$$N = qqq\,, \quad \tilde{N} = \tilde{q}\tilde{q}\tilde{q}\,, \quad \pi = q\tilde{q}\,.$$

Then, it is evident that

$$\sigma_{NN} = 9\sigma_{qq}\,, \quad \sigma_{\tilde{N}N} = 9\sigma_{\tilde{q}q}\,, \quad \sigma_{\pi N} = 3\sigma_{qq} + 3\sigma_{\tilde{q}q}$$

and

$$\frac{\sigma_{NN} + \sigma_{\tilde{N}N}}{\sigma_{\pi N}} = \frac{9\sigma_{qq} + 9\sigma_{\tilde{q}q}}{3\sigma_{qq} + 3\sigma_{\tilde{q}q}} = 3\,, \tag{122}$$

and taking into account the Pomeranchuk theory (see Section 5), according to which $\sigma_{NN} = \sigma_{\tilde{N}N}$, we arrive at

$$\frac{\sigma_{NN}}{\sigma_{\pi N}} = \frac{3}{2}\,.$$

(3) The quark model permits us to explain the experimentally revealed ratio of the neutron and proton magnetic moments, $\mu_n/\mu_p = -0.68 \simeq -2/3$, which, according to the model, is precisely equal to $-2/3$.

(4) The electric charges of the u- and d-quarks having fractional values is confirmed by comparison of the experimental cross sections of electron and neutrino scattering by a light nucleus with the theoretical values calculated under the assumption that $Z_u = +2/3$ and $Z_d = -1/3$. From this comparison it follows that

$$(Z_u^2 + Z_d^2)_{\text{expt}} \simeq \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 = \frac{5}{9}\,. \tag{123}$$

(5) That the quark has three colors is confirmed by comparison of the experimental and calculated values of the ratio

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})} = 3\sum_1^n z_i^2\,, \tag{124}$$

where 3 is the number of colors, z_i is the electric charge of the ith quark, and n is the number of quarks. This comparison not only yielded a satisfactory agreement in the zone of influence of the three-quark model (for $n = 3$), when $R_{\text{theor}} = 2$, but also at higher energies of the e^+e^--beams, when the interaction process starts involving the 4th and 5th quarks (see Section 8.4.3).

(6) The quark spin (1/2) follows from the angular distribution of hadron jets produced in e^+e^--annihilation of their primary $\tilde{q}q$-pairs.

(7) The existence of gluons was primarily confirmed by the fact that in deep-inelastic lepton – hadron processes at large momentum transfers only half of the momentum received by the hadron is shared by its constituent quarks. This is explained by the hadron also containing, besides quarks, particles that do not interact with leptons and carry away the second half of the momentum. Precisely these particles are gluons. Additional confirmation of the existence of gluons was obtained by the observation, firstly, of two-jet events with one jet with a swelling and then, also, of three-jet events, the third jet of which behaved like a purely gluon jet (exhibiting noticeable swelling with an increase of energy). Such events are interpreted as the production of a gluon (g) in the process $e^+e^- \to q\tilde{q}g$ at large angles to the momenta of the quarks and subsequent production of new gluons leading to the jet undergoing swelling. Details of QCD, quarks, gluons and jets can be found in the review by Ya I Azimov et al. [44].

8.4 c(charm)-, b(beauty)-, t(top)-quarks and their families. The drift chamber

During the first years after the creation and triumphal march of the quark model, the three quarks (u, d, s) underlying it seemed to represent a sufficient number of subelementary 'bricks' for 'building up' all the particles existing in nature. However, not everybody was of the same opinion. One can only marvel at the incredible sagacity of Gell-Mann and co-workers [45], who 10 years before the discovery of the fourth c-quark with the new quantum number of charm wrote: "*There may exist hitherto undiscovered quantum numbers that are conserved in strong interactions, the values of which for all known particles are zero. Before strange particles had been discovered, the quantum number of strangeness was precisely such a number. Experiments to be carried out at very high energies, which will be available at accelerators of the next generation, may result in a similar situation with respect to a totally novel quantum number*."

8.4.1 The fourth quark c (charm). Particles with hidden and open charm. In 1970, i.e. 6 years after the assumption of the existence of new quantum numbers and, consequently, of new quarks was voiced in a very general form [45], the concrete theoretical necessity arose for the existence of a fourth quark, which was required for removing the disagreement between the theory of weak interaction and experimental data (the existing theory allowed decays such as $K^0 \to \mu^+ + \mu^-$ and $\Lambda \to n + e^+ + e^-$, but they were not observed in experiments). Moreover, for renormalization of the theory it was necessary for the number of quarks to equal the number of leptons, and at the time four leptons were known: e, μ, ν_e and ν_μ.

From the theory it followed that to overcome these obstacles one had to introduce a fourth quark into the quark model, which it was proposed to call c (charm). The c-quark should have the following set of quantum numbers: $B = 1/3$, $Z = +2/3$, $J^P = 1/2^+$, $I = 0$, $S = 0$, $c = +1$. The new quantum number c (charm) should be conserved in strong and electromagnetic interactions, i.e. by analogy with relation (87) it should satisfy the following generalized formula

$$Z = I_\xi + \frac{B + S + c}{2} = I_\xi + \frac{Y}{2}\,, \tag{125}$$

and the quantity $B + S + c$, like previously, was termed the hypercharge Y. Like strangeness, charm must change by unity in weak interactions. It was assumed that the new c-quark would participate on the same footing as the u-, d- and s-quarks in the formation of hadrons, i.e. contribute to the structure of baryons in the form of a composition cqq, of antibaryons as $\tilde{c}\tilde{q}\tilde{q}$, and of mesons as $c\tilde{q}$ or $q\tilde{c}$, where any one of the u-, d-, s-quarks (or $\tilde{u}_1$-, $\tilde{d}_1$-, $\tilde{s}_1$-antiquarks) could serve as $q(\tilde{q})$. The formation of neutral mesons such as $c\tilde{c}$, in which charm is compensated by 'anticharm' (*hidden charm*), is also possible.

The c-quark was observed at the end of 1974 precisely within a $c\tilde{c}$-particle *with hidden charm* that was named the J/ψ-particle. The double name of this particle is due to its being observed practically at the same time at Brookhaven by S Ting and collaborators [46] (who named it the J-particle) and at Stanford by B Richter and collaborators [47] (who called it the ψ-particle). At the Brookhaven National Laboratory, the new particle was discovered in a reaction caused by protons of energy 26 GeV:

$$p + Be \to e^+ + e^- + X\,, \tag{126}$$

where X stands for 'anything' (in an inclusive process). The layout of the experimental setup is shown in Fig. 12a, b. The electron pairs were detected by a two-arm spectrometer, each arm of which consisted of three magnets $M_1 - M_3$, four multiwire proportional chambers $C_1 - C_4$, two hodoscopes H_1, $H_2 (8 \times 8)$, three rows of shower counters *ShC* and three gaseous Cherenkov counters $CC_1 - CC_3$. The results of measurements are presented in Fig. 12d, from which a clear maximum of width smaller than 5 MeV, signifying the production of a new particle, is observed at the effective mass $m_{e^+e^-} = 3.1$ GeV.

The setup used at Stanford is depicted in Fig. 12c; it permitted the detection of particles produced in the annihilation of electrons and positrons incident upon each other in the SPEAR e^+e^--collider. The results of measurements are presented in Fig. 12e, from which a particle is seen to be produced in the e^+e^--annihilation process and to decay via three channels — into hadrons, a $\mu^+\mu^-$-pair, and an e^+e^--pair with respective widths Γ equal to 70 keV, 5 keV and 5 keV. From the relatively small width of the J/ψ-decay via the hadron channel it follows that the particle lifetime is approximately 10^{-20} s, which is 10^3 times longer than the mean lifetime of other previously considered unstable particles. This was explained by the fact that the quark flavors should change in the decay of the J/ψ-particle into ordinary hadrons (the c- and $\tilde{c}$-quarks transform into u-, $\tilde{u}$-, d-, $\tilde{d}$-, s- or $\tilde{s}$-quarks), while the decays of the previously considered unstable particles left the quark compositions of the primary particle and its decay products unaltered. Below, we shall see that in those cases when the decays of particles such as $c\tilde{c}$ proceed without transformation of the c- and $\tilde{c}$-quarks, the widths Γ are about 50 MeV to an order of magnitude, i.e. $\tau \simeq 10^{-23}$ s. The present-day values of the mass and total width of the J/ψ-particle are $m = 3096.87 \pm 0.04$ MeV and $\Gamma = 87 \pm 5$ keV, respectively.

Besides the J/ψ-particle, several other particles were revealed with hidden charm, the masses and quantum numbers of which are presented in Fig. 13. The spectroscopic transitions of ψ- and χ-particles depicted in this figure permitted the determination of their energy levels which are very similar to the scheme of levels of positronium, i.e. of the

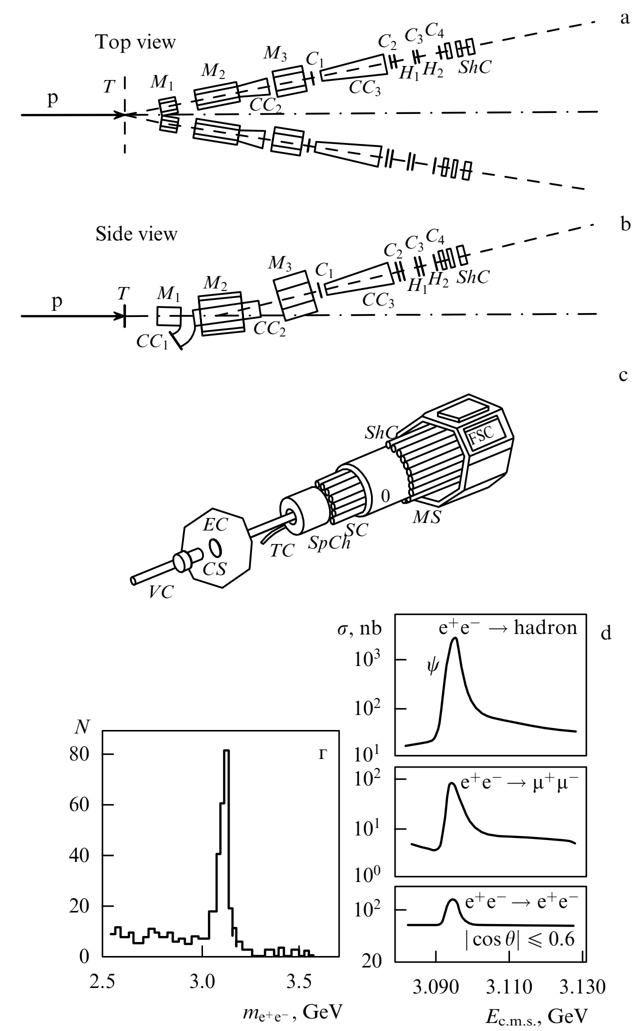

Figure 12. Discovery of the J/ψ-particle: (a, b) layout of the experiment performed by S Ting and co-workers: p — proton beam, T — target, M_1 – M_3 — magnets, CC_1 – CC_3 — gaseous Cherenkov counters, C_1 – C_4 — wire proportional chambers, H_1, H_2 — hodoscopes, ShC — shower counters; (c) layout of the experiment staged by B Richter and co-workers: VC — vacuum chamber, CS — compensating solenoid, EC — end cap, TC — tubular counter, $SpCh$ — cylindrical wire spark chambers, SC — scintillation counters, MC — coil creating magnetic field of 0.4 T in the volume of 20 m^3, ShC — shower counters, MS — magnetic screen (20-cm Fe), FSC — flat spark chambers; (d) results obtained by S Ting and co-workers; (e) — results obtained by B Richter and co-workers.

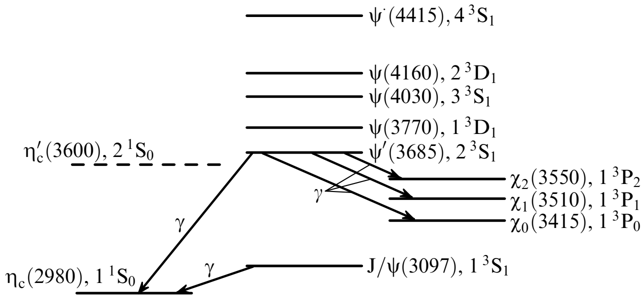

Figure 13. Scheme of charmonium energy levels.

state, studied long ago, of an electron and a positron bound by Coulomb forces. In this connection it was termed *charmonium*, and by analogy with positronium, some of the c$\tilde{c}$-states belong to orthocharmonium ($J = 1$), while others belong to paracharmonium ($J = 0$). Like in the case of positronium, the P- and C-parities of various charmonium states are determined by the formulae

$$P = (-1)^{L+1}, \qquad C = (-1)^{L+J}, \tag{127}$$

where L is the orbital momentum, and J is the spin. Between the levels with opposite C-parities, γ-transitions of high intensity were observed (like it should be in such a case).

The similarity between the charmonium and positronium spectra allowed the reconstruction of the approximate behavior of the interaction potential between the c- and $\tilde{c}$-quarks (Fig. 14), which at small distances is similar to the Coulomb interaction, i.e. it is described by the law $V_1(r) = -\alpha_s/r$, where α_s is the strong interaction constant. At large distances, the potential should increase rapidly [for instance, by the linear law $V_2(r) = br$] to provide for confinement. The total potential

$$V(r) = V_1(r) + V_2(r) = -\frac{\alpha_s}{r} + br \tag{128}$$

has the shape of a funnel, for which it is called a funnel type potential.

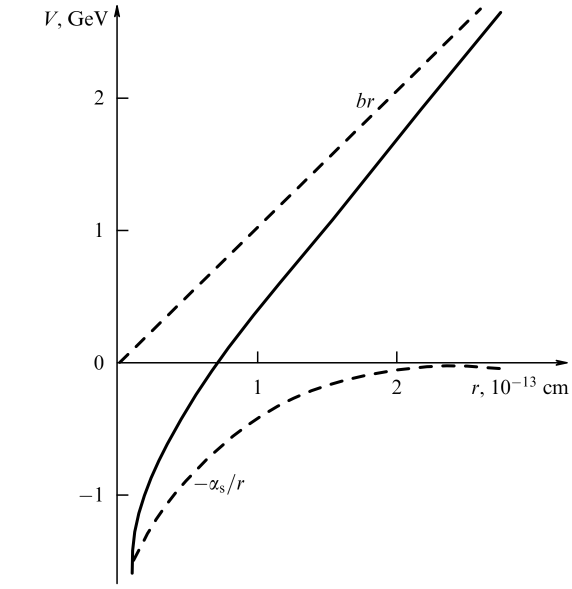

Figure 14. 'Funnel' potential.

Investigation of the properties of particles present in the charmonium scheme revealed that starting from the $\psi(3770)$ they have a width $\Gamma \simeq 25 - 80$ MeV, i.e. they decay via strong interaction in $\tau \simeq 10^{-23}$ s and conserve the c- and $\tilde{c}$-quarks in the decay products. The first to be observed (in 1976) were the decays of the ψ(4030)-particles via the schemes

$$\psi(4030) \begin{array}{l} \nearrow \ D^0 + \widetilde{D}^0\,, \\ \searrow \ D^+ + D^-\,. \end{array} \tag{129}$$

The decay products of the $\psi(4030)$-particle have the following quark composition: $D^0 = c\tilde{u}$, $\widetilde{D}^0 = u\tilde{c}$, $D^+ = c\tilde{d}$, $D^- = d\tilde{c}$, i.e. c and $\tilde{c}$ are contained in them individually (without being mutually compensated by the respective antiquark). Such particles, unlike the $c\tilde{c}$-particles with hidden charm, have been termed *mesons with open charm*. According to the aforementioned scheme for constructing mesons with the participation of c- and $\tilde{c}$-quarks (besides the presented combinations $c\tilde{u}$, $u\tilde{c}$, $c\tilde{d}$ and $d\tilde{c}$), there should also exist two more combinations, $c\tilde{s} = D_s^+$ and $s\tilde{c} = D_s^-$, called charmed strange mesons.

All the six listed charmed mesons (D^0, $\tilde{D}^0$, D^+, D^-, D_s^+ and D_s^-) together with the additional neutral η_c-meson exhibiting hidden charm (see Fig. 13) have been discovered, and they are members of the meson 16-plet of the four-quark model with the quantum numbers $J^P = 0^-$ (see the review by S Glashow [48] and Fig. 15a–d). The previously considered (see Fig. 9a) nonet of ordinary and strange pseudoscalar mesons occupies the middle plane in Fig. 15a, which now has at its center the additional η_c-meson mentioned above. The mesons with open charm are situated in the upper and lower planes in the figure. The upper triplet contains the isodoublet of charmed mesons D^0 and D^+ with $I = 1/2$, $S = 0$, $c = +1$ as well as the strange charmed meson D_s^+ with $c = +1$, $S = +1$ and $I = 0$. The lower triplet comprises the isodoublet D^- and $\tilde{D}^0$ with $c = -1$, $I = 1/2$, $S = 0$ and the strange charmed D_s^--meson with $c = -1$, $S = -1$ and $I = 0$. Charmed mesons decay through the weak interaction mechanism in a time of $\tau \simeq 10^{-13} - 10^{-12}$ s via schemes in which the c($\tilde{c}$)-quark transforms into other quarks:

$$D^0 \begin{array}{l} \nearrow K^- + X\,, \\ \searrow \tilde{K}^0 + X\,, \end{array} \qquad \tilde{D}^0 \begin{array}{l} \nearrow K^+ + X\,, \\ \searrow K^0 + X\,, \end{array} \tag{130}$$

$$D^+ \begin{array}{l} \nearrow K^- + X\,, \\ \searrow \tilde{K}^0 + X\,, \end{array} \qquad \tilde{D}^- \begin{array}{l} \nearrow K^+ + X\,, \\ \searrow K^0 + X\,, \end{array} \tag{131}$$

$$D_s^+ \to \phi + \pi^+\,, \qquad D_s^- \to \phi + \pi^-\,, \tag{132}$$

where X stands for 'something else'. Their masses are presented in Table 3 (see the upper part of the table)

Besides the meson pseudoscalar 16-plet 0^-, in the four-quark model there also exists the vector meson 16-plet 1^- (Fig. 15b) which contains the vector nonet 1^- (see Fig. 9b) supplemented at the center by the J/ψ-particle, as well as two triplets of charmed mesons $D^{*\pm}$, D^{*0}, $\tilde{D}^{*0}$ and $D_s^{*\pm}$ (listed in the lower part of Table 3). Charmed vector mesons exhibit quite large values of $\Gamma \simeq 0.1 - 2$ MeV, i.e. they decay (with the conservation of charm) quite rapidly ($\tau \simeq 10^{-21} - 10^{-20}$ s) via the schemes

$$D^{*0} \begin{array}{l} \nearrow D^0 + \pi^0\,, \\ \searrow D^0 + \gamma\,, \end{array} \qquad \tilde{D}^{*0} \begin{array}{l} \nearrow \tilde{D}^0 + \pi^0\,, \\ \searrow \tilde{D}^0 + \gamma\,, \end{array} \tag{133}$$

$$D^{*+} \begin{array}{l} \nearrow D^0 + \pi^+\,, \\ \searrow D^+ + \pi^0\,, \end{array} \qquad D^{*-} \begin{array}{l} \nearrow \tilde{D}^0 + \pi^-\,, \\ \searrow D^- + \pi^0\,, \end{array} \tag{134}$$

$$D_s^{*+} \begin{array}{l} \nearrow D_s^+ + \gamma\,, \\ \searrow D_s^+ + \pi^0\,, \end{array} \qquad D_s^{*-} \begin{array}{l} \nearrow D_s^- + \gamma\,, \\ \searrow D_s^- + \pi^0\,. \end{array} \tag{135}$$

Besides the 12 charmed mesons mentioned, the constituent quarks of which are in the ground (S) state, excited ($L = 1$) states of charmed mesons have been revealed (called D_1^0, D_2^{*0}, D_2^{*+}, D_{s1}^{*+}, D_{s2}^{*+}) with masses between 2420 MeV and 2573 MeV that decay with the conservation of charm in a time of $10^{-23} - 10^{-22}$ s ($\Gamma = 15 - 30$ MeV).

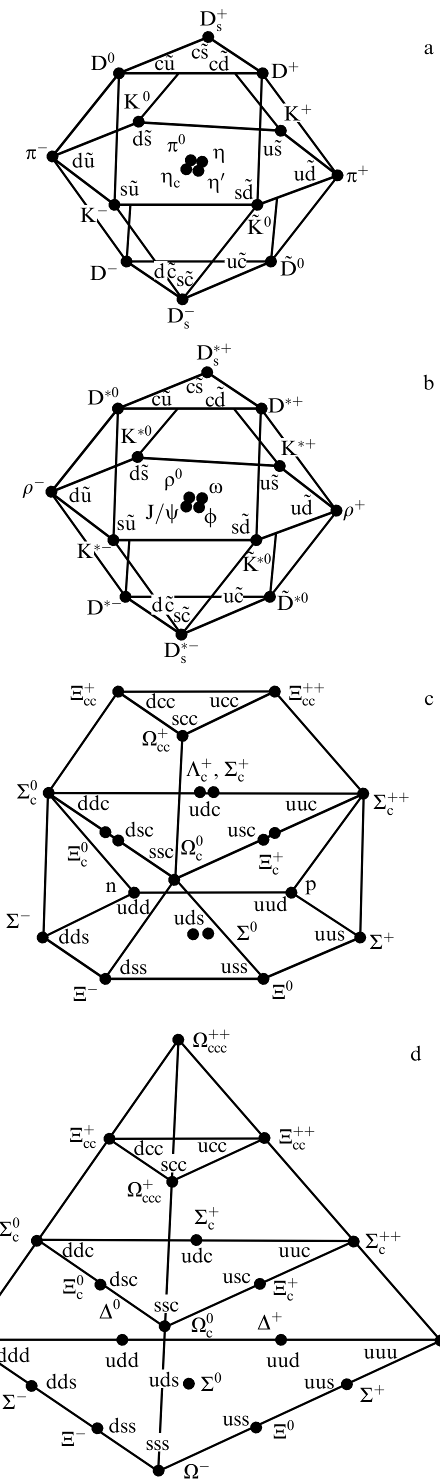

Figure 15. Four-quark unitary multiplets: (a) pseudoscalar meson 16-plet 0^-; (b) vector meson 16-plet 1^-; (c) baryon 20-plet $1/2^+$, and (d) baryon 20-plet $3/2^+$.

As pointed out at the beginning of this section, baryon multiplets are constructed in the four-quark model in the same manner as in the three-quark model, i.e. in the form of compositions of three quarks, but here their number is enhanced owing to the use, besides the u-, d-, s-quarks, of one more — the c-quark. Figure 15c presents the 20-plet of baryons with $J^P = 1/2^+$, the composition of which includes the previously considered baryon octet (see Fig. 9c) that is

Table 3.

Particle (antiparticle)	Quark composition	m, MeV	τ, 10^{-12} s; Γ, MeV	B	J^P	c	S	I	I_ξ
$D^+(D^-)$	$c\tilde{d}(d\tilde{c})$	1869.3	$\tau =$ 1.051	0	0^-	$+1(-1)$	0	1/2	$+1/2(-1/2)$
$D^0(\tilde{D}^0)$	$c\tilde{u}(u\tilde{c})$	1864.5	0.413	0	0^-	$+1(-1)$	0	1/2	$-1/2(+1/2)$
$D_s^+(D_s^-)$	$c\tilde{s}(s\tilde{c})$	1968.6	0.496	0	0^-	$+1(-1)$	$+1(-1)$	0	0
$D^{*+}(D^{*-})$	$c\tilde{d}(d\tilde{c})$	2010	$\Gamma =$ < 0.13	0	1^-	$+1(-1)$	0	1/2	$+1/2(-1/2)$
$D^{*0}(\tilde{D}^{*0})$	$c\tilde{u}(u\tilde{c})$	2007	< 2.1	0	1^-	$+1(-1)$	0	1/2	$-1/2(+1/2)$
$D_s^{*+}(D_s^{*-})$	$c\tilde{s}(s\tilde{c})$	2112	< 19	0	?	$+1(-1)$	$+1(-1)$	0	0

situated in the lower plane of Fig. 15c, the nonet of charmed baryons (the middle plane of Fig. 15c) and the triplet of baryons exhibiting double charm (the upper plane of Fig. 15c).

One more baryon 20-plet of the four-quark model with $J^P = 3/2^+$ (Fig. 15d) can be constructed from the previously considered (see Fig. 9d) decouplet $3/2^+$ (the base of the 'pyramid' depicted in Fig. 15d), the six new charmed baryons (second plane from the bottom), three doubly charmed baryons (third plane from the bottom) and one baryon with a triple charm (vertex of a pyramid). The notation and quark composition of all the particles composing both the baryon 20-plets and the meson 16-plets are immediately presented in Fig. 15a–d. It is necessary to note that not all the particles composing the baryon multiplets have been observed yet. The first to be revealed (in 1980) were the Λ_c^+- and Ξ_c^+-baryons having the respective quark structures udc and usc, masses 2285 and 2460 MeV, quantum numbers $I(J^P)$ — $0(1/2^+)$ and $1/2(1/2^+)$, lifetimes 0.21×10^{-12} s and 0.35×10^{-12} s. The tables of elementary particle properties [49] also incorporate the baryon isotriplet Σ_c^0, Σ_c^+ and Σ_c^{++}, Ξ_c^0 (the partner of Ξ_c^+ in the isodoublet), the isosinglet Ω_c^0 and others, but not a single baryon with double or triple charm has yet been found. The present-day state of affairs in the physics of charmed mesons and baryons is dealt with in greater detail in the review by S V Semenov [50] and, also, in an earlier review by M A Shifman [51], in which what was known at the time of particles with beauty (see Section 8.4.2) is presented. S Ting and B Richter were awarded the Nobel Prize in physics for the discovery of new heavy particles and the investigation of their properties in 1976 (already!).

8.4.2 The fifth quark b (beauty, bottom) and its beautiful families (explicit and hidden). The prediction made by Gell-Mann et al. [45] that new quantum numbers (signifying quarks) would be revealed with the construction of accelerators of consecutive generations was once more confirmed in 1977, when the group led by Professor L Lederman discovered (in a 400 GeV proton beam) the new superheavy Υ-*meson* of mass $m \simeq 10 m_p$(!) that decays into a $\mu^+\mu^-$-pair. The present-day values of the mass and total width of the Υ-meson are

$$m_\Upsilon = 9460 \text{ MeV}, \quad \Gamma_\Upsilon = 52.5 \text{ keV}, \tag{136}$$

from which it follows that it cannot belong to the $c\tilde{c}$-family, since the total width Γ of the ψ-particles increases rapidly with their mass, and already in the case of the $\psi(4160)$ having a mass of 4159 MeV $\ll m_\Upsilon$ it reaches the value of 70 ± 20 MeV. Precisely for this reason, the discovery of the Υ-meson with such unusual properties pointed (like when the J/ψ-particle was discovered) to the existence of a new quantum number forbidding the Υ-meson to decay rapidly into known particles and, consequently, of a new quark that in combination with its antiquark forms this new particle. Owing to the exceptional importance of this discovery we shall deal with it in more detail.

The Υ-meson was discovered at the Fermi National Accelerator Laboratory (Batavia, USA) in the inclusive process

$$p + (\text{Cu}, \text{Pb}) \to \mu^+ + \mu^- + X, \tag{137}$$

where X, like before, denotes 'something else'. For the detection and analysis of $\mu^+\mu^-$-pairs, a two-arm magnetic spectrometer was used, each arm of which involved a magnet (with a current of up to 1500 A) for deflecting charged particles in the vertical plane, 11 multiwire proportional chambers, 7 scintillation counters, a threshold gaseous Cherenkov counter and a drift chamber [37]. The mass resolution of the spectrometer amounted to $\Delta m/m = 0.02$. For its calibration, 15000 J/ψ-particles and 1000 ψ'-particles were used that were detected at a reduced current in the magnets. The counting rate of $\mu^+\mu^-$-pairs with an effective mass $m_{\mu^+\mu^-} \geqslant 5$ GeV was 20 $\mu^+\mu^-$-pairs per hour. During the exposure, a total of 9000 $\mu^+\mu^-$-pairs were recorded. The results of this work are presented in Fig. 16 in which a noticeable maximum is seen at $m_{\mu^+\mu^-} \simeq 9.5$ GeV, which signifies the existence of a new particle with that mass.

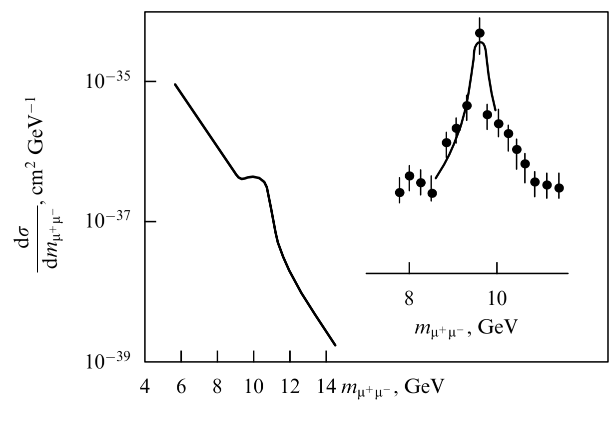

Figure 16. Results of the experiment searching for the Υ-meson.

[37] For the precise determination ($\simeq 0.1$ mm) of the coordinates of a particle traversing a drift chamber, the drift time of ionization electrons was measured in a uniform electric field from the place where they originated on the particle trajectory to one of the positively charged signal wires of the chamber.

The fifth quark was denoted by the letter b (for beauty), so by analogy with the $J/\psi = c\tilde{c}$ the structural formula for the Υ-meson is $\Upsilon = b\tilde{b}$ and, consequently, it is a particle with hidden beauty. In the scientific literature another meaning is often (even more often than the first) attributed to the letter b denoting the fifth quark — bottom. The origin of this name is related, as we shall soon learn, to the existence, besides the bottom quark, of a top t-quark which together with the b-quark forms a pair similar (in values of B and Z) to the pair of u (up)- and d (down)-quarks. The complete set of quantum numbers of the b-quark is the following: $B = 1/3$, $Z = -1/3$, $b = -1$, $c = 0$, $S = 0$, $I(J^P) = 0(1/2^+)$, and $m = 4.0-4.4$ GeV. The new quantum number *beauty* was assumed to be conserved in strong and electromagnetic interactions, so in their case the following relation, similar to formula (125), holds true:

$$Z = I_\xi + \frac{B + S + c + b}{2} = I_\xi + \frac{Y}{2}, \tag{138}$$

where the hypercharge Y now equals $B + S + c + b$.

Like charmonium that is composed of $c\tilde{c}$-particles, the system of $b\tilde{b}$-particles forms *beautium* or *bottomium*, the levels of which are occupied by particles with hidden beauty. We shall list some of them. The Υ-meson, discovered by the group of L Lederman, occupies the 1S state; it has the quantum numbers $I^G(J^{PC}) = 0^-(1^{--})$, mass 9460 MeV, width $\Gamma = 52.5$ keV and decays via the schemes

$$\Upsilon(1S) \begin{array}{l} \nearrow\ e^+ + e^-, \\ \rightarrow\ \mu^+ + \mu^-, \\ \searrow\ \tau^+ + \tau^-; \end{array}$$

the same quantum numbers are exhibited by $\Upsilon(2S)$ of mass 10023 MeV and width $\Gamma = 44$ keV that decays into $\Upsilon(1S)2\pi$, and by $\Upsilon(3S)$ of mass 10355 MeV and width 26 keV that decays into $\Upsilon(2S)X$, $\Upsilon(2S)2\gamma$, and $\Upsilon(1S)2\pi$.

Continuing the analogy with charmed particles, in parallel with the mesons with hidden beauty one might also have expected mesons and baryons with explicit (open) beauty to exist in nature. This expectation was confirmed in 1980, when the next $\Upsilon(4S)$-meson was discovered with the quantum numbers $0^-(1^{--})$, mass 10.58 GeV and a *large* total width $\Gamma = 14 \pm 5$ MeV that pointed to the possible fast (with conservation of beauty) decay of this particle into mesons with explicit beauty:

$$\Upsilon(4S) \begin{array}{l} \nearrow\ B^0 + \widetilde{B}^0, \\ \searrow\ B^+ + B^-. \end{array} \tag{139}$$

The mesons with beauty, $B^+ = u\tilde{b}$ and $B^- = b\tilde{u}$, $B^0 = b\tilde{d}$, $\tilde{B}^0 = d\tilde{b}$, form two isodoublets $B^+ - B^0$ and $B^- - \tilde{B}^0$ with $I(J^P) = 1/2(0^-)$. The $B^\pm$ (as the particle and antiparticle) have the same mass 5.2790 GeV and lifetime $\tau = 1.653 \times 10^{-12}$ s, and they decay via the charge-conjugate schemes $B^\pm \to l^\pm \nu_l X$ (where l stands for lepton, ν_l is the respective neutrino or antineutrino, and X is 'something else') and certain others. B^0- and $\widetilde{B}^0$-mesons also have identical masses and lifetimes (as the particle and antiparticle), which are close to the masses and lifetimes of their isopartners: $m = 5.2794$ GeV, $\tau = 1.548 \times 10^{-12}$ s, and they decay according to the schemes

$$B^0 \begin{array}{l} \nearrow\ l^+ + \nu_{l^+} + X, \\ \searrow\ D^- + l^+ + \nu_{l^+} \end{array}$$

and to others (the decay schemes for $\widetilde{B}^0$ are charge conjugate).

Besides the two isodoublets described, the two strange mesons with beauty, $B_s^0 = s\tilde{b}$ and $\widetilde{B}_s^0 = \tilde{s}b$, and quantum numbers $I(J^P) = 0(0^-)$ were also discovered; they possess $m = 5.3696$ GeV, $\tau = (1.493 \pm 0.062) \times 10^{-12}$ s and follow the main decay scheme

$$B_s^0 \to D_s^- + X. \tag{140}$$

In the tables of particle properties as of 2000, the first information is presented on the beauty-charmed mesons $B_c^+ = c\tilde{b}$ and $B^- = \tilde{c}b$ with $I(J^P) = 0(0^-)$, $m = 6.4 \pm 0.4$ GeV and $\tau \simeq 0.46 \times 10^{-12}$ s [49].

In 1981, the first baryon with beauty $\Lambda_b^0 = udb$ was observed in colliding beams at CERN. Its quantum numbers are $I(J^P) = 0(1/2^+)$, $m = 5.624$ GeV, $\tau = 1.229 \times 10^{-12}$ s and its main decay scheme is the following:

$$\Lambda_b^0 \to \Lambda_c^+ + l^- + \tilde{\nu}_l + X. \tag{141}$$

8.4.3. The sixth quark t (top), a true bachelor. A necessary condition for the theory of electroweak interaction to be renormalizable (see Section 9) consists in the number of leptons being equal to the number of quarks. We mentioned above that at the time, when the existence of four sorts of leptons (e, ν_e, μ, ν_μ) was demonstrated, this circumstance became one of the stimuli to search for the fourth quark. Similarly, after the discovery of the τ-lepton in 1975–1977, when the number of leptons grew to five, and together with the τ-neutrino, ν_τ (which was immediately considered compelled to exist) — up to six, there appeared an additional stimulus to search for the sixth quark t (especially that the fifth b-quark, which is a partner of the t-quark in the third generation of these particles, had already been discovered in the same year of 1977).

We speak of an additional stimulus, because there also existed other theoretical and experimental arguments, from which not only the existence of the sixth quark followed, but also many of its properties. Thus, in particular, according to relation (124), the theory predicts that (under the assumption that the three-color t-quark of charge $Z = +2/3$ actually exists) the ratio R of the production cross sections of hadrons and lepton pairs produced in the e^+e^--annihilation process should equal 5, while experiment yielded $R_{\mathrm{expt}} \simeq 4.5$ (with a positive derivative) at $E_{\mathrm{c.m.s}} = 56$ GeV. Since the values of R_{theor} at lower energies (within the range of influence of the three-, four- and five-quark model) happened to be correct (which, by the way, confirmed the existence of three colors), the result obtained pointed to the existence of a sixth quark with a mass exceeding 28 GeV.

New, even more definite, results of studies relevant to the possible existence of the t-quark and to its properties appeared in the spring of 1994, when the work of Abachi et al. [52] was published; this work, carried out by the DO collaboration in the colliding $p\tilde{p}$-beams of the tevatron at the Fermi Laboratory (Batavia, USA), imposed a lower limit of 131 GeV on the mass of the sixth quark. Finally, in the summer of the same 1994, a communication from F Abe and others of the CDF collaboration appeared [53] on the observation in the same laboratory of events that could be interpreted as the production and decay of a $t\tilde{t}$-quark pair.

From theoretical predictions of the properties of the t-quark as the 'top' [38] partner of the 'bottom' b-quark observed

[38] The t-quark is sometimes also given the name of truth.

in 1977, it followed that the t-quark (if its mass $m_t \geqslant 85$ GeV) should decay into the W-boson of mass 80.42 GeV, discovered at the end of 1982 (see Section 9.5), and the b-quark ($m_b = 4.0 - 4.4$ GeV):

$$t \to W^+ + b\,, \quad \tilde{t} \to W^- + \tilde{b}\,. \tag{142}$$

Therefore, the structure of the expected events was determined by the known decay modes of $W^{\pm}$-bosons. From calculations it followed that about 5% of the events should be two-lepton events, when both the W-bosons decay into $e\nu_e$- and $\mu\nu_\mu$-pairs, producing two leptons (including leptons of high transverse momentum $p_\perp$) with opposite charges, and the b-quarks give rise to two (or more) jets. Moreover, such two-lepton events should be characterized by a large missing transverse energy owing to the two neutrinos not being detectable. In 30% of the events, one W-boson should decay into an $e\nu_e$- or $\mu\nu_\mu$-pair, and the other one into a $q\tilde{q}$-pair (lepton – jet events). In these events one charged lepton with a large transverse momentum $p_\perp$, missing transverse energy and 4 (or more) jets from the decay $W \to \tilde{q}q$ and from two b-quarks will be observed. In the remaining 65% of the cases (not dealt with in Ref. [53] owing to the significant background) both W-bosons decay into $q\tilde{q}$-pairs which, together with the b-quarks, give 6 (or more) jets (pure-jet events).

Lepton – jet events are considered the most convenient events for obtaining a quite precise value of the t-quark mass, since there are relatively many ($\sim 30\%$) such events, and their composition includes only one neutrino, i.e. the produced $t\tilde{t}$-pair decays as follows:

$$t + \tilde{t} \to l + \nu_l + q + \tilde{q} + b + \tilde{b} + X\,, \tag{143}$$

where l stands for the lepton, ν_l is its respective neutrino, and X denotes ‘anything else’. In this scheme the momenta of all the particles, except the neutrino, can be measured (q and $\tilde{q}$ are manifested as hadron jets, while b and $\tilde{b}$ as quark – gluon jets). As to the neutrino, the transverse component of its momentum can be evaluated from the missing transverse energy of the event, and the longitudinal component by equating the mass of the W-boson to the effective mass of the $l\nu_l$-pair. The equality between the W-boson mass and the effective mass of the two hadron jets, or the equality among the effective mass of the two hadron jets and that of one b-quark jet, on the one hand, to the effective mass of the charged lepton, the neutrino and the b-quark jet, on the other hand, can serve as a test of the event identification. Applying these and certain other less obvious relations, one can estimate the mass of the t-quark for each individual event.

In work [53], the CDF (Collider Detector at Fermilab) setup constructed by the CDF collaboration in 1988 [54] was used for measuring the quantities mentioned.

The layout of the setup is shown in Fig. 17a. The setup includes the 2000-ton central detector CDS (containing a solenoidal magnet, a steel yoke, track chambers, electromagnetic shower counters, hadron calorimeters, and muon chambers) and two identical (downstream and upstream) detectors consisting of time-of-flight counters, electromagnetic shower counters, hadron calorimeters and muon toroidal spectrometers. The steel yoke has the following dimensions: height 9.4 m, width 7.6 m, and length 7.3 m. Inside the yoke a superconducting coil of diameter 3 m and length 5 m is secured for creating a magnetic field of 1.4 T. The central calorimeter consists of 48 wedgelike modules com-

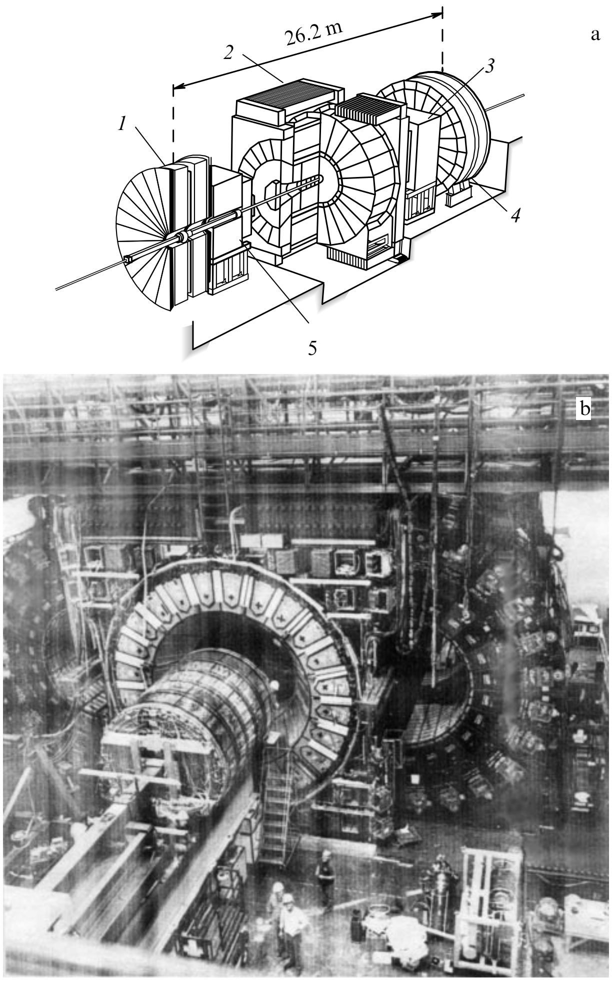

Figure 17. CDF setup with which the t-quark was discovered: (a) layout of the experimental setup; (b) photograph of the setup: *1* — front toroids fabricated from magnetized steel, *2* — central detector, *3* — tail calorimeters (electromagnetic and hadron), *4* — back toroids fabricated from magnetized steel, *5* — front calorimeters (electromagnetic and hadron).

bined into four self-sustaining arclike segments which rest on the base of the yoke. For maintenance of the modules, the segments can be pulled out (see Fig. 17b; note the figures of people shown in the photograph as a scale).

With the aid of this installation, the CDF collaboration reported (in its first work [53]) 12 events which with practically a 100% probability could be interpreted as decays of the t-quark (the probability of these events being background events was 0.26%). The analysis of individual events yielded the following value for the mass of the t-quark:

$$m_t = 174 \pm 10^{+13}_{-12}\ \text{GeV}\,, \tag{144}$$

which is very close to the present-day value given in the tables of particle properties.

The issue of the exact value of the t-quark mass is very important, because this mass is necessary for estimating the mass of the Higgs boson, which is very difficult to predict and which is considered by theoreticians to be responsible for the generation of elementary particle masses (see Sections 9.3 and 10.2). Precise knowledge of the t-quark (and of the W-boson) mass permits us to predict quite a narrow interval of possible values for the mass of the Higgs boson, which significantly facilitates the most difficult task of searching for it. Therefore, all the subsequent activities of both the collaborations (CDF and DO) were devoted to a more reliable determination of the t-quark mass and its other properties on the basis of an enhanced statistics of events. Events of all three mentioned types were analyzed in the work.

In works completed simultaneously (and even published in the same issue of the journal) in 1995 the CDF and DO collaborations obtained the following values for the mass of the t-quark: $176 \pm 8(\text{stat}) \pm 10(\text{syst})$ GeV [55] and $199^{+19}_{-21}(\text{stat}) \pm 22(\text{syst})$ GeV [56], respectively. Comparison of these results show that in spite of the significant difference between the two results they do not contradict each other within the limits of experimental errors.

Both collaborations continued measurements of the t-quark mass in succeeding years. In 1997, the CDF collaboration obtained the value $186 \pm 10(\text{stat}) \pm 12(\text{syst})$ GeV [57] for the t-quark mass from an analysis of pure-jet events, and the DO collaboration obtained $173.3\pm\ 5.6(\text{stat}) \pm 5.5(\text{syst})$ GeV [58] from an analysis of lepton – jet events. In 1998, from an analysis of lepton – jet events, the CDF collaboration obtained the value $175.9 \pm 4.8(\text{stat}) \pm 4.9(\text{syst})$ GeV [59] for the t-quark mass, and from an analysis of two-lepton events $161 \pm 17(\text{stat}) \pm 10(\text{syst})$ GeV [60]. In the same year of 1998, the DO collaboration obtained the value $168.4 \pm 12.3(\text{stat}) \pm 3.6(\text{syst})$ GeV [61] for the t-quark mass from an analysis of dilepton events. The weighted mean value derived from the results obtained by the CDF collaboration is 175.6 ± 6.8 GeV, and by the DO collaboration — 172.1 ± 7.1 GeV. The general result of both the collaborations is expressed by the value

$$m_{\mathrm{t}} = 173.8 \pm 5.2\ \text{GeV}\,, \tag{145}$$

which is practically identical to the present-day tabular value of 174.3 ± 5.1 GeV [49]. The accuracy obtained in the determination of the t-quark mass and the known accuracy of the W-boson mass (0.056 GeV) only allow one to estimate the upper limit for the mass of the Higgs boson: $m_{\mathrm{H}} \leqslant 500$ GeV, which, taking into account the result obtained at the accelerator LEP (CERN) in 1993: $m_{\mathrm{H}} \geqslant 52$ GeV [62], yields too wide a corridor of possible values for its mass. A narrower corridor can be obtained though if the accuracies in determining m_{t} and m_{W} do not exceed 1 GeV and 0.04 GeV, respectively. From other theoretical arguments, the range of values for the Higgs boson mass (m_{H}) is within the limits $m_{\mathrm{Z}^0} < m_{\mathrm{H}} < 2m_{\mathrm{Z}^0}$, where $m_{\mathrm{Z}^0} \simeq 92$ GeV (see Section 9.5).

To conclude this subsection it is necessary to note that, since $\tau \sim m^{-5}$, then owing to its very large mass the t-quark has an extremely short lifetime. Estimates made in Ref. [63] have shown that it is shorter than the nuclear time ($\tau_{\mathrm{t}} < 10^{-23}$ s), so the t-quark can form neither toponium, nor particles with explicit top-flavor. This fact strongly distinguishes it from the luckier c-quarks and b-quarks, which have two families (explicit and hidden) each of particles with charm and with beauty. The top-quark lives so little that it has no time for creating either an open or even a hidden top-family, so it spends all its short life as a *true* bachelor.

8.5 Quark–gluon plasma

In Section 8.2 we said that color quarks and gluons are confined within hadrons, since their interaction energy increases with the distance between them, so they cannot be torn away from each other. This property of hadron matter, termed confinement (of color) is still in force when the interaction energy becomes sufficient for the production of a new quark – antiquark pair, because this process ultimately results in the origination of an additional hadron which again has quarks and gluons confined inside it.

Thus, in ordinary conditions (considering the conditions realized in modern superaccelerators also to be ordinary) the confinement of color is a normal state of hadron matter. Nevertheless, for a relatively long time the possibility of the existence of hadron matter without the confinement of color has already been considered in QCD, i.e. in such a form where the quarks and gluons are free particles. Such a form of the existence of hadron matter is called quark – gluon plasma (QGP). According to modern ideas, the phase transition of hadron matter from the normal state with confinement to the QGP state with quarks and gluons freely moving inside its volume should take place at very high baryon densities and superhigh temperatures. In nature, such conditions could have arisen in the first instants ($\Delta t \simeq 10^{-5}$ s) after the Big Bang, while at present they may exist at the centers of massive neutron stars.

Theoretically, the existence of a phase transition from normal hadron matter to QGP has not been proved (and, by the way, neither has a rigorous proof for color confinement been found). However, confirmation of the existence of both the former and the latter has been obtained with the aid of the so-called lattice method [39].

Experiments in which attempts were made to create artificial QGP for a short time in laboratory conditions began in 1990, in studies of p – p-, p – $\tilde{\mathrm{p}}$-, p-nucleus, and, subsequently, nucleus – nucleus (making use of oxygen and sulphur ion beams) interactions with high transverse momenta. When these experiments were staged, the temperatures and densities to be achieved were assumed sufficient for the formation of short-lived bunches of QGP, which were to manifest themselves by the emission of direct (thermal, not decay) photons.

The energy spectrum of thermal electromagnetic radiation is known to be determined by the temperature of its source. But, regretfully, from the first theoretical estimates (performed in the lowest order of perturbation theory) it followed that the temperature dependences of the yields of direct photons from the QGP bunch and the hadron gas (developing from the QGP in a very short time) are the same, so the registration of direct photons could, apparently, not permit the experimenter to distinguish one from the other. Indeed, the first attempts led to no significant results, although from the data obtained by the experiment WA80 [65], in which S + Au collisions were studied at an energy of $200A$ GeV (A is the mass number of the beam nuclei), an estimate was made of the upper limit for the production of direct photons in hadron gas ($T = 250$ MeV).

New experimental studies of the possible formation of QGP and of its properties in laboratory conditions were

[39] The lattice method in a quantum field theory (including, for instance, QCD) consists in the analysis of the properties of various theoretical models, applying calculations in which continuous spacetime is approximated by a discrete set of points — a four-axis lattice. The choice of the lattice step depends on the conditions of the problem at issue, while the integrals of large multiplicities, arising in the case of small steps, are calculated by the Monte Carlo method on computers. A typical lattice step, applied in QCD, amounts to 10^{-14} cm, with which certain results relevant to continuous spacetime have been achieved already for ~ 10 steps (along each axis). For details see review [64].

initiated in 1994 by a large international collaboration of scientists (with participation of the RRC 'Kurchatov Institute') at CERN, where in February, 2000 a seminar was held for the discussion of the first results of an experiment, WA98, performed with the aid of photon and hadron spectrometers with large acceptances. The main task of the experiment was the separation of direct photons from the (^{208}Pb + ^{208}Pb)-interaction region at an energy of 158A GeV (about 33000 GeV) against an enormous background from the radiative decays resulting from the interaction of hadrons. The photons were registered with the aid of the LEDA photon detector designed and constructed by physicists of the Kurchatov Institute (the laboratory led by V I Man'ko) of 10080 modules on the basis of lead glass and viewed by photomultipliers.

The first results were presented in Ref. [66] from which it follows that the direct photons from central (Pb + Pb)-collisions were recorded at a level exceeding the background by 20% (Fig. 18) and their spectrum corresponded to a source temperature (QGP bunches or hadron gas) equal to $T = 250$ MeV, which is significantly higher than the temperature required for realizing the aforementioned phase transition.

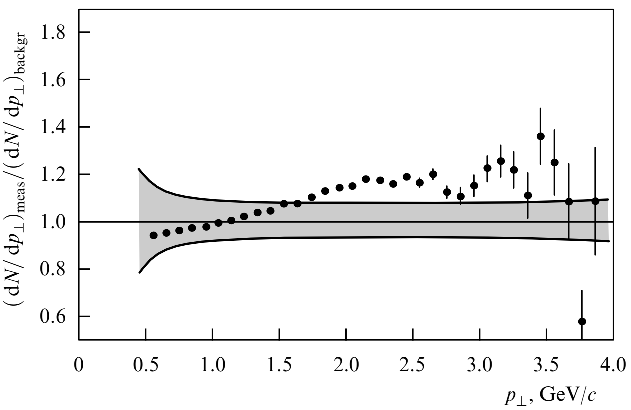

Figure 18. Concerning searches for artificial quark – gluon plasma. Ratio of the measured photon background to the calculated flux versus the transverse momentum. At large $p_\perp$, a 20% excess of direct photons over the background photons is seen.

The reason for considering the source of direct photons to be QGP bunches (and not hadron gas) lies in the recent new calculations [67] performed with due account of the two-loop diagram for the processes of q$\tilde{\rm q}$-annihilation and rescattering, which revealed that the rate of direct photon emission from quark matter is significantly higher than that obtained in previous calculations carried out in the lowest order of perturbation theory. In this connection, a revision was made in Ref. [68] of the previous prediction for the production of direct photons in heavy-ion collisions, and it was shown that at a sufficiently high initial temperature the yield of photons from the QGP may significantly exceed their yield from the hadron gas, so a way for testing observations of QGP has appeared.

The actual authors of experiment WA98 treat their results with more caution than the theoreticians. In the summary of their article [66] they only underline that for the first time a signal of direct photons from the region of ultrarelativistic heavy-ion central collisions at a transverse momentum exceeding 1.5 GeV/c has been registered, and that this result *may* be important for diagnosing the formation of QGP.

At the aforementioned seminar at CERN, the decision was taken to continue studies into the properties of an artificial QGP with the purpose of confirming them at the nuclear collider of Brookhaven (work is already under way) and at the large hadron collider under construction at CERN.

9. The idea of weak and electroweak interactions

Of the sciences describing the interaction between elementary particles, quantum electrodynamics (QED) is known to be the most precise with an accuracy of calculations related to the smallness of the fine-structure constant $\alpha_{\rm el} = e^2/\hbar c = 1/137$ and to the property of renormalizability permitting the theorist to obtain reliable results in calculating quantities in higher orders of perturbation theory. The weak interaction constant $\alpha_{\rm weak}$ is significantly smaller than $\alpha_{\rm el}$ at low energies [40], so the quantitative results are already successfully obtained by perturbation methods in the first order. However, unlike QED, the theory of weak interaction is not renormalizable, which was always deplored by the theoreticians and gave rise to a sort of internal protest. The theory of weak interaction lacked the elegance of QED.

This difficulty was brilliantly overcome in the theory of electroweak interaction, which not only retains all the achievements of the universal theory of weak interaction in the region of relatively low energies, but also permits the researcher to obtain precise results at high energies. The theory of electroweak interaction (TEWI) possesses all the properties required of an exact theory: a great power and precision of prediction, and renormalizability. Moreover, the new theory makes it possible to deal in the same manner with the two most precise interactions — electromagnetic and weak, which seemed to exhibit such drastically differing properties. This common approach resulted, in particular, in one of the most important predictions of TEWI — the prediction of the existence of neutral weak currents and of their quantum — the Z^0-boson (the $W^\pm$-bosons had been much spoken of in some way or another even before TEWI was created). In this section we shall try to present a popular exposition of the concepts underlying TEWI, first recalling the history of the development of its predecessor — the theory of universal four-fermion weak interaction. In writing this section we have freely taken advantage of the books written by L B Okun' [36, 69], to which we refer the readers wishing to familiarize themselves in greater detail with the material presented below. Besides their main contents, these books also include very useful thematic reviews of the scientific literature, and one of them [36] also contains a dictionary of terms, many of which are encountered in the present article. For a review on the unified theory of elementary particles at a more popular level we recommend the article written in 1981 by H Georgi [70], i.e. before the discovery of the Z^0- and $W^\pm$-bosons (which must be taken into account when reading it).

9.1 The Fermi theory

The first version of weak interaction theory describing the β-decay of atomic nuclei was proposed in 1934 by E Fermi [71], who constructed it by analogy with the theory of electro-

[40] $\alpha_{\rm weak}$ grows rapidly with energy (as r decreases), and at $r \simeq 10^{-16}$ cm it is already of the same order of magnitude as $\alpha_{\rm el}$ (see Section 10.2).

magnetic interaction, although he did substitute a pointlike (contact) interaction for the interaction at a distance. According to Fermi, the β-decay of a neutron, for instance, represents a contact interaction between the four fermions n, p, e^- and ν, of which two (e and ν) originate, like a photon, at the instant they are emitted by the neutron transforming into the proton [41]. In the same fashion as in electrodynamics, the Fermi theory assumed fulfilment of the parity and angular momentum conservation laws, and of the five feasible Lorentz-invariant versions of the theory (V, A, S, T, P) Fermi chose (again, by analogy with electrodynamics) the vector version (V), in which the operator employed is similar to that applied in electromagnetic interaction theory.

According to Fermi, the weak interaction between n, p, e^- and ν is described by the Hamiltonian

$$\hat{H} = \frac{G}{\sqrt{2}}\, j^+ j\,, \tag{146}$$

here G is the weak interaction constant, j is the charged (i.e. that alters the electric charge of the particle undergoing transformation) weak vector current, and j^+ is the Hermitian conjugate current. Each of them consists of two terms

$$j = \bar{e}v + \bar{n}p\,, \tag{147}$$

$$j^+ = \bar{v}e + \bar{p}n\,, \tag{148}$$

where $\bar{e}v$ and $\bar{v}e$ represent lepton currents, and $\bar{n}p$ and $\bar{p}n$ nucleon currents.

The symbols e, v, n, p in expressions (147), (148) stand for the four-component annihilation operators (bispinors) of the respective particles (or creation operators of their antiparticles), while the symbols $\bar{e}, \bar{v}, \bar{n}, \bar{p}$ denote the creation operators of the respective particles (or annihilation operators of their antiparticles). The vector version of weak interaction is realized with the aid of the Dirac γ-matrices, so that a more accurate form of the weak current contains the 4-row γ_μ-matrix ($\mu = 1,\ 2,\ 3,\ 4$):

$$j_\mu = \bar{e}\gamma_\mu v + \bar{n}\gamma_\mu p\,. \tag{149}$$

From expressions (146), (148) it is seen that the product of currents $\bar{e}v$ and $\bar{p}n$ is responsible for the β^--decay ($n \to p + e^- + \tilde{\nu}$), while the product of currents $\bar{v}e$ and $\bar{n}p$ bears the responsibility for the β^+-decay ($p \to n + e^+ + \nu$) (for reasons of brevity we omit the symbol γ_μ).

The Fermi theory has played an exceptional part in developing the physics of weak interaction. With its aid, it not only turned out to be possible to explain the main regularities of β^-- and β^+-decays (the behavior of spectra, the decay probabilities, the scale of the G constant) but also to predict new processes (e-capture, inverse β-decay, νe-scattering, weak nuclear forces) as well as to propose the experiments for confirmation of the existence of neutrinos and antineutrinos.

9.2 The (V – A) version of weak interaction theory

In spite of its outstanding services, the vector version of weak interaction theory possesses an essential disadvantage: it cannot explain the β-decay of certain nuclei, for example, the experimentally examined β-decay of the ^{6}He nucleus, which proceeds with a high probability. This difficulty of the theory was overcome by applying, besides the vector (V) version, one more of the five aforementioned versions of the theory — the so-called axial-vector version (A). It turned out that the two constants of both weak interaction versions are approximately equal to each other ($g_A \simeq 1.27 g_V$) and that one must apply both versions in the form of the difference between the vector and axial vector [the (V – A)-version of weak interaction theory]. The (V – A)-version of the theory was finally confirmed experimentally by the years 1956–1957, which actually happened to be a turning-point in the development of weak interaction physics. We recall that precisely at that time Lee and Yang arrived at the conclusion that the parity conservation law is violated in weak interactions (see Section 6.1), whereas Wu and Lederman proved this experimentally (see Section 3.4). At the same time, from these experiments followed a left-hand polarization of the order of v/c for leptons and a right-hand polarization of the order of $-v/c$ for antileptons, and from a joint analysis of their results together with the CPT-theorem (see Section 4.1) followed violation of C-invariance in weak interactions. In 1957, L D Landau [72], A Salam [73], and T D Lee and C Yang [74] [42] put forward the theory of the two-component neutrino, according to which the neutrino and antineutrino have zero masses and opposite helicities (the neutrino exhibits left-handed helicity, and the antineutrino right-handed helicity). The left-handed helicity of the neutrino was confirmed in an elegant experiment performed by Goldhaber and collaborators [75]. At the time, the existence of the electron neutrino ν_e and its distinction from the antineutrino $\tilde{\nu}_e$ had already been confirmed experimentally by Reines and Cowan (see Section 3.5), and the idea had been put forward of an experiment for demonstrating the existence and the difference between the muon neutrino and antineutrino. Finally, by that time, also, the approximate equality (noticed by Fermi back in 1948) between the interaction constants G_V, $G_{\mu p}$ and $G_{\mu\to e}$ for three seemingly totally different processes

$$n \to p + e^- + \tilde{\nu}_e\,, \quad \mu^- + p \to n + \nu_\mu\,,$$
$$\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu \tag{150}$$

was ultimately confirmed, which was interpreted as the law of conservation of weak vector current (Ya B Zel'dovich and S S Gershteĭn [76]). Somewhat later the weak decays of strange particles (for example, $\Lambda \to p + \pi^-$) were also noticed to be characterized by a constant G_S of the same order of magnitude, and the parity conservation law was also violated in such decays (see Section 6.5).

With due regard for the new weak processes and for the violation of the parity conservation law, the weak charged current, instead of the expression $\bar{e}v + \bar{n}p$, is now written as

$$\bar{e}v_e + \bar{\mu}v_\mu + \bar{n}p + \bar{\Lambda}p\,, \tag{151}$$

where the current $\bar{e}v_e$ has the form

$$\bar{e}\gamma_\mu(1+\gamma_5)v_e = \bar{e}\gamma_\mu v_e + \bar{e}\gamma_\mu\gamma_5 v_e\,, \tag{152}$$

[41] In those years the existence of various sorts of neutrinos (ν_e, ν_μ, ν_τ) was not yet known. For this reason we shall simply write ν and $\tilde{\nu}$, for the time being.

[42] All four are Nobel Prize winners in physics: Lee and Yang (1957) for the discovery of parity violation in the weak interaction (see Section 6.1); Salam (1979) for the creation of the unified theory of weak and electromagnetic interactions, and Landau (1962) for the development of the theory of superfluidity of liquid helium II in 1941 and for creating the theory of a quantum Fermi liquid in 1956.

and the others likewise. The first term $\bar{e}\gamma_{\mu}\nu_{e}$ entering into expression (152) is a polar four-vector and it determines the vector part of the weak current, which changes sign under the P-operation of spatial inversion. The second term $\bar{e}\gamma_{\mu}\gamma_{5}\nu_{e}$ — an axial four-vector — determines the axial-vector part of the weak current, which (owing to the properties of the matrix $\gamma_5 = i\gamma_1\gamma_2\gamma_3\gamma_4$) does not alter sign under spatial inversion P. Thus, the product of the weak current j and its Hermitian conjugate current j^+ gives rise to scalar and pseudoscalar terms in the Hamiltonian, which reflects the nonconservation of P-parity in weak interaction. By transforming expression (152) it can be shown that the factor $1+\gamma_5$ selects particles with left-handed polarization, i.e. the (V – A)-current is left-handed. Similarly, all antiparticles are right-handed (expression $1-\gamma_5$ selects right-handed polarization).

The theoretical and experimental achievements listed above brought several physicists (Feynman and Gell-Mann [77], Sudarshan and Marshak [78], and Sakurai [79]), practically at the same time (in 1958), to conclude formulation of the universal four-fermion theory of weak interaction, the principal points of which were the following eight items:

(1) extreme weakness (slowness) of the interaction compared with the strong and electromagnetic interactions;

(2) universality (conservation of the weak vector current: $G_V \simeq G_{\mu p} \simeq G_{\mu \to e} \simeq G_S$);

(3) pointlike (contact) interaction;

(4) (V – A)-version;

(5) violation of P- and C-invariance;

(6) left-handed polarization of all leptons, and right-handed of all antileptons;

(7) lepton number conservation;

(8) consistency of theoretical conclusions with the assumption that $m_\nu \equiv 0$.

The universal (V – A) theory of weak interaction has been tested many times in numerous experiments, which always confirmed its validity. Let us recall some of the most important results (obtained after 1957): the proof by L Lederman, M Schwartz and co-workers of the existence of and difference between the muon neutrino and antineutrino ([12, 13], Section 3.5); the discovery by Yu G Abov, P A Krupchitsky and co-workers of weak nuclear forces [80]; the consistency with theory of the experimental results for the lifetime and angular correlations obtained in studies of neutron β-decay (see, for example, review [33]).

However, as time passed and experimental data underwent correction, difficulties started to arise in the theory. The vector current, for instance, turned out to be not fully conserved, but only in part, i.e. $G_S < G_V$, and even G_V happened to be somewhat smaller than G_μ. This inconsistency was dealt with by Cabibbo [81], who showed that

$$G_V = G_\mu \cos\theta_C\,, \quad G_S = G_\mu \sin\theta_C\,, \tag{153}$$

where the angle θ_C equal to approximately 13° was subsequently termed the Cabibbo angle. From Cabibbo's theory it followed that currents such as $\bar{n}p$ and $\bar{\Lambda}p$ have to be dealt with together, i.e. in the form of the current $(\bar{n}\cos\theta_C + \bar{\Lambda}\sin\theta_C)p$ which is correlated with the purely lepton current $\bar{\mu}\nu_\mu$ or $\bar{e}\nu_e$ alone (since $G_V^2 + G_S^2 = G_\mu^2$).

The second difficulty with the (V – A)-theory is related to the problem of the existence of weak neutral currents (i.e. currents such as $\bar{e}e,\ \bar{\mu}\mu,\ \bar{n}\Lambda$ and so on, which do not alter the charge of the particle being transformed). As we said above, the foundation of the universal (V – A)-theory is the idea of a weak interaction realized with the aid of charged currents alone such as $\bar{e}\nu_e$, $\bar{\mu}\nu_\mu$ and (after the improvement of the theory proposed by Cabibbo) by the combined hadron current $(\bar{n}\cos\theta_C + \bar{\Lambda}\sin\theta_C)p$. However, the problem of the existence of neutral currents had actually been discussed even back in the years 1958 – 1962 [82 – 84], i.e. long before the triumph of TEWI in which they were convincingly predicted and some years later discovered (see Section 9.3). But during the reign of the universal (V – A)-theory neutral currents were not found. 'Passive' experiments in search of certain decay modes (for example, $\Lambda \to n + e^+ + e^-$) pointed to their absence (for details see Section 9.4), while active experiments such as the investigation of neutrino interactions with nucleons could not be carried out at the time. And, frankly speaking, the (V – A)-theory could apparently do quite well without any neutral currents. So this obstacle was not so serious for it. The gravest difficulty remained the nonrenormalizability of the theory, owing to which it was sometimes called a 'first-order theory' (meaning the possibility of applying perturbation theory). Only the unified theory of electroweak interaction that superseded the (V – A)-theory turned out to be successful in overcoming this difficulty.

9.3 Elementary notion of the theory of electroweak interaction

The unified theory of electroweak interaction (TEWI) was created in the 1960s owing to the efforts of S Glashow [85], S Weinberg [86] and A Salam [87]. According to this theory, the weak interaction is not pointlike (contact), as considered by Fermi, but like the electromagnetic interaction — an exchange interaction, the role of quanta being assumed by the intermediate vector bosons W^+, W^- and Z^0 with spins equal to unity, as in the case of the photon, but, unlike the massless photon, with very large masses amounting to 80 – 90 GeV [43]. W^+- and W^--bosons participate in transferring weak charged currents, while Z^0-bosons transfer weak neutral currents (which are predicted by this theory). The large masses of the intermediate bosons are necessary to provide for the exceptionally small weak interaction radius $R_{\text{weak}} \simeq 10^{-16}$ cm [compare with formula (2) of Section 2].

In this connection the development of TEWI immediately met with an apparently insuperable obstacle: in this theory one could not postulate the existence of heavy (*massive*) intermediate bosons to provide for small R_{weak}, since this contradicts the other principal goal — the development of a renormalizable theory. [Because, in particular, unlike the massless quantum of renormalizable QED — the photon (that, although it possesses spin $J = 1$, has only two spin projections directed along and against its momentum), the massive $W^\pm$- and Z^0-bosons with the same spin $J = 1$ also have a third projection — normal to the momentum, which impedes the renormalization procedure.]

Thus, massless exchange bosons are required for developing a renormalizable theory of weak interaction, but they cannot provide for the small radius of weak interaction. A vicious circle arises, from which it is not clear how to get free. A quite ingenious way out, nevertheless, was found, and it

[43] We note that in this case the exchange interaction implies emission of a quantum of this interaction by one of the interacting particles and its absorption by another particle (following the Yukawa scheme described in Section 2). Not to be confused with the specific quantum-mechanical exchange interaction between identical particles.

comprised two stages. In the first stage Glashow constructed a renormalizable version of the theory with massless bosons. In the second, Weinberg and Salam transformed, *without spoiling the property of renormalizability*, Glashow's massless bosons into the massive $W^{\pm}$- and Z^0-bosons, retaining the massless photon. These two stages can be described in somewhat greater detail as follows.

As the basis of his theory Glashow took advantage of gauge $SU(2) \times U(1)$-symmetry, where SU(2) is the *weak* isospin group, and U(1) is the *weak* hypercharge group (which have nothing in common with the previously considered isospin I and hypercharge Y). Since $SU(2) \times U(1)$-symmetry was considered exact — not violated in Glashow's theory — it is characterized by four *massless* gauge bosons W^+, W^-, B^0 and W^0.

The idea of spontaneous gauge symmetry violation with the aid of spinless, but massive, Higgs bosons (which we mentioned in Sections 7.4.3, 8.4.3) underlies the theory of Weinberg and Salam. As a result of interaction with the Higgs field, Glashow's massless gauge bosons acquire mass, and two of them (W^+ and W^-) become the actual weak interaction quanta responsible for the weak charged currents, while the two others (W^0 and B^0) give rise, in the form of two mutually orthogonal superpositions, to the massless photon and the massive Z^0-boson, responsible for the electromagnetic interaction and weak neutral currents, respectively:

$$\gamma: \quad B^0 \cos\theta_W + W^0 \sin\theta_W\,, \tag{154}$$

$$Z^0: \quad W^0 \cos\theta_W - B^0 \sin\theta_W\,. \tag{155}$$

Here, θ_W is the Weinberg angle, which can be determined from comparison of the theory with experiments relevant to the investigation of weak neutral currents. The masses of the $W^{\pm}$- and Z^0-bosons are expressed through this angle:

$$m_{W^{\pm}} = \frac{1}{\sin\theta_W}\left[\frac{\pi\alpha}{\sqrt{2}G}\right]^{1/2}, \tag{156}$$

$$m_{Z^0} = \frac{m_{W^{\pm}}}{\cos\theta_W}\,. \tag{157}$$

9.4 The first success and the most important predictions of TEWI: renormalizability, neutral currents, the Weinberg angle, the masses of $W^{\pm}$- and Z^0-bosons

The works of G t'Hooft [88] carried out in 1971, in which renormalizability of the new theory was demonstrated, can be considered the first significant success achieved by TEWI [44], and the second was the discovery in 1973 and investigation of weak neutral currents that made it possible to obtain the numerical value of the Weinberg angle θ_W and, consequently, to predict the numerical values of the $W^{\pm}$- and Z^0-boson masses, which was very important for organizing searches for these particles. Since the discovery of neutral currents was preceded by quite an interesting event, we shall dwell upon it in greater detail.

The point is that a serious difficulty arose from the very beginning of the studies of neutral currents on the basis of the new theory. Above, we have already said that no decay of the Λ-hyperon via the channel $\Lambda \to n + e^+ + e^-$ had been observed in nature, which is described by the weak neutral current $(\bar{n}\Lambda)(\bar{e}e)$ apparently allowed by the new theory. This can be illustratively explained if one arranges the weak current components in the form of two equivalent matrices, one of which contains the leptons e, ν_e, μ, ν_μ and the hadrons n, Λ, p considered above, while the other (which will be needed later) contains the same leptons and the respective quarks (d, s, u) corresponding to the hadrons mentioned:

$$\begin{matrix} e & \mu & (n\cos\theta_C + \Lambda\sin\theta_C) \\ \nu_e & \nu_\mu & p \end{matrix} \qquad \begin{matrix} e & \mu & (d\cos\theta_C + s\sin\theta_C) \\ \nu_e & \nu_\mu & u\,. \end{matrix} \tag{158}$$

Then, to obtain charged currents it is necessary to move along the columns of the matrix $[\bar{e}\nu_e,\ \bar{\mu}\nu_\mu,\ (\bar{n}\cos\theta_C + \bar{\Lambda}\sin\theta_C)p]$, and to obtain neutral currents — along the rows $[\bar{e}e,\ \bar{\nu}_e\nu_e,\ \bar{\mu}\mu,\ \bar{\nu}_\mu\nu_\mu,\ \bar{p}p,\ (\bar{n}\cos\theta_C + \bar{\Lambda}\sin\theta_C)\ (n\cos\theta_C + \Lambda\sin\theta_C)]$. The last current is the one leading to the neutral current component, unobserved in nature, of the type $\bar{n}\Lambda$ (as well as $\bar{\Lambda}n$, which had also not been observed).

To forbid them from appearing in the theory, Glashow et al. [91] introduced an expression $(\Lambda\cos\theta_C - n\sin\theta_C)$ orthogonal to the Cabibbo current, and put it in correspondence with the fourth c-quark (not yet discovered, but discussed among theoreticians). In the 'quark' language [the second version of matrix (158)], the proposal made by Glashow and co-workers looked like the following:

$$\begin{matrix} e & \mu & (d\cos\theta_C + s\sin\theta_C) & (s\cos\theta_C - d\sin\theta_C) \\ \nu_e & \nu_\mu & u & c\,. \end{matrix} \tag{159}$$

The total neutral current of the d-, s-quarks can now be readily seen to equal

$$(\bar{d}\cos\theta_C + \bar{s}\sin\theta_C)(d\cos\theta_C + s\sin\theta_C) + (\bar{s}\cos\theta_C - \bar{d}\sin\theta_C)(s\cos\theta_C - d\sin\theta_C) = \bar{d}d + \bar{s}s\,, \tag{160}$$

i.e. it contains neither the $\bar{d}s$, nor the $\bar{s}d$ (neither the $\bar{n}\Lambda$, nor the $\bar{\Lambda}n$) components. We note that the expressions in parentheses in matrix (159) are conventionally called 'turned' quarks and denoted by d′ and s′. In this notation, the charged current looks quite symmetric with respect to the leptons and quarks:

$$j = \bar{e}\nu_e + \bar{\mu}\nu_\mu + \bar{d}'u + \bar{s}'c\,. \tag{161}$$

The neutral currents allowed by the theory were revealed, as we have already mentioned, in 1973. The experiment was performed at CERN with the aid of a large freon bubble chamber 1.85 m in diameter and 4.8 m long with a magnetic field of 2 T, exposed to a beam of muon neutrinos [92]. Scanning of 290,000 photographs revealed 576 events caused by the charged currents $(\bar{\nu}_\mu\mu)(\bar{d}'u)$ or $(\bar{\nu}_\mu\mu)(\bar{u}d')$:

$$\nu_\mu(\tilde{\nu}_\mu) + N \to \mu^-(\mu^+) + \text{hadrons}, \tag{162}$$

and 166 by the neutral currents $(\bar{\nu}_\mu\nu_\mu)(\bar{u}u)$ or $(\bar{\nu}_\mu\nu_\mu)(\bar{d}d)$:

$$\nu_\mu(\tilde{\nu}_\mu) + N \to \nu_\mu(\tilde{\nu}_\mu) + \text{hadrons}, \tag{163}$$

i.e. their production cross sections are comparable to each other. Moreover, the scanning of 735,000 photographs revealed one event of the type $\tilde{\nu}_\mu + e^- \to \tilde{\nu}_\mu + e^-$, caused by the neutral current $(\bar{\nu}_\mu\nu_\mu)(\bar{e}e)$. Later on, some other neutral

[44] In 1999, G t'Hooft and M J G Veltman (who created the most suitable mathematical apparatus for describing the proof of the renormalizability of gauge theories) were awarded the Nobel Prize "for revealing the quantum structure of electroweak interactions in physics" [89, 90].

currents were also observed: $(\bar{e}e)(\bar{u}u)$ and $(\bar{e}e)(\bar{d}d)$, which were found by L M Barkov and M S Zolotorev in 1978 at Novosibirsk as a result of observing the rotation of the polarization plane of laser radiation passing through a vapor of atomic bismuth [93, 94].

Investigation of reactions (162), (163) made it possible to determine (from the ratio of cross sections) the numerical value of the Weinberg angle:

$$\sin^2 \theta_{\mathrm{W}} \simeq 0.25\,, \tag{164}$$

and from it to predict, with the aid of formulae (156) and (157), the numerical values of the $\mathrm{W}^{\pm}$- and Z^0-boson masses [45]:

$$m_{\mathrm{W}^{\pm}} = 78 \pm 3 \ \mathrm{GeV}, \quad m_{\mathrm{Z}^0} = 89 \pm 3 \ \mathrm{GeV}. \tag{165}$$

The confidence in this last prediction was so great that 'for this very prediction' at the end of the seventies the construction of a new accelerator, Sp$\tilde{\mathrm{p}}$S, was initiated, on which it would be possible to detect $\mathrm{W}^{\pm}$- and Z^0-bosons, although the Nobel Prize Committee decided not to wait for their discovery and in 1979 awarded S Weinberg [95], S Glashow [96] and A Salam [97] the Nobel Prize in physics for the creation of a unified theory of weak and electromagnetic interactions.

In conclusion of this subsection we shall say a few words concerning the present-day structure of charged and neutral currents. With the discovery of the c-quark in 1974 (Section 8.4.1) and, then, of the b-quark (Section 8.4.2) and τ-lepton in 1977 (Section 3.6), as well as the t-quark in 1994 (Section 8.4.3), and the τ-neutrino in 2000 (Section 3.6), the number of weak charged currents considered in the theory increased significantly and thus the total weak charged current now comprises six terms:

$$j = \bar{e}\nu_{\mathrm{e}} + \bar{\mu}\nu_{\mu} + \bar{\tau}\nu_{\tau} + \bar{d}'u + \bar{s}'c + \bar{b}'t\,. \tag{166}$$

All the components of the charged current can be clearly demonstrated moving along the columns of a new matrix, similar to the matrix (159) presented above, if the parentheses in it are replaced by the symbols d′ and s′:

$$\begin{matrix} \mathrm{e} & \mu & \tau & \mathrm{d}' & \mathrm{s}' & \mathrm{b}' \\ \nu_{\mathrm{e}} & \nu_{\mu} & \nu_{\tau} & \mathrm{u} & \mathrm{c} & \mathrm{t}\,. \end{matrix} \tag{167}$$

In this matrix, all three lower quarks are 'turned', and this time the 'rotation' is applied, instead of the to two-row Cabibbo matrix, to the three-row Kobayashi–Maskawa matrix [98], so each 'turned' quark now consists of three lower quarks, instead of two, resulting in the number of quark currents tripling: $\bar{d}u$, $\bar{d}c$, $\bar{d}t$, $\bar{s}u$, $\bar{s}c$, $\bar{s}t$ and so on, nine in all, which together with the three lepton currents $\bar{e}\nu_e$, $\bar{\mu}\nu_{\mu}$, $\bar{\tau}\nu_{\tau}$ yields twelve charged currents.

Neutral currents, the number of which is also twelve, now, taking into account the new particles, can be obtained moving along the rows of matrix (167):

$$\bar{e}e,\ \bar{\mu}\mu, \bar{\tau}\tau,\ \bar{\nu}_e\nu_e,\ \bar{\nu}_{\mu}\nu_{\mu},\ \bar{\nu}_{\tau}\nu_{\tau},\ \bar{u}u,\ \bar{d}d,\ \bar{s}s,\ \bar{c}c,\ \bar{b}b,\ \bar{t}t. \tag{168}$$

[45] We note that after the $\mathrm{W}^{\pm}$- and Z^0-bosons were discovered and precise values of their masses obtained, the same formulae (156) and (157) were applied to correcting the quantity $\sin^2\theta_{\mathrm{W}}$, for which the following value was found: $\sin^2\theta_{\mathrm{W}} = 0.23 \pm 0.01$.

Such currents transforming a particle into itself are called diagonal. Neutral currents of the type $\bar{d}s$, $\bar{d}b$, $\bar{u}c$ and similar ones (changing the quark flavor) are not predicted by the theory and have not been observed in nature (like in the case of the current $\bar{d}s$ discussed above).

9.5 The discovery of $\mathrm{W}^{\pm}$- and Z^0-bosons

The aforementioned Sp$\tilde{\mathrm{p}}$S-collider was put into operation in 1981 under the leadership of Van der Meer. The energy of the colliding beams in it was 2×270 GeV, which should have been sufficient (but without any significant excess) for the production of $\mathrm{W}^{\pm}$- and Z^0-bosons. Indeed, although the $\mathrm{W}^{\pm}$- and Z^0-bosons were sought in the reactions

$$\tilde{\mathrm{p}} + \mathrm{p} \to \mathrm{W}^{\pm} + \mathrm{X} \quad \text{and} \quad \tilde{\mathrm{p}} + \mathrm{p} \to \mathrm{Z}^0 + \mathrm{X}\,, \tag{169}$$

in which it seems particles with masses up to 270 GeV should be produced, the energy of the protons and antiprotons was actually only just sufficient for the efficient production of particles of masses of the order of 90 GeV. The point is that $\mathrm{W}^{\pm}$- and Z^0-bosons are produced via the interaction of one of the three proton constituent quarks (p = uud) with one of the antiquarks of the antiproton ($\tilde{\mathrm{p}} = \tilde{\mathrm{u}}\tilde{\mathrm{u}}\tilde{\mathrm{d}}$):

$$\mathrm{u} + \tilde{\mathrm{d}} \to \mathrm{W}^+,\ \tilde{\mathrm{u}} + \mathrm{d} \to \mathrm{W}^-,\ \mathrm{u} + \tilde{\mathrm{u}} \to \mathrm{Z}^0,\ \mathrm{d} + \tilde{\mathrm{d}} \to \mathrm{Z}^0. \tag{170}$$

By this means, of the 270 GeV the share of each quark (antiquark) of the proton (antiproton) only amounts to 45 GeV, since half of the proton and antiproton energy is concentrated in the gluons. Thus, nearly all the energy of the colliding quarks is spent on creating the $\mathrm{W}^{\pm}$- and Z^0-boson masses, as a result of which they have no large longitudinal momentum. And this is very important when searching for them in the experiment (see below).

Two special detectors UA-1 and UA-2 (abbreviated from 'Underground Area') were made for finding the $\mathrm{W}^{\pm}$- and Z^0-bosons, and below we shall describe the construction of one of them (Fig. 19). The main parts of the detector UA-1 are the magnet with the volume of the magnetic field equal to 86 m^3 and a field intensity of 0.7 T, a 5.8×2.3-m drift chamber surrounded by an electromagnetic calorimeter 27 radiation lengths thick (scintillators alternating with layers of lead) and a hadron calorimeter (iron). The general dimensions of the

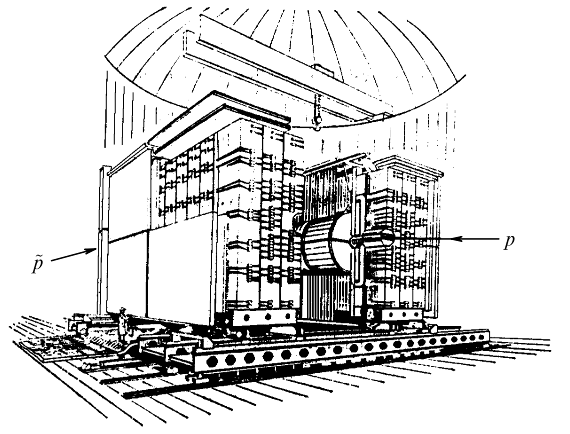

Figure 19. Experimental setup UA-1 with which the $\mathrm{W}^{\pm}$- and Z^0-bosons were discovered.

detector were $10 \times 5 \times 10$ m, and its total mass 2000 tons (the size of the detector can be judged by the person standing at the left in the lower part of Fig. 19). Maintenance of the detector was implemented using 24 computers. A total of 135 physicists from 11 institutions participated in the work led by the Italian physicist C Rubbia.

The experiment turned out to be very difficult, since the cross section for the $W^{\pm}$-boson production reaction (169) is 0.5×10^{-33} cm^2, i.e. 10^8 times smaller than the total interaction cross section of protons with antiprotons at the given energy ($\sigma^{\text{tot}}_{p\tilde{p}} \simeq 60$ mb), considered in Section 5.3. This means it was necessary to be able to identify a single useful event against 10^8 background $p\tilde{p}$ interactions.

The main idea of identifying W-bosons consisted in the selection of electrons from their decays, moving with an energy $E \simeq m_W/2$ in a direction normal to the primary beams. The background in this direction is relatively small, since it mainly contains light hadrons present in the jets moving in the direction of the primary beams, whereas the W-bosons produced, as we saw above, have no large longitudinal momentum component, so the probability of their decaying in the perpendicular direction is not small. In the ideal case, the W-bosons are produced altogether at rest and the electrons originating in the two-particle decay of the W^--boson via the scheme $W^- \to e^- + \tilde{\nu}_e$ carry away half of the rest mass of the W^--boson, which can be relatively easy to reveal in the particularly favorable case of a decay in the direction normal to the proton and antiproton beams. What 'relatively easy' means will now be seen from a detailed description of the selection procedure of the first 6 events with a W-boson, recorded at the very end of 1982 [99].

At the beginning 10^6 events were recorded, of which 1.4×10^5 contained an electron identified by the characteristic profile of the electromagnetic shower. Of these, 28,000 events were selected that had a large transverse energy $E > 15$ GeV (remember the procedure described in Section 8.4.3 for finding t-quarks that were discovered after the W-bosons, but described by us earlier). Of the latter, 2125 events were chosen that had a good single track of a charged particle with a transverse momentum $p_{\perp} > 7$ GeV$/c$. Of these only 39 satisfied the criterion for electrons, and only 6 were considered to be W-boson production events after each of the 39 were treated individually. It is interesting to note that another selection procedure in which, after the 2125 events were singled out, the further analysis was done by measuring the missing energy carried away by the neutral particles that were not detected, i.e. the neutrinos, since all the other neutral particles were registered by the setup (this method was also applied in searching for the t-quark), extracted the same 6 events. It is remarkable that already from the analysis of the first 6 selected cases of the W^--boson decay via the scheme $W^- \to e + \nu_e$ the obtained value of the W-boson mass practically coincided with the mass predicted by the theory ($m_W^{\text{expt}} = 81 \pm 5$ GeV), and when the several tens of events obtained during the second run [100] were taken into account, it was significantly corrected:

$$m_W^{\text{expt}} = 81 \pm 2 \text{ GeV}. \tag{171}$$

The Z^0-boson production cross section is 10 times smaller than the production cross section of W-bosons, however during the second run it turned out to be possible to reveal 5 cases of their production, which were identified by the decay modes

$$Z^0 \begin{array}{l} \nearrow \; e^+ + e^- , \\ \searrow \; \mu^+ + \mu^- . \end{array} \tag{172}$$

The group of physicists that worked with the detector UA-2 also registered several cases of W- and Z^0-boson production [101]. The experimental value obtained for the Z^0-boson mass in these studies was

$$m_{Z^0}^{\text{expt}} = 93 \pm 2 \text{ GeV}, \tag{173}$$

which also practically coincides with the theoretical prediction. The present-day values of the $W^{\pm}$- and Z^0-boson masses are [49]:

$$m_{W^{\pm}}^{\text{expt}} = 80.419 \pm 0.056 \text{ GeV},$$
$$m_{Z^0}^{\text{expt}} = 91.1882 \pm 0.0022 \text{ GeV}. \tag{174}$$

In approximately 70% of the cases the W-boson decays into hadrons, and in 30% into leptons (about 10% via each of the following channels: $e\nu_e$, $\mu\nu_\mu$ and $\tau\nu_\tau$); the total width of the W-boson is $\Gamma = 2.12 \pm 0.05$ GeV. The Z^0-boson has a total width $\Gamma = 2.4952 \pm 0.0026$ GeV and in 70% of the cases it decays into hadrons, and in 10% into leptons (3.3% via each of the channels: $e\nu_e$, $\mu\nu_\mu$ and $\tau\nu_\tau$). In 20% of the cases, the decay mode is not seen.

We note that the total widths of the $W^{\pm}$- and Z^0-bosons correspond to lifetimes $\tau \simeq \hbar/\Gamma$ equal, respectively, to the following:

$$\tau_{W^{\pm}} = 3.2 \times 10^{-25} \text{ s} \quad \text{and} \quad \tau_{Z^0} = 2.6 \times 10^{-25} \text{ s}. \tag{175}$$

Both the lifetimes exceed the value required for the intermediate bosons to play the part of weak interaction quanta:

$$\tau_{\text{weak}} = \tau_{\text{virt}} = \frac{\hbar}{\Delta E} = \frac{\hbar}{m_W c^2} \simeq 0.7 \times 10^{-26} \text{ s}.$$

In this time, the intermediate bosons cover a distance equal to the weak interaction radius

$$R_{\text{weak}} = c\tau_{\text{weak}} \simeq 2 \times 10^{-16} \text{ cm}. \tag{176}$$

We also note that from the comparison of total and partial decay widths of the $W^{\pm}$- and Z^0-bosons follows a restriction on the number of light ($m_\nu < 45$ GeV) sorts of neutrinos:

$$3.09 \pm 0.13, \tag{177}$$

which, thus, cannot exceed three.

In 1984, only one year after the discovery of $W^{\pm}$- and Z^0-bosons S Van der Meer and C Rubbia were awarded the Nobel Prize in physics for proposing the principle of stochastic cooling, employed in creating and putting into operation the $p\tilde{p}$-collider, and for the discovery of $W^{\pm}$- and Z^0-bosons [102, 103]. This is one more example of when the prize was awarded quickly, this time for experimental work.

10. Some results, questions, predictions and hopes

10.1 Fundamental particles and preons

We have considered the properties of several tens of elementary particles, but they are far from being all the particles hitherto discovered, since together with the unstable particles they make up several hundred. However, we have really dealt with all the 'most elementary' or, as they are sometimes called, *fundamental* particles. At present, 16 particles are considered to be fundamental — 12 fermions (6 quarks and 6 leptons) and 4 bosons (the photon, the W- and Z^0-bosons, and the gluon). We have written quite a lot about the properties of each of these particles in various sections of the review, but, so to say, separately. And now we shall try to characterize them altogether, and precisely under the 'banner' of fundamentality.

First of all, we note that in the theory of nonviolated gauge symmetry, underlying the Standard Model of strong and electroweak interactions, the masses of all fundamental particles are zero. They become nonzero as a result of spontaneous symmetry violation in the process of interaction with the Higgs field, the quanta of which are the Higgs bosons with zero spin and unknown (poorly predicted theoretically) mass. The existence of Higgs bosons is predicted in the theory of electroweak interaction, while searching for them is one of the most important tasks of elementary particle physics in the near future.

Now, let us see, what more can be said about the 'modern', i.e. massive, fundamental particles, in addition to their having acquired mass (with the exception of the photon and, maybe, the neutrino)? Let us start with the fermions, recalling that both the leptons and quarks have no internal structure up to 10^{-16} cm and that they form a symmetric system involving three generations of quarks and leptons.

Symmetry in the number and properties of leptons and quarks was long ago predicted by theoreticians, but it really became complete only in 1994–1995 after the discovery of the sixth t-quark (see Section 8.4.3). Now, the six leptons (three neutral — ν_e, ν_μ, ν_τ, and three charged — e, μ, τ with $Z = -1$) correspond to six quarks (three 'upr' ones — u, c, t with $Z = +2/3$, and three 'down' — d, s, b with $Z = -1/3$). The difference in charges between the neutral and charged leptons equals the difference in charges between the 'up' and 'down' quarks. The four first (the lightest) particles of each triplet (ν_e, e, u, d) form the first generation of fundamental fermions, the four second (ν_μ, μ, c, s) — the second generation, and the four last ones (ν_τ, τ, t, b) — the third.

Of the three listed generations, only the role of the first is quite clear. Indeed, the three particles of this generation are the main 'building bricks' used by Nature for arranging the surrounding world and ourselves. These are the u-, d-quarks composing the nucleons, of which atomic nuclei consist, and the electrons e that form the electron shells in atoms. One more particle — the electron neutrino ν_e — is also known not to play an insignificant role: it is this particle that makes our world warm and alive by providing for thermonuclear reactions to take place in the Sun.

The role of the second and third generations of fundamental fermions is less evident and, as we have already said, seemed quite incomprehensible ever since the discovery of muons. However, now this opinion has changed. At present physicists assume that the second and third generations of fundamental fermions have played a very important role in forming the early Universe, because they are precisely responsible for the violation of CP-invariance (see Section 6.7). "*And without the violation of* CP-*invariance* (as L B Okun' said quite metaphorically in his talk [5] at a seminar dedicated to the 90th anniversary of L D Landau's birthday) *the Universe could not have created the baryon asymmetry at the early stages of its evolution: there would have been equal numbers of protons and antiprotons, electrons and positrons; all of them would have turned into photons and neutrinos as a result of annihilation. And we would never exist!*"

Luckily, this did not happen, so we have the possibility of verifying that all the 12 fundamental fermions are equally needed and they are all equally important. And to be really precise, there are actually not 12, but 48! Indeed, each of the 6 leptons has its antiparticle — that already makes 12, and each of the 6 quarks and 6 antiquarks may have three different colors, which amounts to 36 more. So we have $12 + 36 = 48$.

Instead of 4 fundamental bosons, as we said at the beginning of this section, there are actually 12, because there exist 2 W-bosons (W^+ and W^-), and 8 gluons of different color charges (the color $SU(3)_c$-octet). Together with the photon and the Z^0-boson that makes 12. Like the fermions, they are all structureless and constitute quanta — the carriers of the respective interactions: the photon — of the electromagnetic interaction, the $W^\pm$-bosons — of the weak charged interaction, the Z^0-bosons — of the weak neutral interaction, and gluons — of the strong interaction.

Thus, we have $48 + 12 = 60$ fundamental particles. Not so few, actually! [46] In this connection, the issue has already been under discussion for a long time concerning the existence of a small number of subparticles or, as they are sometimes termed, preons, subquarks, etc., of which all fundamental particles may, possibly, be composed. The point is that their being structureless has only been demonstrated experimentally down to a depth of $\simeq 10^{-16}$ cm! But this is a difficult task, and not only from an experimental point of view. Its difficulties are an issue of principle: a contradiction arises with the uncertainty principle (for details see monographs [36, 69]).

10.2 Are the constants constant? The prospects of unifying interactions. The proton decay

The question posed in the title seems not to have sense. What kind of constants are they, if they are not constant? Indeed, in the usual sense of this word, in ordinary conditions they are constant. For example, it is well known that at nuclear distances ($\simeq 10^{-13}$ cm) the constant of electromagnetic interaction (the fine-structure constant) $\alpha_{el} = e^2/\hbar c = 1/137$, the constant of strong interaction $\alpha_s \simeq 1$, and of weak interaction $\alpha_{weak} \simeq 10^{-10}$. However, the relationship between these values changes drastically as the distance decreases. We already mentioned the dependence of the strong interaction constant α_s on distance in the section devoted to QCD. At very small distances (of the order of quark dimensions, 10^{-16} cm), the quarks and gluons behave like free particles (*asymptotic freedom*), i.e. α_s is so small ($\alpha_s \simeq 0.1$) that one can apply perturbation theory and obtain quantitative results (for example, in calculations relevant to hadron jets). And, vice versa, at 'large' distances ($r \simeq 10^{-13}$ cm) α_s becomes so large that it causes confinement.

The exceptional smallness of the weak interaction constant ($\alpha_{weak} \simeq 10^{-10}$) at nuclear distances ($r \simeq 10^{-13}$ cm) does not certainly demonstrate the actual weakness of this very interaction, because its radius, as we saw in Section 9.4, is determined by the very large (~ 90 GeV) masses of the $W^\pm$-

[46] To be fair, we shall mention that one of the most prominent theoreticians, S Glashow, once wrote [48] that the number of quarks and antiquarks is not obliged to triple owing to the existence of three different colors, because all three colors can be present in a quark and antiquark as if simultaneously (alternating in equal very short intervals of time). Then there would be 12 fundamental particles of each sort (leptons, quarks and gauge bosons), and so a total of 36, instead of 60. But that is still a lot!

and Z^0-bosons, namely, it is 2×10^{-16} cm. And there, at this distance, the weak interaction behaves like a 'strong' interaction with a constant of the same order of magnitude as α_{el} or α_s. But at a distance of $r \simeq 10^{-13}$ cm, its 'strength' reduces drastically and we observe it as a weak interaction.

Thus, at $r \simeq 10^{-16}$ cm all three constants are quite close to each other. Moreover, theoretical physicists consider that, when $r \ll 10^{-16}$ cm, they become 'running', i.e. as the distance decreases (the momentum transferred increases) α_{el} increases somewhat, while α_s and α_{weak} decrease. The reason for the constants to change value with the distance from the source of quanta of the respective interaction (charges) is common. It consists in the polarization of the respective physical vacuum — electron, gluon or $W^{\pm}$- and Z^0-boson. The simplest is to understand the role of polarization of the electron vacuum, which results in the electric charge of an electron giving rise to a cloud of virtual electron – positron pairs surrounding it. The positrons of these pairs that are attracted by the electron, partially neutralize its charge (*screen* it). Observed from a large distance, this electron will exhibit a reduced charge and, consequently, the constant α_{el} will seem reduced compared to the case, when no screening of the electron charge occurs, i.e. if the electron is viewed from a very small distance (from 'inside' the cloud of virtual electron – positron pairs). Theoreticians consider that at a distance of the order of 10^{-17} cm from the electron charge α_{el} increases from 1/137 up to 1/129.

Unlike screening by which polarization of the electron vacuum is accompanied, when the gluon vacuum polarization takes place (i.e. virtual gluons originate), the phenomenon of *antiscreening* should be observed. The effective color charge of the quark does not decrease with the distance, like in the case of an electron, but, on the contrary, it increases owing to the creation of gluons that have the same dominating color charge as the quark. At the same time as the charge, an increase of the distance also leads to an increase in α_s which, as the distance decreases down to $r \simeq 10^{-16}$ cm, is thus reduced, as we already said, down to approximately 1/10. Similarly, polarization of the physical vacuum in the case of weak interaction (i.e. the formation of virtual $W^{\pm}$- and Z^0-bosons) also results in antiscreening, i.e. in diminution of α_{weak} from its 'strong' value at $r = r_{weak}$ down to, as considered by theoretical physicists, 1/30 at distances $r \simeq 10^{-17}$ cm.

Thus, at very small distances $r \simeq 10^{-17}$ cm all three constants actually happen to be quite close to each other, while at fantastically small distances $r \simeq 10^{-28}$ cm (for $q \simeq 10^{14}$ GeV) they tend, as considered by theoreticians, toward one and the same value $\alpha_{GU} \simeq 1/40$, which allows one to hope for the creation in the future of a Grand Unified theory (GU) — the Grand Unification of all three interactions considered with the unique aforementioned constant α_{GU}. Such a hope is reinforced by all the mentioned interactions being of a gauge nature, i.e. satisfying the general principle of local gauge symmetry which must be related to a wider symmetry group than the octet color $SU(3)_s$-symmetry of the strong interaction (see Section 8.2) and the $SU(2)\times U(1)$-symmetry of the electroweak interaction (see Section 9.3). For example, this group may be SU(5) which includes the product $SU(3)_s\times SU(2)\times U(1)$ as a subgroup.

The existing GU models cannot be tested directly in experiments at the aforementioned absolutely unattainable energies. It is possible, however, to test the predictions of these models in the low-energy region. One such prediction is the decay of the proton. The feasibility of this process is related to the fact that both the quarks and leptons are dealt with in the model of Grand Unification on the same footing, and transitions between them are allowed, i.e. processes proceeding with violation of the baryon (B) and lepton (L) numbers (but with conservation of the difference $B - L$ between them) such as, for example, the following:

$$\mathrm{p} \to \mathrm{e}^+ + \pi^0 \quad \text{or} \quad \mathrm{p} \to \mathrm{e}^+ + \pi^+ + \pi^- . \tag{178}$$

Theoretical estimate of the proton lifetime results in the value of $\tau \simeq 10^{31} - 10^{32}$ years, which renders experimental searches for proton decay extremely complicated. Nevertheless, such experiments are under way at present in twenty or so underground (down to a water equivalent of 7.5 km) laboratories equipped with detectors with masses of several thousand tons of working material viewed by several thousand photomultipliers. Physicists hope to reveal proton decay by the Cherenkov radiation of the charged decay products. The present-day experimental estimate of the proton lifetime is $\tau_p^{expt} > 10^{32}$ years. Detailed discussions of the issues touched upon here can be found in the aforementioned books by L B Okun' [36, 69] and, also, in the popular review by H Georgi [70].

10.3 Exotic particles

In Section 8.2 devoted to QCD we saw that all known hadrons are colorless, i.e. they consist of either three quarks of different colors (baryons B = qqq) or of a quark and antiquark with complementary colors (mesons $M = q\tilde{q}$). There can be no colored hadrons, because all colored objects (quarks and gluons) are closed inside the hadrons under the safe, opaque to color, lock of confinement. Having adopted this point as an indisputable axiom, one can however assume that, besides the ordinary colorless hadrons, there may also exist colorless compositions of colored particles arranged differently from qqq and $q\tilde{q}$. Such hypothetical (not yet reliably revealed) particles are called *exotic*. We shall now touch upon their proposed properties and searches for them, following the recent review by L G Landsberg [104].

Exotic particles can be arbitrarily divided into three groups. The first group with the most evident (so to say, 'explicit') exotics (do you remember particles with explicit and hidden charm and beauty?) includes colorless five-quark baryons such as $qqqq\tilde{q}$, six-quark dibaryons qqqqqq and four-quark mesons $q\tilde{q}q\tilde{q}$. The second group of exotic particles consists of colorless compositions of quarks q and gluons g (so-called hybrids). These are baryons such as qqqg, and mesons such as $q\tilde{q}g$. Finally, the third group of exotic particles includes so-called glueballs, i.e. mesons comprising only of gluons.

It is easy to see that exotic particles with explicit exotics can differ drastically in properties (flavors and charges) from ordinary baryons and mesons. Indeed, the baryon $uuuu\tilde{d}$, for example, must have a charge $Z = +3$, while the maximum charge of ordinary baryons is $+2$ (the charge of a Δ^{++}-isobar). All ordinary baryons possess either zero or negative strangeness ($S = 0, -1, -2, -3$), while an exotic baryon of the form $uuud\tilde{s}$ must have $S = +1$. In a similar manner, exotic mesons should also exhibit quite clear distinctions. From Section 7.2 we remember that ordinary mesons possess $|Z|$ and $|S|$ that do not exceed unity, while an exotic meson such as $uu\tilde{s}\tilde{s}$ should exhibit $Z = S = +2$.

Such a striking difference between exotic and ordinary hadrons gave promise that they would soon be found.

However, as far as we know, they have not yet been revealed by the indications mentioned. Another sign of a hadron being exotic may be an anomalous combination of quantum numbers J^{PC}, such as 0^{+-}, 0^{--}, 1^{-+}, whereas ordinary mesons, as we recall, have $J^{PC} = 0^{-+}$ (the π^0-meson), $0^{++}(f_0(980)$, 1^{--} (ρ- and ω-mesons). However, it would be very difficult to seek exotic particles by this indication, and there still exists no reliable information concerning their observation (although data on several meson candidates with $J^{PC} = 1^{-+}$ have been published).

Besides particles with 'explicit exotics', there may exist particles with 'hidden exotics', which are termed cryptoexotic. These particles have the same quantum numbers as ordinary hadrons, but differ from the latter in their dynamic properties (peculiarities of their production mechanism, anomalously narrow decay width, unusual probability branching ratios for different reaction channels). During the past decade several unusual states have been discovered, which may aspire to be candidates for cryptoexotic hadrons. We shall now present some of them.

The most convincing data concerning the possible existence of an exotic five-quark baryon with hidden strangeness of the type $qqqs\bar{s}$ (where q stands for either u or d) were obtained in 1994–1996 with the aid of an experimental setup SPHINX exposed to a proton beam with $E_p = 70$ GeV of the IHEP accelerator at Protvino [105–110]. The SPHINX setup is a wide-aperture magnetic spectrometer with a large set of scintillation, track and Cherenkov counters permitting the complete information on the events studied to be obtained and their kinematics to be reconstructed. Of the many reactions studied with this setup, the most interesting was the diffractive reaction [47]

$$p + N \to [\Sigma^0 K^+] + N \qquad (179)$$

(with the subsequent decays $\Sigma^0 \to \Lambda + \gamma$ and $\Lambda \to p + \pi^-$). The investigation was carried out in three stages. In the first stage, events were selected with Λ-decays, K^+-mesons and single photons; in the second, the method of effective Λγ-mass was applied to single out events involving Σ^0-hyperon production (Fig. 20a), and in the third stage (Fig. 20b) events relevant to reaction (179) were selected by the method of effective $\Sigma^0 K^+$-mass. In Fig. 20b one can see a clear maximum in the $\Sigma^0 K^+$-system at $M = 1986 \pm 6$ MeV with $\Gamma = 98 \pm 21$ MeV, marked by the authors as a new baryon X(2000). In later works [111, 112], the X(2000) baryon was observed in the reaction

$$p + C \to [\Sigma^+ K^0] + C \qquad (180)$$

(by the decay into $\Sigma^+ K^0$), and, also, in the reaction of a totally different type:

$$\Sigma^- + N \to [\Sigma^- K^+] + N\,, \qquad (181)$$

studied at the hyperon beam [48] of the tevatron of the Fermi Laboratory with the aid of the experimental setup SELEX [111] (Fig. 20c).

[47] In the most general sense, the term diffractive reaction (or reaction of diffractive dissociation) signifies the process of inelastic collision between hadrons (or between hadrons and nuclei) resulting in excitation of one of the hadrons without any change of the internal state of the other.

[48] See footnote 11 in p. 0000.

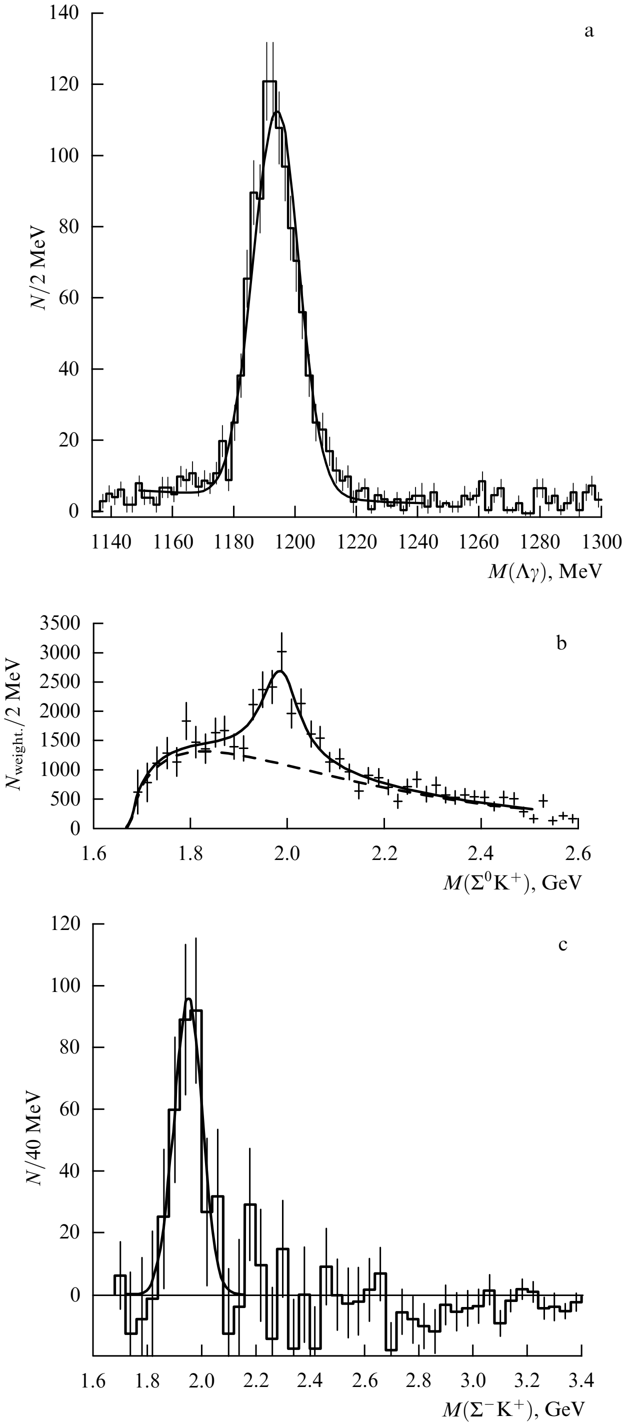

Figure 20. Results of searches for exotic particles: (a) identification by the method of effective Λγ-mass of the events with production of the Σ^0-hyperon in the reaction $p + N \to [\Sigma^0 K^+] + N$, studied with the experimental setup SPHINX; (b) identification by the method of effective $\Sigma^0 K^+$-mass of the events relevant to production of the exotic baryon X(2000); (c) identification by the method of effective $\Sigma^- K^+$-mass of the events relevant to the production of X(2000) in the reaction $\Sigma^- + N \to [\Sigma^- K^+] + N$, studied with the setup SELEX.

As to the searches for exotic meson states, here several candidates of various sorts were also found (multiquark mesons, hybrids, glueballs). One of the possible hybrid states, called π(1800) by the authors, was studied at the IHEP π-meson beam with $p = 37$ GeV/c using the VES setup (Russian abbreviation for vertex spectrometer) [113–

116], with which diffractive dissociation reactions of π-mesons on nucleons or beryllium nuclei were investigated. This setup permitted the researchers to complete kinematical reconstruction of the events studied and to perform partial wave analysis (i.e. by studying angular distributions of particles to identify production processes of meson systems in states with certain J, P and C). The studies revealed that the meson state found has $M = 1800$ MeV, $\Gamma = 200$ MeV and $J^{PC} = 0^{-+}$, so that two interpretations are possible: either it represents a second radial excitation of the π-meson (the first with $M = 1300$ MeV was observed in 1981 – 1982 [117]) or it is a hybrid of the form $q\tilde{q}g$. On the basis of the decay properties the authors consider the second version to be more probable.

In the work with the VES setup, other meson states, besides the hybrid π(1800), were revealed with exotic sets of quantum numbers $J^{PC} = 1^{-+}$ that cannot be exhibited by ordinary mesons of the type $q\tilde{q}$. However, the data obtained cannot yet be considered conclusive.

In the review [104], a discussion is also presented concerning the problem of the existence of hadrons with heavy (c or b) quarks, for example, of a $cs(\tilde{u}\tilde{d})$-meson with the quantum numbers $c = 1$, $S = -1$, $I = 0$, $Z = 0$ (which differ from the quantum numbers of the strange charmed mesons $D_s^{\pm}$ with $S = +1$, $Z = \pm 1$, considered in Section 8.4.1) or of a five-quark strange-anticharmed baryon $\tilde{c}$sudd with $c = -1$, $S = -1$, $I = 1/2$ and $Z = -1$ (differing from the strange charmed Ξ^{+}-baryon with $c = 1$, $S = -1$, $I = 1/2$ and $Z = +1$, mentioned in Section 8.4.1). Searches for such particles are under way at the tevatron of the Fermi National Accelerator Laboratory.

11. Conclusions

We gave our article the title "Old and new exotic phenomena in the world of elementary particles", intending 'old exotics' to represent those numerous puzzles that accompanied the discovery and investigation of the properties of practically all particles, starting from the muon and ending up with the t-quark and τ-neutrino [49]. We did our best to show how, with the passage of time, owing to the joint efforts of theoreticians and experimenters, these 'old exotics' gradually turned into the orderly picture called the Standard Model of strong and electroweak interactions. The success achieved in this process is indeed enormous, but the picture created still has some blank spots, and 'painting' them will certainly give rise to the results that are sure to be no less exotic than the 'old exotics' described above. We also touched upon the hitherto unresolved future 'new exotics', but slightly and by hints. Now we shall try to formulate in a more concrete manner what puzzles of Nature still remain unresolved in elementary particle physics. But, before we list them we note that, while we were writing this article, some of them were to pass from the category of future tasks to the category of modern achievements. Thus, to-day the list of unresolved (or only partly resolved) problems, in our opinion, is the following:

(1) In the preceding section we spoke about the first achievements in searches for new particles with unusual exotic properties, which are termed *exotic* precisely for this reason. If their existence is ultimately confirmed, then it will serve as the first example of the 'new exotics'.

(2) Several exotic discoveries can be expected in neutrino physics, which we spoke about in Section 3. Naturally, the main unresolved issue, here, concerns the neutrino mass: is it zero or not? There is no answer to this question yet, although quite recently Japanese physicists obtained the first reassuring results in the experiment K-2-K (KEK – Kamioka), which apparently confirm the existence of neutrino oscillations such as $\nu_\mu \leftrightarrow \nu_\tau$, observed previously within the range of $\Delta m^2 = (2 - 5) \times 10^{-3}$ eV^2 and $\sin^2 2\theta > 0.83$ in studies of atmospheric neutrinos [50].

A significantly lower number of neutrino interactions was found in the experiment than expected from the calculations (3 and 12, respectively), which is interpreted by the authors as the existence of neutrino oscillations (i.e. $m_\nu \neq 0$). However, in the opinion of the authors of the present review, a more convincing demonstration of the existence of oscillations would be, instead of a certain fraction of the beam neutrinos disappearing (which could have another cause), the *origination* of neutrinos of another sort.

The second important issue of neutrino physics is the nature of the deficit of solar neutrinos. Up to this point it is unaccountable why the experimentally examined flux of solar neutrinos ν_e is smaller than the value predicted in the solar model by a factor of 3 [51]. We intended to present experimental confirmation of the τ-neutrino's existence as the third issue, but already after the Conclusions had been written, we learned that this most complicated experiment has recently been completed, so the article had to be supplemented (see Section 3.6). By the way, the aforementioned experiment based on the 'appearance of the ν_τ' may now become realistic, but then a pure ν_μ-beam is required without any contamination of ν_τ (in the above-mentioned K-2-K experiment, the ν_μ-beam contained an admixture of ν_τ).

(3) In Section 10.2 we spoke of the prospects for unifying the three main interactions, in connection with which the possibility arises of the proton (or neutron) decaying with violation of the baryon number ($\Delta B = 1$). This hypothetical process is being sought in many underground laboratories of the world, and in the case of success it will be a great exotic discovery (the most recent estimate gives $\tau_p^{\text{expt}} > 1.6 \times 10^{33}$ years [119]).

(4) In Sections 8.4.3, 9.3 and 10.1 we mentioned the exceptional importance of discovering the Higgs bosons,

[49] Numerous mysteries, naturally, also accompanied the discovery of 'very old' particles: the electron, the photon, the proton, the positron and, especially, the neutron. But at the beginning of the article we agreed to consider the properties of these particles to be known. Anyhow, in the section on antinucleons, something had to be said about the history that preceded the discovery of the positron.

[50] Determination of the parameters Δm^2 and $\sin^2\theta$ from experimental results, as well as the general state of affairs concerning the issue of searches for neutrino oscillations, is presented in reviews [17, 122].

[51] When the work on our article was near completion, we learned of the communication made on 18.06.01 by the SNO collaboration (Canada) concerning the preliminary results of a measurement of the solar neutrino flux, which took advantage of the reaction $\nu_e + d \rightarrow p + p + e^-$ sensitive only to ν_e, and of the elastic scattering process $\nu_x + e^- \rightarrow \nu_x + e^-$ (where $x = e, \mu, \tau$) that can also be due to ν_μ and ν_τ, truly, with a lower probability. Measurements were performed with the aid of a large (1000 tonnes of ultrapure heavy water, D_2O) Cherenkov detector situated deep underground (6010 m of water equivalent) [118]. The solar neutrino flux calculated from the results of elastic scattering measurements turned out to be greater than the flux derived from the reaction. This, evidently, points to both ν_μ and ν_τ, also being present in the neutrino flux, besides ν_e. Thus, the solar-neutrino problem of the deficit of solar neutrinos, which physicists have been trying to resolve for several decades, may probably be explained by the existence of neutrino oscillations leading to the ν_e created inside the Sun being partially transformed into ν_μ and ν_τ.

with the aid of which massless fundamental fermions and gauge vector bosons acquire mass in the process of spontaneous gauge symmetry violation. The discovery of the Higgs boson (or bosons), predicted in the theory of electroweak interaction, would add still another important stroke to the picture of the Standard Model. But this is a difficult task, since the corridor of predicted mass values for the Higgs boson is still very wide [52].

(5) Another quite evident exotic problem consists in searching for preons, i.e. hypothetical particles of which all fundamental particles may consist.

(6) In Section 6.7 we wrote about the violation of CP-invariance in neutral K-meson decays, in connection with which the neutron should have an electric dipole moment. Its discovery would be extremely important for confirming the validity of one or another theoretical prediction concerning the magnitude of this quantity, for which the range of values is quite wide (see, for example, Ref. [33]).

(7) One of the most important tasks for the near future is the creation in laboratory conditions of the exotic phase of a hadron matter — the quark–gluon plasma, which was the form of existence of our world during the first microseconds after the Big Bang. In Section 8.5 we had to write about certain achievements along this direction as about a partially resolved problem of the future.

(8) Naturally, there will much work to do in 'cleaning up' what has already been done, for example, in searching for radially excited meson and baryon states, in correcting the parameters of the neutron β-decay that are important for the development of weak interaction theory, in correcting the mass values of the t-quark and the W-boson, and in obtaining other not too exotic, but very useful, results.

(9) Theoretical physicists ponder on the existence of a supersymmetry (SUSY) that unites bosons and fermions into sypersymmetric pairs of particles differing in spins. According to this theory there should exist, at the same time as the known photon ($J = 1$), a hypothetical photino ($J = 1/2$), and the above-discussed quarks ($J = 1/2$) should have corresponding squarks ($J = 0$), the Higgs boson ($J = 0$) — a higgsino ($J = 1/2$), and so on. Theoreticians not only ponder on the existence of such superexotic particles, but also dream that they will be discovered some day on accelerators.

(10) At the same time as supersymmetric generalization of the Standard Model, the possibility of the origination of new particle physics beyond the Standard Model is at present widely discussed (see, for example, the review by V A Rubakov [120]). The foundation for such expectations is the possible (but not fully demonstrated, yet) existence of neutrino oscillations, i.e. $m_\nu \neq 0$ (in the Standard Model $m_\nu \equiv 0$), and the serious difficulties encountered in cosmology, which within the framework of the Standard Model cannot resolve, for instance, the issue of the nature of non-baryon dark matter. The appearance of a new particle physics and the essential renovation of cosmology, closely related to it, can be expected in the not too distant future.

(11) So as not to be accused of exceeding our competence level, we cannot permit ourselves to deal with other plans of theoreticians (the authors of this article are experimenters) and, instead of this, we once again (how many times!) refer the reader to the short but very informative talk of L B Okun' [5], and to the recent, even broader, review of V L Ginzburg [121], in which problems of the entire physics and astrophysics of the 21th century are considered.

Upon having read these two reviews, the reader will not only get to know significantly more about what we dealt with, to a greater or lesser extent, in our article (for example, about the violation of CP-invariance, the Higgs boson, proton decay, the parameters and problems of modern and future accelerators, etc.), but will also learn many things that we did not even attempt to speak about. Such, for instance, are the theory of superstrings, the fundamental length, the properties of the graviton and the magnetic monopole, nonlinear phenomena in vacuum and in superstrong magnetic fields, the unified self-consistent and omnicomprehensive M-theory and other most interesting problems, of which, recalling all the remarkable things already invented by theoreticians, we can only say, to quote Socrates: "What I have understood is magnificent, so I conclude that everything else, which I did not understand, is also magnificent".

In conclusion we express our sincere gratitude to Yu G Abov, who made a number of valuable comments, V N Maĭorov and O O Patarakin for the discussion of some sections of the article, and, also, to O K Alekseeva and A F Sustavov for help in our work.

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[52] According to unconfirmed rumors, the Higgs boson has already been observed at LEP of CERN. Its mass is 115 GeV. The statistical uncertainty of its observation is 3σ. For confirmation of this result the work was to be continued, but LEP has been closed down.

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