Physics – Uspekhi **42** (12) 1193 – 1203 (1999)

TO THE 275th ANNIVERSARY OF THE RUSSIAN ACADEMY OF SCIENCES PACS numbers: 11.15.Kc, 11.30.Fs, **12.15.–y**, 95.30.Cq

Elementary particle physics and cosmology: current status and prospects [1]

V A Rubakov

Contents

Abstract. The current status of elementary particle physics can be briefly summarized as follows: the Standard Model of elementary particles is perfectly (at the level of radiation effects!) adequate in describing all the available experimental data except for the recent indications of neutrino oscillations. At the same time, much (and possibly most) of today's cosmology is not encompassed by the Standard Model — a fact which, together with intrinsic theoretical difficulties and the neutrino oscillation challenge, strongly indicates that the Standard Model is incomplete. It is expected that in the current decade a 'new physics', i.e. particles and interactions beyond the Standard Model, will emerge. Major advances in cosmology, both in terms of qualitatively improved observations and theoretical analysis of the structure and evolution of the Universe, are expected as well.

1. The Standard Model

The Standard Model (see, for example, Ref. [1]) is based on the following ideas.

1. Interactions between particles are written out on the basis of the gauge principle and represent non-Abelian generalizations of quantum electrodynamics. The strong interactions correspond to the $SU(3)_c$ color gauge group, while eight [for the number of $SU(3)_c$ generators] massless vector particles — gluons G^a — serve as their carriers. Weak and electromagnetic interactions are described by gauge theory with the $SU(2) \times U(1)$ group. The corresponding vector particles are the massless photon γ, the massive charged vector bosons W^+ and W^-, and the neutral vector boson Z^0. Thus, the $SU(3)_c \times SU(2) \times U(1)$ group serves as the gauge group of the Standard Model.

2. Besides vector particles possessing spin 1, there exist in nature particles with spin $1/2$ — fermions. These are quarks (particles possessing color) and leptons. The interactions of fermions and of vector bosons between themselves are fully determined by their quantum numbers with respect to the gauge group $SU(3)_c \times SU(2) \times U(1)$.

3. Interactions related to the $SU(3)_c$ group are strong at large distances (of the order of or exceeding 10^{-13} cm). This provides for the absence in nature of free colored particles — quarks and gluons (confinement of color). Instead of these particles, their colorless bound states — hadrons — are observed. At distances significantly smaller than 10^{-13} cm, the strength of color interactions decreases ('asymptotic freedom'), and they can be studied by the methods of perturbation theory.

4. The $SU(2) \times U(1)$ gauge symmetry of electroweak interactions is spontaneously broken down to the $U(1)_{em}$ gauge symmetry of electromagnetic interactions. Precisely for this reason the vector bosons $W^{\pm}$ and Z^0 possess masses, while weak interactions are short-ranged with a scale of the order of 10^{-15} cm.

5. Like the masses of the W- and Z-bosons, the quark and lepton masses stem from $SU(2) \times U(1)$ gauge symmetry breaking down to $U(1)_{em}$. This symmetry breaking results in the mixing of quarks, which is responsible, for instance, for the weak decays of strange particles, for oscillations of K- and B-mesons, etc.

Most of the ideas underlying the Standard Model have already been reliably confirmed by experiment. The last of the

[1] This review is based on a talk presented at the joint Anniversary scientific session of the Division of General Physics and Astronomy together with the Division of Nuclear Physics of RAS held on 1 June 1999 at the P N Lebedev Physics Institute, RAS.

V A Rubakov Institute for Nuclear Research,
Russian Academy of Sciences,
prosp. 60-letiya Oktyabrya 7a, 117312 Moscow, Russian Federation
Tel. (7-095) 135 77 60
E-mail: rubakov@ms2.inr.ac.ru

Received 5 August 1999
Uspekhi Fizicheskikh Nauk **169** (12) 1299 – 1309 (1999)
Translated by G Pontecorvo; edited by A Radzig

aforementioned particles, the t-quark, was discovered only recently [2] in experiments at the proton – antiproton collider Tevatron (Fermilab, USA) with energy 1.8 TeV in the center-of-mass frame. The theory of strong interactions of quarks and gluons — quantum chromodynamics — has undergone direct experimental tests in numerous experiments at high-energy accelerators.

It must, however, be noted that in quantum chromodynamics there still remain a number of unsolved dynamical problems, among which the problem of color confinement clearly stands out. In this field, an important role is to be assumed by the discovery and investigation of exotic hadrons: while ordinary hadrons can be considered as bound states $\bar{q}q$ of a quark and antiquark (the mesons — π^0, $\pi^{\pm}$, ρ^0, $\rho^{\pm}$, K^0, $K^{\pm}$, etc.) or of three quarks qqq (the baryons — the proton, the neutron, Δ, Λ, etc.), exotic hadrons are bound states of gluons GG (glueballs), of gluons and quarks $\bar{q}qG$ (hybrids) or of four quarks $\bar{q}\bar{q}qq$ (four-quark mesons). The search for and investigation of exotic hadrons is actively being pursued in experiments at the U-70 accelerator in Protvino, the SPS accelerator of CERN (Geneva, Switzerland), and some others.

Of other interesting problems in quantum chromodynamics we shall point out the problem of describing interactions at high energies and relatively small momentum transfer (here an important role is played by experiments at the electron – proton collider HERA of the DESY laboratory in Hamburg, Germany), and the problem of quark – gluon plasma production (the construction of a heavy ion collider RHIC is under way at Brookhaven, USA, precisely for the investigation of this problem).

The theory of weak and electromagnetic interactions has also been tested experimentally with high accuracy. Precise measurements of the parameters of the Z-boson have been performed at the electron – positron collider LEP-I (CERN) with an energy of about 90 GeV in the center-of-mass frame. To characterize the accuracy of these data we present, as an example, the values of the Z-boson mass [3], its total width (a quantity equal to the inverse lifetime), and the branching ratio for the decay of the Z-boson into e^+e^--pair:

$$m_Z = 91.187 \pm 0.007 \text{ GeV},$$

$$\Gamma_{Z,\text{tot}} = 2.490 \pm 0.007 \text{ GeV},$$

$$\frac{\Gamma_{Z,e^+e^-}}{\Gamma_{Z,\text{tot}}} = 3.366 \pm 0.008\,\%\,.$$

One can see that the precisions at issue are of the order of tenths of a percent!

In the case of such an accuracy an essential part is played by radiative corrections due to weak interactions (similar to the Lamb shift, or to the anomalous magnetic moment of the electron in quantum electrodynamics). Analysis of these radiative corrections [4, 5] not only makes it possible to test the Standard Model, but also to predict the masses of yet unobserved particles. Thus, before the t-quark was actually discovered experimentally, a prediction was made concerning its mass: $m_t = 170 \pm 20$ GeV, and a subsequent direct measurement yielded the value $m_t = 174 \pm 5$ GeV.

Intense studies of the properties of the W-bosons are under way at the Tevatron and at the electron – positron collider LEP-II (CERN) with an energy in the center-of-mass frame amounting to 196 GeV (June 1999). Today their mass is well known [5]: $m_W = 80.39 \pm 0.04$ GeV.

During the past one and a half years measurements were performed of the interaction parameters of the W-bosons with the photon and with the Z-boson. The point is that the theory with the $SU(2) \times U(1)$ gauge group predicts quite definite 'nonminimal' electromagnetic interactions of the W-bosons, i.e. the values of their magnetic moment, electric quadrupole moment, etc. This is also true for interactions between W- and Z-bosons. The measurements performed up to now exhibit an accuracy of about 10% and are completely consistent with the Standard Model [6]. Thus, the non-Abelian nature of interactions within the Standard Model has received experimental confirmation.

2. Spontaneous symmetry breaking

If the $SU(2) \times U(1)$ gauge symmetry was realized in the same manner as in electrodynamics, i.e. was not spontaneously broken, then the W- and Z-bosons, like the photon, would be massless. Moreover, quarks and leptons would also have no mass. The latter circumstance is due to the left-handed and right-handed components of quarks and leptons transforming differently under the SU(2) group; in other words, they have different weak isospins.

The left-handed components have weak isospin 1/2 and transform as doublets under SU(2):

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \text{(quarks)}\,;$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad \text{(leptons)}\,.$$

The right-handed components $u_R, d_R, \ldots, e_R, \ldots$ are $SU(2)_L$ singlets; they have zero weak isospin. The explicit mass terms $m\overline{(e_R)}e_L$ in the fermion Lagrangian (and likewise for quarks) are forbidden by the weak isospin, therefore the quark and lepton masses can only result from spontaneous electroweak symmetry breaking.

The mechanism of spontaneous symmetry breaking is, apparently, the most vital issue for particle physics. Spontaneous symmetry breaking requires the formation of a condensate possessing nontrivial quantum numbers with respect to the SU(2) group. The situation here is quite similar to the one in superconductivity theory where a charged [i.e. possessing nontrivial quantum numbers with respect to the $U(1)_{em}$ group of electromagnetism] condensate spontaneously breaks $U(1)_{em}$ gauge symmetry, and electromagnetic interactions become short-ranged (the Meissner effect). In electroweak theory it is weak interactions that become short-ranged, which corresponds to the W- and Z-bosons having mass.

A priori there exist two possibilities: either an elementary scalar field (this field has to be scalar, because the vacuum condensate must not violate Lorentz invariance) undergoes condensation, or the composite field. The first possibility — the Higgs mechanism — is similar to the Ginzburg – Landau theory of superconductivity, should the Ginzburg – Landau field be elementary. The second possibility is similar to the condensation of Cooper pairs; it is realized in models such as the technicolor model [7] and seems to require new strong interactions at distances of the order of $10^{-16} - 10^{-17}$ cm. Today, the Higgs mechanism appears preferable, since it makes possible an economical explanation of the existence of quark and lepton masses. On the contrary, realistic models involving the composite condensate are very cumbersome and, moreover, many of them have been discarded by precision measurements at the electron–positron collider LEP.

In the theory leaning upon the Higgs mechanism and a single elementary scalar field φ [a doublet with respect to SU(2)], the vacuum condensate is uniquely related to the Fermi weak interaction constant [which, in turn, is expressed via the W-boson mass and the gauge constant of the SU(2) group] and equals $\langle\varphi\rangle = 246$ GeV. A characteristic prediction is the existence of an electrically neutral scalar particle — the Higgs boson H, while the prediction of its mass regretfully fails.

The quark and lepton masses are obtained as follows. With due account of the Higgs field φ possessing weak isospin 1/2, symmetries allow interactions of the Yukawa type, such as

$$h_{\rm e}\overline{({\rm e_R})}{\rm L_e}\varphi^+ + {\rm H.c.}, \qquad (1)$$

where

$${\rm L_e} = \begin{pmatrix} \nu_{\rm e} \\ {\rm e} \end{pmatrix}_{\rm L}$$

is the left-handed lepton doublet, $h_{\rm e}$ is a dimensionless coupling constant. In the vacuum of electroweak theory $\langle\varphi^+\rangle \neq 0$ and expression (1) passes into the electron mass term with $m_{\rm e} = h_{\rm e}\langle\varphi^+\rangle$. The masses of other leptons and quarks arise in a similar way; the same mechanism gives rise to the mixing of quarks.

The price paid for such a simple explanation of the origin of fermion masses consists in the introduction of a large number of dimensionless parameters into the theory. Indeed, all the six quark masses and the three charged lepton masses (to be more precise, the respective Yukawa constants $h_{\rm f} = m_{\rm f}/\langle\varphi\rangle$) are unexplained parameters; the four mixing parameters in the quark sector are also free.

Moreover, the values of Yukawa constants differ very significantly: while the Yukawa constant of the t-quark, $h_{\rm t} = m_{\rm t}/\langle\varphi\rangle$, is close to unity, in the case of electron one finds

$$h_{\rm e} = \frac{m_{\rm e}}{\langle\varphi\rangle} \approx 2\times10^{-6}\,.$$

The hierarchy of fermion masses (i.e. of Yukawa constants) is one of the puzzles of the Standard Model, which has hitherto not been resolved satisfactorily. The same holds true for the hierarchy of mixing angles in the quark sector.

Experimental examination of the Higgs boson H would serve as a direct confirmation of the Higgs mechanism of electroweak symmetry breaking. This particle can be produced in electron–positron collisions via interactions with the Z-boson (Fig. 1) and in a similar manner in proton–proton and proton–antiproton collisions. The Higgs boson has not yet been found experimentally; a limitation has only been imposed on its mass, which follows from experiments at LEP-II [5]:

$$m_{\rm H} > 95\ {\rm GeV}\,.$$

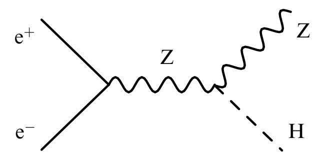

Figure 1. Production of a Higgs boson H in e^+e^--collisions.

Analysis of contributions of the Higgs boson to the radiative corrections to quantities measured with high precision at the LEP collider and the electron–positron collider SLC (SLAC laboratory in Stanford, USA) serves as an indirect method for determining its mass. This analysis yields [5]

$$m_{\rm H} = 66^{+74}_{-39} \pm 10\ {\rm GeV}\,,$$

i.e. $m_{\rm H} < 220$ GeV at a 95% confidence level.

Hopes for observation of the Higgs boson are based on an increase of the energy of the electron–positron collider LEP-II up to 205 GeV in the center-of-mass frame, and on enhancement of the luminosity of the proton–antiproton collider Tevatron. And if the Higgs boson is not be observed at these machines, it will be found (if it actually exists) at the proton–proton collider LHC with a cms energy of 14 GeV that will be in operation at CERN by the second half of this decade.

Thus, discovery of the Higgs boson is the immediate task of current and intended experiments in high-energy physics. Disclosure of this last missing link of the Standard Model will by no means signify the end of fundamental physics, since a number of convincing arguments point to the Standard Model being incomplete. Observation of the Higgs boson will just be the beginning of the 'new physics'! (Spontaneous symmetry breaking not being due to the Higgs mechanism, but to some other mechanism probably absolutely unknown to theorists, can also not be fully excluded.)

3. Neutrino oscillations

The results of observations pointing to the existence of neutrino oscillations (see, for example, the review [8]) serve as one of a few experimental indications of the incompleteness of the Standard Model. Among these results, most notable are measurements of the flux of solar neutrinos in various parts of the spectrum, as well as the measurement of the properties of neutrinos produced in the Earth's atmosphere by cosmic rays.

3.1 Solar neutrinos

The absolute flux and spectrum of neutrinos produced in central regions of the Sun are reliably calculated within the framework of the standard solar model (SSM) [9, 10]. At present, measurements of the solar neutrino flux are performed with the aid of four underground detectors sensitive to neutrinos of different energies.

The gallium experiments SAGE (Baksan Neutrino Observatory of the Institute for Nuclear Research, Russian Academy of Sciences) and GALLEX (Gran Sasso Laboratory, Italy) make use of the reaction

$$\nu_{\rm e} + {}^{71}{\rm Ga} \to {\rm e}^- + {}^{71}{\rm Ge}\,,$$

and measurement of the flux of soft neutrinos ($E_\nu > 0.23$ MeV) is performed.

In the chlorine experiment at Homestake (USA), the reaction

$$\nu_{\rm e} + {}^{37}{\rm Cl} \to {\rm e}^- + {}^{37}{\rm Ar}$$

proceeds, and neutrinos of higher energies ($E_\nu > 1.2$ MeV) are detected.

The water-Cherenkov detector Super-Kamiokande (Japan) registers recoil electrons produced in the elastic scattering process

$$\nu_e + e^- \to \nu_e + e^- ,$$

and measures the neutrino flux in the hard region of the spectrum ($E_\nu > 6.5$ MeV). Unlike the radiochemical detectors SAGE, GALLEX and Homestake, the detector Super-Kamiokande not only permits determination of the integral flux, but also the solar-neutrino spectrum, i.e. the flux dependence on energy.

In all these experiments, the solar-neutrino flux registered (in the respective parts of the spectrum) turned out to be noticeably lower than that obtained from SSM calculations. The ratios of the integral fluxes measured in these experiments to the calculated flux are:

0.52 ± 0.06 (SAGE [11]),
0.60 ± 0.06 (GALLEX [12]),
0.33 ± 0.03 (Homestake [13]),
0.47 ± 0.02 (Super-Kamiokande [14]).

Oscillations of electron neutrinos ν_e transforming them into other types of neutrinos (ν_μ, ν_τ or a totally new, 'sterile' neutrino ν_s) in their path from the central regions of the Sun to the Earth serve as the most probable interpretation of the 'solar-neutrino deficit'. A very interesting and quite realistic possibility consists in electron neutrinos ν_e being transformed into ν_μ, ν_τ or ν_s as they pass through solar matter (the Mikheev – Smirnov – Wolfenstein effect).

3.2 Atmospheric neutrinos

Electron and muon neutrinos of relatively high energies ($E_\nu \gtrsim 1$ GeV) produced in the Earth atmosphere by cosmic rays are registered by large-scale underground detectors. Calculated results for the angular dependence of the atmospheric neutrino flux are reliable, and deviations of the measured angular dependence from the computed one point to neutrino oscillations. The most reliable observation of such a deviation (only for the muon neutrino) has been made (Fig. 2) with the Super-Kamiokande installation [15]. This finding serves as a plausible indication of oscillations $\nu_\mu \to \nu_\tau$ (or $\nu_\mu \to \nu_s$); the possible explanation based on $\nu_\mu \to \nu_e$ oscillations has been ruled out by the recent negative result of the reactor experiment CHOOZ carried out in France [16].

3.3 Neutrino masses and new physics

The results presented indicate that neutrinos possess mass. A possible explanation consists in that one of the massive neutrino states (mainly ν_e) has a very small mass: $m_{\nu 1} \ll 10^{-3}$ eV, while the second and third states (superpositions of ν_μ and ν_τ) have masses $m_{\nu 2} \sim 10^{-3}$ eV, and $m_{\nu 3} \sim 10^{-1}$ eV.

The existing data are also consistent with other interpretations, for example, with a strong degeneracy of the neutrino mass spectrum. Moreover, the accelerator experiment LSND (Los Alamos, USA) searching for neutrino oscillations has provided indications of oscillations [17] $\bar\nu_\mu \to \bar\nu_e$ with $\Delta m^2 \approx (0.2-2)$ eV^2. If the above is correct, then the introduction of a 'sterile' neutrino ν_s is required.

In any case, the masses of all the neutrinos are small: direct measurements of the neutrino mass in the β-decay of tritium

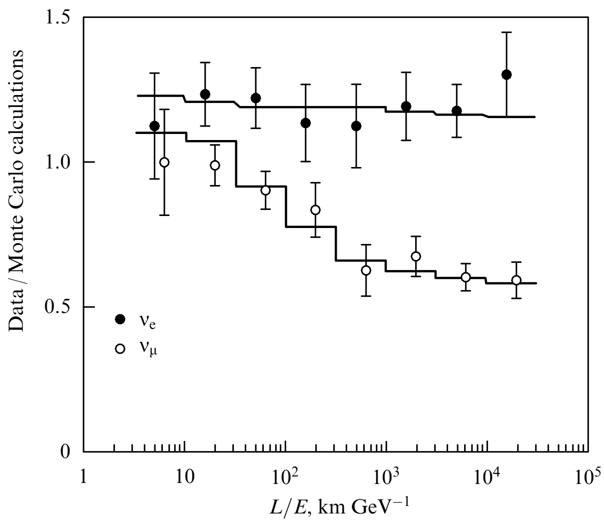

Figure 2. Ratio of the number of events measured by the Super-Kamiokande detector to the calculated number of events (in the absence of neutrino oscillations) versus the ratio of the neutrino effective path length to the neutrino energy [15]. Events that are mainly due to electron (dark circles) and muon (light circles) neutrinos are shown separately. The solid lines represent the expected ratios, assuming the existence of neutrino oscillations $\nu_\mu \to \nu_\tau$ (or $\nu_\mu \to \nu_s$) with $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2 and maximum mixing.

in Troitsk and Mainz (Germany) give [18, 19]

$$m_{\bar\nu_e} < 2.5 \text{ eV} ,$$

and the limit on the Majorana neutrino mass obtained in the Heidelberg – Moscow experiment (Gran Sasso, Italy) amounts to [20]

$$m_{\nu_e}^{\text{Majorana}} \lesssim 0.5 \text{ eV} .$$

Thus, the neutrino masses are extremely small in comparison with the masses of quarks and of the charged leptons.

For the explanation of small, but nonzero neutrino masses a new energy scale $M \sim 10^{12} - 10^{16}$ GeV has to be introduced (the masses of the right-handed counterparts of the known neutrinos may be related to this scale). Then the neutrino masses will be suppressed by this large scale:

$$m_\nu = \text{const} \cdot \frac{\langle\varphi\rangle^2}{M} ,$$

where $\langle\varphi\rangle$ is the vacuum expectation value of the Higgs field in the Standard Model.

Thus, establishment of the neutrino mass spectrum and of their mixing parameters opens up the door to studies of the new physics in an energy range that is not accessible to direct accelerator experiments.

In the near perspective investigation is expected of the solar-neutrino flux in the underground experiments SNO (Canada), Borexino (Gran Sasso, Italy) as well as accurate measurement of the spectrum (not only of the integral flux) of hard solar neutrinos with the Super-Kamiokande detector. Experiments will be continued with the gallium detectors SAGE and GNO (Gran Sasso, on the base of GALLEX). In the experiment mini-BooNE (Fermilab, USA) and, maybe, at CERN a test of the experiment LSND is to be implemented.

From the point of view of confirmation of the Super-Kamiokande results an important role will be played by experiments in which accelerators will serve as neutrino sources, while the detectors will be underground installations located hundreds of kilometers away from them: KEK–Super-Kamiokande (Japan, the experiment has started), Fermilab–Soudan (USA), and, possibly, CERN–Gran Sasso. All these experiments together will, most likely, permit not only to confirm the existence of neutrino oscillations, but also to reliably determine their parameters.

Further prospects in the field of studying neutrino properties are related both to the construction of underground detectors of the new generation and to the construction of a neutrino factory — a high-intensity neutrino source based on a muon storage ring. Quite probably that high-precision research in this difficult, but attractive, field will yield new surprises.

4. Incompleteness of the Standard Model and supersymmetry

From a theoretical viewpoint, an essential difficulty arises in the Standard Model. It is natural to imagine the Standard Model to be a low-energy limit of a certain, more general (free of ultraviolet divergences?) theory, for example, superstring theory. Indeed, a complete description of the fundamental interactions should include the gravitational interaction. Therefore, the Standard Model is clearly incomplete at very high energies comparable to the Planck scale $M_{\mathrm{Pl}} \sim 10^{19}$ GeV. Given such a point of view, the ultraviolet cutoff parameter Λ (which in any case has to be introduced for regularization of the ultraviolet divergences in the Standard Model) has the meaning of an energy scale, at which the new physics emerges.

Unlike quantum electrodynamics where radiative corrections depend logarithmically on Λ (and are, therefore, small given reasonable values of Λ and a small coupling constant α), in the Standard Model the radiative corrections to the mass parameter of the Higgs field are linear in Λ. Thus, for example, the diagram depicted in Fig. 3 gives the correction

$$\delta m^2 = -\frac{h_{\mathrm{t}}^2}{4\pi^2}\,\Lambda^2\,, \qquad (2)$$

where $h_{\mathrm{t}} \sim 1$ is the Yukawa constant of the t-quark. As a consequence, the vacuum expectation value of the Higgs field must be large in the case of sufficiently large Λ:

$$\langle\varphi\rangle \gtrsim \frac{\Lambda}{2\pi}\,,$$

which contradicts the observed value [2] $\langle\varphi\rangle = 246$ GeV.

This argument can be reversed by assuming the new physics to belong to the TeV energy range (or even lower). Then $\Lambda \lesssim 1$ TeV, and the contradiction is removed. In the theory with an elementary Higgs field the effects of the new

[2] Actually, this does not mean that the Standard Model is inherently inconsistent. Contradictions can be avoided by introducing the bare mass term of the Higgs field in an appropriate manner, so that it nearly exactly cancels out contributions like (2). Such a procedure can be carried out in all the orders of perturbation theory (renormalizability). This procedure, however, is not satisfactory from a physical point of view, since when Λ is large, it requires accurate fitting of the bare mass term (in other words, the subtraction of large numbers of a different nature is required to result in a small value of $\langle\varphi\rangle$).

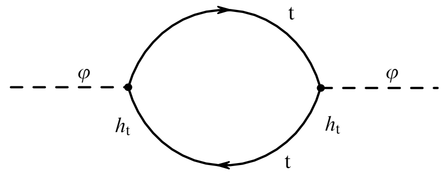

Figure 3. Radiative correction to the mass parameter of the Higgs field due to the t-quark loop.

physics should lead to additional contributions to the mass parameter of the Higgs field, which would render the correction δm^2 ultraviolet-finite. Such a possibility is realized in models with (softly broken) supersymmetry (see, for example, Ref. [21]).

In supersymmetric theories each known particle has a superpartner with a spin differing by 1/2. Thus, to each quark (with spin 1/2) corresponds a squark with spin 0 (actually two squarks as according to the number of spin states of the quark), the gluon G has the gluino $\tilde{\mathrm{G}}$ corresponding to it, and so on. The remaining quantum numbers of the particles coincide with those of their superpartners, and the coupling constants are uniquely related to each other. In the case of exact supersymmetry the masses of particles and of their superpartners must coincide. The contributions from superpartners cancel out the dangerous radiative corrections to the mass parameter of the Higgs field. For example, in the case of exact supersymmetry the contribution of the sum of diagrams presented in Fig. 4 is identically zero.

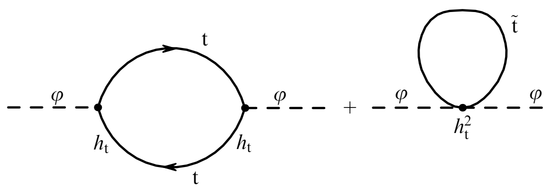

Figure 4. Loop of the scalar t-quark ('stop') which cancels out the t-quark loop in supersymmetric theories.

None of the superpartners of known particles have yet been found experimentally. This means that supersymmetry is broken in nature and the masses of superpartners are large. Searches for superpartners at the colliders LEP-II and Tevatron have imposed the following limitations on the masses of the scalar electron, the scalar t-quark, and the gluino:

$$m_{\tilde{\mathrm{e}}} > 75 \text{ GeV},$$
$$m_{\tilde{\mathrm{t}}} \gtrsim 100 \text{ GeV},$$
$$m_{\tilde{\mathrm{G}}} > 190 \text{ GeV}.$$

Such limitations have also been imposed on the masses of other superpartners.

In a situation when the masses of particles and of their superpartners differ, diagrams of the sort depicted in Fig. 4 do not cancel out exactly. Their sum remains ultraviolet-finite (!), and their total contribution has the structure (2), where Λ is the mass scale of the superpartners.

The arguments presented above indicate that the masses of superpartners should lie within the TeV energy range, or even lower. This energy range will be accessible for studies at the LHC collider under construction (the observation of superpartners at LEP-II or at the Tevatron before LHC is put into operation cannot also be excluded). From the point of view of the observation of supersymmetry, the possibilities to be made available by LHC are discussed, for example, in Ref. [22].

A natural question arises at this time: why are the masses of superpartners large as compared to the masses of known particles? A general and quite elegant answer consists in that the masses of ordinary particles must be equal to zero in the limit of unbroken electroweak $SU(2) \times U(1)$ symmetry (see Section 2). In this connection, the masses of ordinary particles are said to be protected by the symmetries of the Standard Model.

No such protection exists for the superpartners; thus, the explicit squark mass term $m_{\tilde{q}}^2 \, \tilde{q}^+ \tilde{q}$ is allowed even in the case of unbroken $SU(2) \times U(1)$ symmetry. For this reason, the masses of ordinary particles are determined by the scale of electroweak symmetry breaking (by the magnitude of the Higgs condensate $\langle \varphi \rangle = 246$ GeV), while the masses of superpartners are determined by the scale of a supersymmetry breaking, which may be noticeably larger.

Thus, the difference between the masses of ordinary particles and their superpartners seems quite natural in supersymmetric models.

A characteristic prediction of supersymmetric theories is that the lightest Higgs boson (in supersymmetric theories there exist at least two Higgs fields, so exactly the lightest Higgs boson is meant) should have a relatively small mass: $m_{\rm H} \lesssim 130$ GeV. This prediction is quite consistent with the results, already discussed, of the analysis of radiative electroweak corrections, while observation (at LEP-II, the Tevatron or LHC machines) of the light Higgs boson will serve as a serious indication that low-energy supersymmetry is actually realized in nature.

The arguments presented at the beginning of this section are of a very general character and permit, with a high degree of confidence, the assertion that there appears a totally new physics in the TeV energy range. The most attractive (and popular) idea is the concept of supersymmetric generalization of the Standard Model; however, one cannot exclude the possibility of some other physics (beyond the Standard Model) being realized in nature. In any case, most interesting discoveries are to be expected in collider experiments during the current decade.

5. Cosmology and new physics

The modern development of cosmology is binding it to particle physics more and more. Here, both theoretical and observational cosmological results often raise unexpected questions before the physics of the microcosm and thus strongly influence the line of research in the field of particle physics.

Among such issues the following are to be singled out: the problem of nonbaryonic dark matter, the origin of cosmic rays of superhigh energies, the generation of the baryon asymmetry of the Universe, the mechanism of inflation of the early Universe and the nature of the inflaton field, and the problem of the cosmological constant. All these questions point to the necessity of going beyond the limits of the Standard Model of particle physics and, therefore, are of particular interest.

5.1 Nonbaryonic dark matter

The problem of nonbaryonic dark matter (see, for example, review [23]) is conveniently formulated in terms of the ratio of the energy density of one or another component of matter in the Universe to the critical density: $\Omega_i = \rho_i / \rho_{\rm crit}$.

Comparison of the calculated results on the abundances of light elements in the Universe (the theory of primordial nucleosynthesis) with observational data yields a conservative estimate of the density of baryon (ordinary) matter $\Omega_{\rm B} < 0.1$ (here, most likely, a noticeable fraction of this matter emits no light, i.e. shows evidence of being baryonic dark matter). At the same time, numerous observational data indicate that significantly more matter was concentrated within galaxies and clusters of galaxies: $\Omega_M \gtrsim 0.3$; we stress that the distribution of this matter over the Universe is not uniform.

Such an estimate is also consistent with the theory of structure formation in the Universe, which provides serious indications that the nonbaryonic dark matter (if not all of it, then its greater part) is 'cold', i.e. decouples from ordinary matter in the early Universe, being nonrelativistic. Consequently, the nonbaryonic dark matter cannot be fully explained by the relic neutrinos having mass; these neutrinos stop interacting with matter at a temperature of the order of 1 MeV and are ultrarelativistic at the initial stage of evolution of the Universe.

The results obtained gave rise to the idea that a greater part of matter in the Universe consists of new stable particles (with a lifetime comparable to or exceeding the age of the Universe: $\tau \gtrsim 10^{10}$ years). Of the numerous candidates for dark-matter particles the most realistic are axions [3] and WIMPs — weakly interacting massive particles (with masses of the order of hundreds of GeV or several TeV). The latter arise naturally in supersymmetric extensions of the Standard Model, which results in their being of particular interest.

In many (if not most) supersymmetric extensions of the Standard Model, including the so-called Minimal Supersymmetric Standard Model (MSSM), the lightest superpartner of an ordinary particle (LSP) is stable. Regretfully, it has not yet been possible to predict its mass, or even its nature (whose superpartner it is).

If LSP is an electrically neutral colorless particle — the neutralino χ (the superpartner of the photon, or of the Z-boson, or of the Higgs boson, or their superposition) — then it is quite consistent with being the particle of cold dark matter. Such a particle has not yet been observed in experiment; direct searches at LEP-II impose a restriction on its mass

$$m_\chi > 35 \text{ GeV} .$$

The LSP mass density in the Universe has also not been unambiguously calculated, since it depends on numerous unknown parameters present in MSSM and other supersymmetric theories (for example, on the masses of superpartners). It is remarkable that within a broad range of values of these parameters the present-day LSP density in the Universe lies in the cosmologically interesting range

[3] Axions are predicted by models with Peccei – Quinn symmetry proposed for resolving the problem of CP-conservation in strong interactions. The axion mass is small ($m_{\rm a} \lesssim 1$ eV) but owing to the specific mechanism of their generation in the early Universe, they could play the part of cold dark matter (see also reviews [24]).

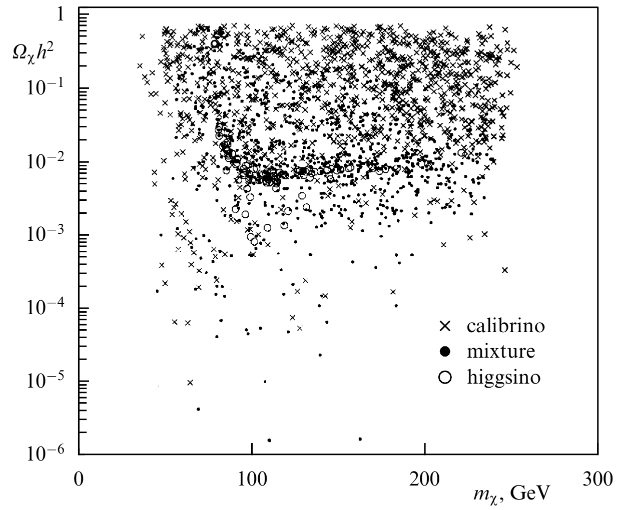

Figure 5. Neutralino density χ as function of its mass. The dots, crosses and circles correlate with different sets of MSSM parameters. The region of interest to cosmology corresponds to $\Omega_\chi h^2 \gtrsim 0.1$ (h is the present value of the Hubble parameter in units of 100 km s^{-1} Mpc^{-1}).

$\Omega_\chi = 0.2-1$ (see Fig. 5). Thus, the hypothesis claiming LSP to be the dark-matter particle is quite vigorous.

This hypothesis is amenable to experimental tests. LSP (like other WIMPs) interacts with ordinary matter, albeit extremely weakly. Therefore, attempts can be made to register rare elastic collisions of dark matter particles with nuclei employing low-background underground detectors. The energy of the recoil nuclei is then determined by the velocities of the dark matter particles in the Galaxy: $v \sim 300$ km s^{-1}, and it amounts to a value of the order of 100 keV. Such a small energy release in the detector and a low frequency of the events impose serious requirements on the background and the detector sensitivity; usually, scintillation or low-temperature techniques are applied.

Direct searches for dark matter particles are under way in many underground laboratories around the world, including the Baksan Neutrino Observatory of the Institute for Nuclear Research, RAS. From Fig. 6 one can see that already today the sensitivity of experiments is comparable to the predictions of supersymmetric theories. Development of the experimental technique will result in direct observation of dark matter particles becoming quite feasible.

Another way of searching for dark matter is opened up by the possibility that dark matter particles accumulate at the center of the Earth or of the Sun and annihilating there. Among the products of neutralino annihilation there are muon neutrinos:

$$\chi + \bar{\chi} \to \nu_\mu(\bar{\nu}_\mu) + \ldots ,$$

with energies amounting to tens or hundreds of GeV. These neutrinos (to be more exact, the muons produced in neutrino interactions with matter near the experimental device) can be detected by underground or deep-underwater neutrino telescopes.

Today, the strongest restrictions on the fluxes of such neutrinos have been obtained at the underground installations BUST (the Baksan Neutrino Observatory), MACRO (Gran Sasso, Italy), Super-Kamiokande and the deep-underwater Baĭkal Neutrino Telescope. From Fig. 7 it can be seen that this method also exhibits good possibilities. Hopes for

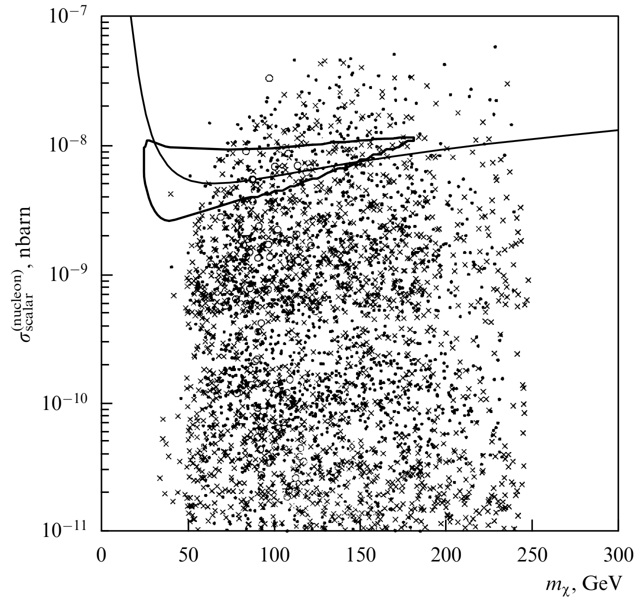

Figure 6. Cross section of neutralino scattering from a nucleon under the assumption that the local neutralino density amounts to 0.3 GeV cm^{-3}. The thin solid line shows the upper experimental limit. The closed contour corresponds to the positive, but hitherto not confirmed, result of searches carried out in the DAMA experiment.

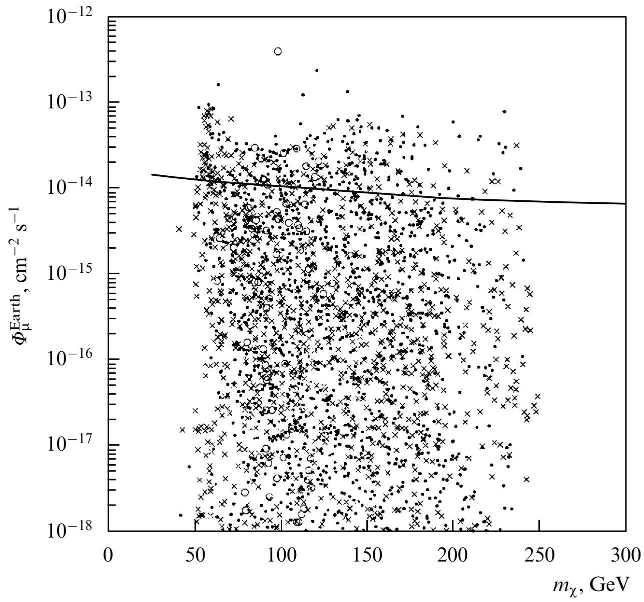

Figure 7. Flux of muons produced by the neutrinos from neutralino annihilation and directed away from the center of the Earth. The solid line presents the upper experimental limit. The dots, crosses, and circles have the same meaning as in Fig. 5.

further sensitivity enhancement are related primarily to the development of the Baĭkal Neutrino Telescope, to the construction of other deep-underwater neutrino detectors, and to operation of the Cherenkov detector AMANDA in Antarctica.

Thus, the search for nonbaryonic dark matter particles, initiated relatively not so long ago, has good prospects. We note that for the hypothesis that the lightest superpartner is the dark matter particle to be confirmed or discarded, the future experiments to be performed at LHC and subsequently at NLC (Next Linear Collider is an electron–positron collider with a center-of-mass energy equal to 0.5 – 1 GeV) are extremely important: these experiments will reveal low-energy supersymmetry (if it really exists) and determine the mass spectrum of superpartners.

5.2 Cosmic rays of superhigh energies

A noticeable event that occurred recently was the recording by the installation in Yakutiya and by the detectors AGASA (Japan) and Fly's Eye (USA) of extensive air showers (EAS) produced in the atmosphere by cosmic ray particles with energies higher than 3×10^{19} eV. The energy of the primary particles in several events was 3×10^{20} eV (50 J!). The acceleration of protons or nuclei up to so high energies is difficult to explain by ordinary mechanisms. Moreover, a sharp cutoff of the spectrum was expected to occur in this energy region owing to a significant enhancement of the interaction cross section of protons with relic photons (the Greisen – Zatsepin – Kuzmin cutoff).

Remarkably, experimental data (Fig. 8) point to the absence of the Greisen – Zatsepin – Kuzmin cutoff (though the statistics is small). This means that cosmic rays of superhigh energies are generated at a distance smaller than 50 Mpc from us (if the particles in cosmic rays of such energies are photons, then their mean free path in the Universe filled with electromagnetic radiation is also 50 – 100 Mpc owing to the process of e^+e^--pair production in the interaction of two photons).

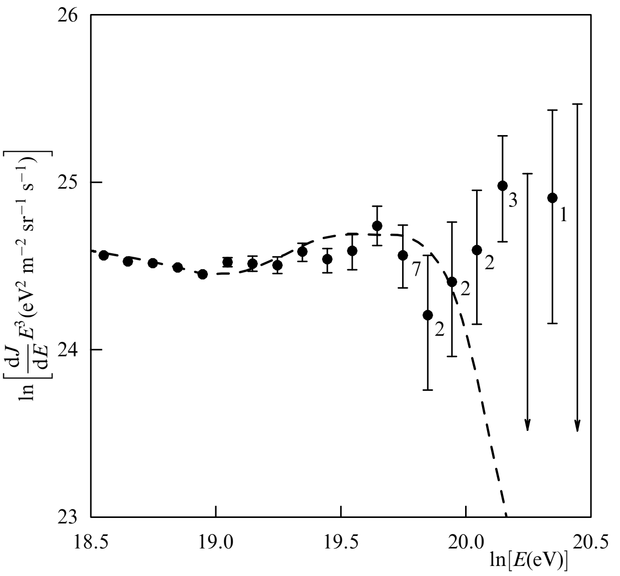

Figure 8. Spectrum of cosmic rays observed with the AGASA detector [25]. The numbers of events within the respective energy intervals are shown alongside the experimental points. The dashed line displays the spectrum expected in the case of sources uniformly distributed over the Universe.

The problem is rendered even worse by the protons of superhigh energies not being deflected by galactic and, most likely, intergalactic magnetic fields, while no possible sources of such protons (for example, active galactic nuclei) exist at such distances in the directions from where the cosmic rays arrive.

All the above points to the possible (or, maybe, even necessary) existence of new mechanisms generating cosmic rays of superhigh energies. The following could be such mechanisms: the decays of heavy long-lived relic particles (with masses $M \gtrsim 10^{13}$ GeV and lifetimes $\tau \sim 10^{10} - 10^{20}$ years), the self-intersection of cosmic strings, and other just as exotic processes (see the review article [26]).

Such objects could constitute a significant part of the dark matter (or even all the nonbaryonic dark matter), and their distribution in the Universe should coincide with the distribution of dark matter. In this case, a significant fraction (of the order of 50%) of the cosmic rays of superhigh energies should arrive from the halo of our Galaxy.

The interest in this hypothesis is primarily related to the possibility of testing it at installations to be constructed: EAS – Pierre Auger (Argentina, USA), the Telescope Array (USA), and EAS-1000 (in the vicinity of Volgograd). These installations will cover an area of $10^3 - 10^4$ km^2 (for comparison, the area covered by the AGASA installation amounts to 100 km^2), will provide the possibility for identifying primary particles (are protons the nuclei or electromagnetically interacting particles, photons, and electrons?), and exhibit quite a good angular resolution (several ang. degrees).

A characteristic prediction due to the generation mechanisms mentioned above consists in that the primary particles intended are mainly photons and electrons (even when only strongly interacting particles — quarks and gluons — are produced in the initial process: the fraction of protons in an hadronic jet is small as compared to π-mesons which ultimately decay into electrons and photons).

Moreover, the noticeable contribution of the halo of our Galaxy to the overall flux will result in a significant anisotropy in the arrival of cosmic rays inward to the center of the Galaxy [27], since the Solar System is at the periphery of the Galaxy. If such predictions are confirmed, then cosmic rays of superhigh energies will become a unique source of information on the new physics at superhigh energies, on exotic heavy objects in the Universe, and on the early stages of its evolution, at which these objects were created.

5.3 Baryon asymmetry of the Universe

The issue of the mechanism generating the observed baryon excess in the Universe that was raised over 30 years ago [28] has still not been resolved. Quantitatively, the baryon excess is characterized by the ratio of the number density of baryons to the entropy density: $(n_B - n_{\bar{B}})/s$. In the case of adiabatic evolution of the Universe and baryon number conservation this quantity is independent of time; at present the density of antibaryons, $n_{\bar{B}}$, is practically zero, and the ratio

$$\frac{n_B - n_{\bar{B}}}{s} = (3 - 10) \times 10^{-11} .$$

This means that in the early Universe there existed only one extra quark per approximately one billion quark – antiquark pairs (!), which is difficult to attribute to the properties of the initial state of the Universe [4].

For the baryon asymmetry to be generated, three Sakharov conditions must be fulfilled simultaneously at a certain stage of evolution of the Universe: (1) the baryon number must not be conserved; (2) thermodynamic equilibrium must not exist, and (3) CP-symmetry must be broken.

In principle, these conditions can be fulfilled within the framework of the Standard Model (see review [29]), since it

[4] In inflationary models $(n_B - n_{\bar{B}})/s = 0$ immediately after inflation is completed.

has the following features: (1) there exists a nonperturbative mechanism of violation of the baryon number; (2) thermodynamic equilibrium may be strongly violated if the electroweak phase transition is a phase transition of the first order, and (3) there exists a source of CP-violation (the CP-violating phase in the Cabibbo–Kobayashi–Maskawa matrix).

For a long time the issue of possible baryon asymmetry generation within the Standard Model at temperatures of the order of 100 GeV gave rise to significant interest; today there exists an answer that is negative. The point is that a necessary condition is that the mass of the Higgs boson be small ($m_H \lesssim 50$ GeV), while experiments at LEP-II yield $m_H > 95$ GeV. If the mass of the Higgs boson is so large, no electroweak first-order phase transition occurs in the Standard Model (instead, a smooth crossover is involved). Thus, an explanation of the baryon asymmetry of the Universe requires going beyond the Standard Model.

Interestingly, the possibility of the observed baryon excess being generated within the MSSM framework [30] cannot be excluded. To this end, the mass of one of the superpartners of the t-quark — of the right t-squark — should not be large: $m_{\tilde{t}_R} \lesssim 175$ GeV, and the mass of the lightest Higgs boson must be smaller than 115 GeV. This range of MSSM parameters is accessible to experimental studies at LEP-II and the Tevatron.

In more complicated extensions of the Standard Model there appear additional possibilities for electroweak generation of the baryon asymmetry. In any case, the possibility that precisely nonperturbative electroweak processes at temperatures of the order of 100 GeV are responsible for the observed asymmetry will be either confirmed or ruled out experiments at colliders in the TeV energy range.

If it turns out that the physics of electroweak interactions is not sufficient for explaining the baryon excess, this will mean that the baryon excess must be created by virtue of hitherto unknown interactions violating baryon and/or lepton numbers. Those mechanisms are still viable that are based on Grand Unified Theories or on the hypothesis of lepton number violation due to the Majorana mass of the heavy right-handed neutrino (for a review of the modern state of affairs on this problem see Ref. [31]). The latter version is interesting in that it relates the baryon asymmetry of the Universe to the masses of ordinary neutrinos and, consequently, to neutrino oscillations. Regretfully, it will, most likely, be extremely difficult to obtain an unambiguous answer as to precisely which one of these mechanisms was actually realized in the early Universe.

5.4 Inflationary Universe and the inflaton

The idea that at a certain early stage of evolution of the Universe it was undergoing inflation permits the resolution of many fundamental problems of cosmology (problems of the horizon, flatness, entropy, etc.) and provision for the generation of the primordial density perturbations which ultimately result in the creation of structures in the Universe (see, for example, Ref. [32]).

Most versions consider inflation to be a stage of exponential expansion of the Universe: $R(t) \propto \exp(Ht)$, $H \approx \text{const}$, at which the equation of state is close to the vacuum equation: $p = -\rho$. The inflationary stage is realized when in the theory there exists a new scalar field — the inflaton ϕ with a very flat scalar potential $V(\phi)$. Under certain conditions the inflationary field varies slowly with time; here, the Hubble parameter

$$H = \sqrt{\frac{8\pi}{3} \frac{V(\phi)}{M_{Pl}^2}}$$

is actually nearly constant in time.

A characteristic prediction of the inflationary theory consists in the spectrum of primordial density perturbations being close to the scale-invariant Harrison–Zel'dovich spectrum. On the whole, this prediction is consistent both with available observational data on the large-scale structure of the Universe and with anisotropy measurements of the relic radiation [33], which makes the inflationary theory especially attractive.

The success of the inflationary theory has raised the issue of the nature of the inflaton field. Such a field should exhibit quite unusual properties from the point of view of particle physics: its potential must be sufficiently flat up to values of $\phi \gtrsim M_{Pl}$. This, for instance, means that the potential should not contain terms such as ϕ^6/M_{Pl}^2, ϕ^8/M_{Pl}^4, etc. (more exactly, the coefficients of these terms should be extremely small) which, as a rule, arise in realistic theories (see the discussion about the inflaton from the standpoint of particle physics in Ref. [34]).

Future high-precision anisotropy measurements of the relic radiation at various angular scales, measurements of its polarization (in particular, by satellites — projects MAP and Planck; of the detectors located on the Earth's surface, an important role may be attributed to RATAN-600), and studies on the characteristics of the large-scale structure of the Universe (the Sloan Survey and others) will permit progress in the understanding of the inflaton nature. The point is that the details in the spectrum of primordial density perturbations depend on the shape of the scalar potential $V(\phi)$.

Besides the above, a noticeable contribution to the anisotropy of the relic radiation at large angular scales can be due to relic gravitational waves. Identification of this contribution (in particular, by measuring the polarization of relic photons) will permit determination of the scale of inflation, i.e. the magnitude of the Hubble parameter at the inflationary stage. The prospects for quantitative studies of the very early (and extremely unusual) stage of evolution of the Universe and of the new physics related to it at high-energy scales (10^3 GeV?, 10^{10} GeV?, 10^{16} GeV?) are becoming quite realistic.

5.5 The cosmological constant

The problem of the cosmological constant is probably the most difficult topic of modern fundamental physics (see review [35]). Essentially, it is the problem of the energy density of vacuum. Contributions to the energy density of vacuum are, generally speaking, provided by all interactions. The contributions of strong and electroweak interactions can be expected to depend on the energy scales and, to an order of magnitude, to equal Λ_{QCD}^4 and M_W^4, i.e. 10^{-3} and 10^8 GeV^4, respectively. At the same time, it is quite clear that the present-day value of the energy density of vacuum cannot exceed significantly the critical density $\rho_{crit} \sim 10^{-46}$ GeV^4. The question is what can explain such a strong discrepancy between theoretically expected values and observational data.

No answer to this question even close to being satisfactory has yet been obtained. We stress that the problem of the cosmological constant reduces to a problem of large distances, and the new physics at distances smaller than 10^{-15} cm (the energy scales above 100 GeV) is unlikely to be somehow relevant. Rather, we are dealing here with the physics of ultralow energies, for example, with new massless or nearly massless fields. However, attempts at achieving compensation of the energy of vacuum by introducing such fields have hitherto not been successful [5].

Recently, the problem of the cosmological constant has undergone a new development. A series of cosmological arguments (listed, for example, in reviews [38]) was put forward in favor of the energy density of vacuum differing from zero today and taking on a noticeable fraction (0.4 – 0.8) of the critical density at the modern stage of evolution of the Universe, i.e. the value of Ω_Λ being close to unity.

The greatest interest was shown in the argument based on studies of Ia supernovae at large red shifts [39] (Fig. 9). If indeed $\Omega_\Lambda \approx 1$ in the present epoch, then an additional problem arises for the explanation of this remarkable relationship. Actually, when the scale factor $R(t)$ changes, the energy densities of matter, radiation and vacuum behave like R^{-3}, R^{-4} and const, respectively. Therefore, at the early stages of evolution the contribution of the energy density of vacuum to the total energy density in the Universe was extremely small; it began being revealed only at a stage close to the present epoch. If this coincidence is accidental, then it requires very special initial data (i.e. the problem of fine-tuning arises); if not, then the appropriate mechanism must be found. The mechanisms proposed till now (for instance, with the 'tracker field' [40]) require the introduction of new fields with exotic properties which are difficult to realize in models of particle physics.

Most likely, both the observational and theoretical aspects of the problem of the cosmological constant will be at the center of interest in the coming years. It cannot be excluded that relevant research will result in a drastic revision of the ideas underlying long distance physics.

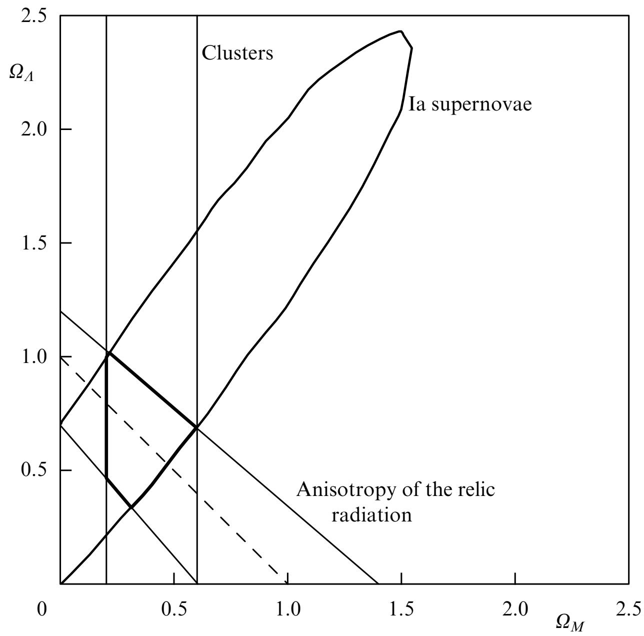

Figure 9. Bounds on Ω_M and Ω_Λ following from studies of Ia supernovae, of the anisotropy of the relic radiation, and of matter clusters at a level of 2σ. The bold line shows the boundary of the allowed region where $\Omega_M \sim 1/3$, and $\Omega_\Lambda \sim 2/3$.

[5] One of the most recent such attempts was undertaken by Dolgov [36], but the scheme proposed by him also turned out to be unsuccessful [37].

6. Instead of conclusion

Particle physics and cosmology are at the threshold of a new, very interesting stage of development. At the beginning of the present millennium we are to expect the revelation of the mechanism of electroweak symmetry breaking and of particle mass generation, the discovery of new particles and of their interactions (supersymmetry?), and the confirmation of neutrino oscillations and measurement of their parameters (neutrino mass differences and mixing angles). Finally, the mechanism of CP-violation in the quark sector will be clarified, and maybe CP-violation will be found in the neutrino sector.

The development of observational and computational methods in cosmology has made it a quantitative science. In this field one can hope for confirmation of the inflationary theory and for measurement of the inflaton field parameters, and for reliable measurement of the present magnitude of the cosmological constant. Quite probably, the nature of dark matter will be revealed, and cosmic rays of superhigh energies will become the source of valuable information on exotic objects in the Universe.

Undoubtedly, the mutual influence of particle physics and cosmology, of microphysics and macrophysics will ensure rapid development of fundamental physics in the foreseeable future.

References

1. Okun' L B *Leptony i Kvarki* (Leptons and Quarks) (Moscow: Nauka, 1990) [Translated into English (Amsterdam: North-Holland, 1984)]
2. CDF Collab. *Phys. Rev. Lett.* **74** 2626 (1995); DO Collab. *Phys. Rev. Lett.* **74** 2632 (1995)
3. 'Review of Particle Properties' prepared by Particle Data Group, in *European Phys. J.* **C3** 1 (1998)
4. Vysotsky M I, Novikov V A, Okun L B, Rozanov A N *Usp. Fiz. Nauk* **166** 539 (1996) [*Phys. Usp.* **39** 503 (1996)]
5. Alcaraz J et al. (LEP Electroweak Working Group) http://www.cern.ch/LEPEWWG/Welcome.html
6. Ibid., http://www.cern.ch/LEPEWWG/tgc
7. Farhi E, Susskind L *Phys. Rep.* **74** 277 (1981)
8. Bilenky S M, Giunti C, Kim C W "Finally neutrino has mass?" hep-ph/9902462
9. Bancall J N, Pinsonneault M H, Wasserburg G J *Rev. Mod. Phys.* **67** 781 (1995); Brun A S, Turck-Chieze S, Morel P *Astrophys. J.* **506** 913 (1998)
10. Bahcall J N *Neutrino Astrophysics* (Cambridge: Cambridge Univ. Press, 1989)
11. SAGE Collab. "Measurement of the solar neutrino capture rate with gallium metal" *Phys. Rev. C* **60** 055801 (1999), astro-ph/9907113
12. GALLEX Collab. *Phys. Lett. B* **388** 384 (1996)
13. Cleveland B et al. *Astrophys. J.* **496** 505 (1998)
14. Super-Kamiokande Collab. *Phys. Rev. Lett.* **81** 1158 (1998)
15. Super-Kamiokande Collab. *Phys. Rev. Lett.* **81** 1562 (1998)
16. CHOOZ Collab. *Phys Lett. B* **420** 397 (1998)
17. LSND Collab. *Phys. Rev. Lett.* **81** 1774 (1998)
18. Lobashev V M *Talk presented at Neutrino'98* (*Takayama, Japan — June 1998*) http://www-sk.icrr.u-tokyo.ac.jp/nu 98
19. Weinheimer C *Talk presented at Neutrino'98* (*Takayama, Japan — June 1998*) http://www-sk.icrr.u-tokyo.ac.jp/nu 98
20. Heidelberg – Moscow Collab. *Prog. Part. Nucl. Phys.* **32** 261 (1994)
21. Nilles H P *Phys. Rep.* **110** 1 (1984); Vysotskiĭ M I *Usp. Fiz. Nauk* **146** 591 (1985) [*Sov. Phys. Usp.* **28** 667 (1985)]; Kazakov D I *Surveys in*

High-Energy Phys. **10** 153 (1997); Nelson A E *Nucl. Phys. Proc. Suppl.* **62** 261 (1998); Gorbunov D S, Dubovskiĭ S L, Troitskiĭ S V *Usp. Fiz. Nauk* **169** 705 (1999) [*Phys. Usp.* **42** 623 (1999)]
22. Krasnikov N V, Matveev V A *Fiz. Elem. Chastits At. Yadra* **28** 1125 (1997) [*Phys. Part. Nucl.* **28** 441 (1997)]
23. Bottino A, Fornengo N "Dark matter and its particle candidates", hep-ph/9904469
24. Krasnikov N V, Matveev V A Tavkhelidze A N *Fiz. Elem. Chastits At. Yadra* **12** 100 (1980); Kim J E *Phys. Rep.* **150** 1 (1987)
25. Takeda M et al. *Phys. Rev. Lett.* **81** 1163 (1998)
26. Berezinsky V S "Ultra high energy cosmic rays from cosmological relics", astro-ph/9811268
27. Dubovsky S L, Tinyakov P G *Pis'ma Zh. Eksp. Teor. Fiz.* **68** 99 (1998) [*JETP Lett.* **68** 107 (1998)]
28. Sakharov A D *Pis'ma Zh. Eksp. Teor. Fiz.* **5** 32 (1967) [*JETP Lett.* **5** 24 (1967)]; Kuz'min V A *Pis'ma Zh. Eksp. Teor. Fiz.* **12** 335 (1970) [*JETP Lett.* **12** 228 (1970)]
29. Rubakov V A, Shaposhnikov M E *Usp. Fiz. Nauk* **166** 493 (1996) [*Phys. Usp.* **39** 461 (1996)]
30. Carena M, Quiros M, Wagner C E M *Phys. Lett. B* **380** 81 (1996)
31. Riotto A, Trodden M "Recent progress in Baryogenesis" *Ann. Rev. Nucl. Part. Sci.* **49** 35 (1999), hep-ph/9901362
32. Linde A D *Fizika Elementarnykh Chastits i Inflyatsionnaya Kosmologiya* (Elementary Particle Physics and Inflationary Cosmology) (Moscow: Nauka, 1990) [Translated into English (Chur, Switzerland: Harwood Acad. Publ., 1990)]; Kolb E W, Turner M S *The Early Universe* (New York: Addison-Wesley, 1990)
33. Turner M S "Cosmology update 1998", astro-ph/9901168
34. Lyth D H, Riotto A *Phys. Rep.* **314** 1 (1999)
35. Weinberg S *Rev. Mod. Phys.* **61** 1 (1989)
36. Dolgov A D *Phys. Rev. D* **55** 5881 (1997)
37. Rubakov V A, Tinyakov P G "Ruling out a higher spin field solution to the cosmological constant problem", hep-ph/9906239
38. Sahni V, Starobinsky A "The case for a positive cosmological Lambda-term", astro-ph/9904398; Turner M S "Why cosmologists believe the Universe is accelerating", astro-ph/9904049
39. Perlmutter S et al. "Measurements of Omega and Lambda from 42 high-redshift supernovae", astro-ph/9812133; Riess A et al. *Astron. J.* **116** 1009 (1998)
40. Ratra B, Peebles P J E *Phys. Rev. D* **37** 3406 (1988); Zlatev I, Wang L, Steinhardt P J *Phys. Rev. Lett.* **82** 896 (1999)