Eleventh school on quantum chromodynamics and grand unification models (Bakuriani, Georgian SSR, January 16–23, 1986)

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Usp. Fiz. Nauk 150, 472–479 (November 1986)

The 11th Winter School, devoted to current problems in elementary particle physics, was held at the Institute of Physics of the Georgian SSR Academy of Sciences in Bakuriani from January 16 to January 23, 1986. Thirty-six lectures and reports were presented, and ten seminars were held.

In the theoretical part attention was devoted primarily to the following subjects: a) the theory of superstrings and its phenomenological manifestations; b) supersymmetry and supergravitation; c) cosmology and astrophysics; d) composite models of quarks and leptons and grand unification; e) theory of hadrons and hadronic processes within the framework of quantum chromodynamics.

The discussion of superstrings—the most promising and rapidly developing fundamental approach—started with a lecture by Ya. I. Kogan entitled "Strings for pedestrians." The basic concepts used in this field were introduced on a popular level. A brief historical review of the subject, from the Veneziano model up to modern ideas, associated with the compactification of the ten-dimensional superstring into four dimensions, was given.

In a report entitled "Supergravitation and superstrings" R. É. Kallosh examined the field-theoretic limit of superstrings and the theory of supergravitation following from it. The necessity for introducting additional terms in the determination of field intensities, in particular in $H_{\mu\nu\rho}$, and in the laws of supertransformations was demonstrated.

In a review report entitled "Phenomenology of superstrings" A. Yu. Morozov emphasized the problem of compactification into four dimensions $M_{10}\to M_4\times K$. Examples of Calabi-Yao manifolds, which provide an acceptable phenomenology with three or four generations, were presented. Different variants of the breaking of gauge symmetry $E_8\times E_8$ to $E_6\times E_8$, $SU(3)\times SU(2)\times U(1)\times U(1)\times E_8$, etc., were examined. It was shown that because of the specific structure of the generations, generally speaking, the problem of fast decay of the proton owing to the exchange of Higgs particles could arise. The probability of proton decay is determined by some (super) Yukawa constants in the Lagrangian. In some variants of compactification the latter have a topological character and vanish with an appropriate choice of the manifold K.

An original report by the same author was devoted to purely theoretical aspects of boson strings. There exists a well developed technique for carrying out single-loop calculations. The generalization of this technique to many loops is an extremely nontrivial problem, which was solved by A. Yu. Morozov and coauthors. Rigorous closed results (in the form of quaratures) were presented for two-, three-, and four-loop contributions to the S matrix. Further progress is based on the work on complex analyticity in the theory of strings, carried out by A. A. Belavin and V. G. Knizhnik.

R. É. Kallosh gave an original report on work performed by R. É. Kallosh and B. Nielsen "Scaling-invariant ($d = 10$) superspace and the heterotic string." Supergravitation with $d = 10$, interacting with the Yang-Mills theory, is described in superspace, which has a manifestly scaling-invariant form. In addition, the fields are coupled in a natural manner with the variables arising in the heterotic string, and have simple supersymmetry transformation laws. This approach can facilitate the study of the effects of introducing terms with higher order derivatives induced by the string.

The report on algebraic quantum theory by Ya. I. Kogan was devoted to the covariant second quantization of the string, based on the BRST approach and proposed by Siegel, Neveu and West, Banks and Peskin, Kaku, and Lykken. Witten's work, in which it was shown that the action for the string field has the Chern-Simons form, was discussed, in addition, the analog of the gauge transformations are BRST-transformations. The generalization to the case of non-oriented strings, which requires the introduction of Jordan algebras, was examined.

The section on supersymmetry and supergravitation was introduced by a lecture by M. I. Vysotskiĭ and K. A. Ter-Martirosyan entitled "Experimental consequence of supersymmetric models." In recent years models with low-energy supersymmetry have been intensively studied by both theoreticians and experimenters. In these models the existence of a large number of new fundamental particles on the mass scale $M_W \sim 100$ GeV is predicted. Today the lower experimental limit on the mass of new particles is near 40 GeV. Nevertheless lighter particles could also exist: the weakly interacting photino with a mass of several GeV, the gluino with a mass from 5 to 10 GeV. A number of currently popular variants of the theory predict the existence of a light neutral Higgs boson with a mass of several GeV. The direct confirmation of the theoretical ideas can be expected when the new accelerators are started up: the SLC e^+e^- collider and the $p\bar{p}$ collider in 1986–1987. Indirect evidence for SUSY was discussed: the large magnitude of the dipole moment of the neutrino, proton decay in the mode $p\to K\nu$, and the light Higgs boson mentioned above.

D. I. Kazakov reported on work on the construction of finite ($N = 1$)-supersymmetric grand unification models. Kazakov and coauthors start from the idea that with a sufficiently large number of Yukawa constants in the theory it is always possible to form a relation between the Yukawa (h) and gauge (g) constants $h = \alpha g + \beta g^3 + \gamma g^5 + \ldots$ so as to ensure that all renormalizations are finite. This requires the elimination of the divergence in g in a single loop by appropriate selection of matter and ensuring that $\gamma_i(h,g) = 0$, where γ_i are the anomalous dimensions of the matter fields. Both conditions are satisfied in a number of concrete models.

In the report "Solution of the problem of anomalies in supersymmetry gauge theories and operator decomposi-

 0038-5670/86/111071-04$01.80

tion" A. I. Vaĭnshteĭn and M. A. Shifman summarized the series of works on the β functions and the problem of anomalies. It was shown how exact expressions for β functions are obtained in the standard perturbation theory. The key observation is this: the Wilson effective action is not equal to the sum of the diagrams for the vacuum loops in an external field. The difference is determined by infrared effects. The coefficient $1/g^2$ in front of W^2 in the Wilson action is required only at the single-loop level, which leads to the single-loop form of the anomalous operator equation for the supercurrent (generalization of the Adler-Bardeen theorem). The full Gell-Mann–Low function arises after the matrix element is calculated. The most unexpected finding is the observability of the bare Z factor of the matter fields.

In a report entitled "Superinstanton calculus" V. A. Novikov discussed in detail the progress achieved in the last three years in instanton calculations in supersymmetric gauge theories with matter. The use of a manifestly superinvariant technique automatically ensures general properties, such as factorization and clusterization of correlation functions and coordinate-independence of the n-point functions induced by superfields with the same chirality. The practical result is the possibility of reliable calculation of condensates (arising only nonperturbatively) in the weak-coupling regime. The most important example is the condensate of gluino fields $\langle \text{vac}|\lambda^{a}_{\alpha}\lambda^{a\alpha}|\text{vac}\rangle \neq 0$.

The participants were intensely interested in the section devoted to the interface of cosmology and astrophysics, on the one hand, and elementary particles on the other. The section was introduced by a report by A. D. Dolgov on "Cosmology and new particles." The present status of cosmology, beginning from currently accepted views on the creation of our universe up to the theory of the development of the first nonuniformities in the galaxy and their clusters, was briefly reviewed. Methods for obtaining the cosmological limits on the parameters of elementary particles with the help of limits on the age of the universe, on the spectrum of the relic radiation, on the primary nucleosynthesis, etc., were described in general form, and the limits on the properties of supersymmetric partners of elementary particles were derived.

In the lecture entitled "Anisotropy of relic radiation and the dark matter in the universe" V. M. Lukash showed that the investigation of the angular fluctuations $\Delta T/T$ of the background radio radiation in different models of the universe and their comparison with the observed limits on $\Delta T/T$ enables drawing conclusions about the physical nature and quantity of invisible cosmic matter and also imposition of strict limits on the theories of the very early universe. The most sensitive manifestation of the invisible mass, which already enables rejection of a number of models now, are the large-scale fluctuations $\Delta T/T$, which are uniquely related to the field of primary cosmological perturbations. The minimum predicted level of background anisotropy in the standard models of the inflationary universe can be achieved in the RELIKT experiment with a sensitivity of $\Delta T/T \sim 5\cdot 10^{-6}$. The discovery of fluctuations $\Delta T/T$, on angular scales $\theta > 5°$ would make it possible to determine both the spectrum of the primary density perturbations and the total mass of the invisible matter in the universe.

B. I. Luchkov gave an excellent review of cosmic sources of neutrinos and photons with $E > 10^{15}$ eV of the Cygnus X-3 type. The lastest data on muons induced by Cygnus X-3 became a real sensation—no known elementary particle can be a source of this effect! It is possible that here we encounter for the first time a cluster of the "hypothetical stable quark matter" making up pulsars. Methods for measuring the radiation from such sources and results which can now be regarded as reliable were described in detail.

As always, efforts directed toward the investigation of composite schemes of quarks and leptons are not abating. Composite models as well as the concomitant questions of grand unification were discussed in a number of reports. We call attention first to the lecture by Dzh. L. Chkareuli "Composite quarks and leptons and horizontal symmetry." In this lecture the composite model of quarks and leptons with a preon confinement radius of the order of the Planck distances was examined. It was shown that the chiral metacolor of preons $SO(9)_L \times SO(9)_R$ uniquely (according to the condition of 't Hooft self-consistency) selects as the symmetry group of the composite quarks and leptons the SU(8) group, containing the standard grand unification symmetry SU(5) and the horizontal symmetry $SU(3)_H$, transforming the quark-lepton generations into one another. A variant of the model with composite gauge fields was discussed. In conclusion, arguments from the theory of superstrings supporting the existence of a new level of elementarity, corresponding to preons, were presented.

In the report entitled "Composite leptons and quarks: experimental limitations and consequences" Yu. F. Pirogov discussed the present status of composite models of leptons and quarks. The method of effective Lagrangians for the analysis of possible manifestations of composite nature was examined. Limitations on the inverse radius of composite quarks (leptons) Λ were found from analysis of rare processes and scattering at relatively low energies. The theoretical uncertainties in determining this scale were analyzed. It was shown that the value $\Lambda \gtrsim 1$ TeV is consistent with the modern experimental data. Possibilities for improving this limit (or observing the effects of compositeness) using future accelerators were discussed. It was shown that an advancement up to values $\Lambda \lesssim (10)$ TeV is realistic.

A. A. Tyapkin gave a report entitled "A variant of the composite structure of quarks." In this report the composite model of quarks based on the postulated strong attraction between the primary fermions and antifermions, analogous to the attraction in the Fermi-Yang model, was examined. Color was interpreted as the ability of the quark to be in three states, distinguished by sets of integer values of the charge and baryon number. Exchange of charged and neutral antifermions, in the opinion of the author, changes the color of the quarks and binds them into a unified system—the hadron.

The phenomenology of grand unification was discussed in three interesting reports, which continued the ideas presented in the lectures by J. L. Chkareuli and M. I. Vysotskiĭ. The report "Horizontal symmetry and status of the Kobayashi-Maskawa model" by Z. G. Berezhiani and J. L. Chkareuli was devoted to the phenomenological consequences of the horizontal symmetry of quark-lepton generations $SU(3)_H$; the main points were the inverse hierarchy of the neutrino mass $m_{\nu_e}:m_{\nu_\mu}:m_{\nu_\tau} = m_u^{-1}:m_c^{-1}:m_t^{-1}$; amplification of the channel for proton decay through color scalar triplets; small Kobayashi-Maskawa angles $s_1 = 0.22$, $s_2 = 0.04–0.1$, $s_3 = 0.01–0.025$ [depending on the composition of the scalars breaking $SU(3)_H$] and the phase of spontaneous CP violation $\delta = \pi/2$; the mass of the t quark $m_t = 35–75$ GeV. The status of the Kobayashi-Maskawa model for these values of the parameters was examined and good agreement with experiment was obtained.

The supersymmetric variant of horizontal symmetry $SU(3)_H$, transforming generations of quarks and leptons into one another, was examined in a report by Z. G. Berezhiani, G. R. Dvali, M. R. Dzhibuti, and J. L. Chkareuli "Supersymmetry and quark and lepton generations." It was shown that unlike the usual potential [admitting two possible solutions for vacuum-averaged scalars breaking $SU(3)_H$], the superpotential in the most general case leaves only one solution—with a mass hierarchy between generations.

The orientation toward experimental aspects was even stronger in the report by V. A. Kartvelishvili, E. T. Chikovani, and Sh. M. Ésakiya entitled "Heavy vector mesons in Higgs particle creation and decay processes." Calculation of the cross section for the creation of Higgs particles and partial widths of their decays into heavy quarkonia (toponium, bottomium) was reported. It was shown that the background conditions fully permit discovery of the Higgs particle (in a reasonable mass range) on accelerators under construction.

The traditional subject—strong interactions at high energies and the theory of hadrons—was also presented quite completely. In a report entitled "How to distinguish additive and subtractive quarks" B. Z. Kopeliovich proposed studying quasifree charge exchange reactions on nuclei of the type $\pi^- \to \pi^0$, $\pi \to \eta$ etc. The second type of model predicts in this case "bleaching" of the nuclei for hadronic configurations of small dimensions. The data and the theoretical situation for the asymptotic behavior of the nucleon-nucleon cross sections were reviewed by N. N. Nikolaev. It was shown that the position of the effective Pomeranchuk pole $\Delta_{\rm eff} \approx 0.25–0.35$, since $\sigma_{\rm eff}$ (pp) reaches 160–200 mb at $E = 10^8–10^9$ GeV.

In a lecture entitled "Quantization of chromoelectric flux and the action of a relativistic string" G. S. Iroshnikov discussed the quantization of the flux and the action from the condition of uniqueness of the solution of the field equations. These equations arise from the variation of the effective action for hadronic field correlation functions in QCD. Their solution describes a relativistic string with quarks at the ends. The number of quanta Q in the flux is a topological number. The quantization is entirely determined by the nonabelian character of the theory and vanishes in the abelian limit.

A. B. Kaĭdalov reviewed the new data and the theoretical situation for hadronic collisions. According to his results on the description of hadronic spectra $\Delta_{\rm eff}$ is smaller than the value obtained by Nikolaev, approximately 0.15. O. I. Piskunova described interesting work on the creation of charmed particles in collisions of high-energy hadrons.

É. V. Shuryak reported on investigations of the structure of the QCD vacuum within the framework of the "instanton liquid" model. It was shown that this model correctly reproduces the phenomena associated with the spontaneous breaking of chiral symmetry.

M. A. Shifman reviewed the theoretical situation arising after recent measurements of the lifetimes of charmed particles. We demonstrated the fundamental role of the exchanges of soft gluons for understanding the mechanism of these decays. The possibilities of QCD in describing the enormous mass of data on exclusive decays of D and F mesons were demonstrated.

Questions pertaining to the physics of quark-gluon plasma were discussed at the school. An interesting report about the discovery of anomalous events in the Pamir experiment was given by G. B. Zhdanov, and the theoretical situation was reviewed by L. V. Fil'kov. He considered especially $\bar{\rm p}$ and $\bar{\rm d}$ annihilation in nuclei as a method for producing highly excited clusters of hadronic matter.

A report by I. M. Dremin on hadronic spectroscopy evoked a great response. It was shown in the report that a quite sharp transition from "current" to "constituent" quarks at a distance of ~ 0.1 fm can solve a number of problems in the theory of the upsilon mesons with completely new predictions for toponium.

I. I. Roĭzen discussed another manifestation of the increase in the effective mass of constituent quarks with distance: he found pomeron and vector meson trajectories within the framework of some model assumptions.

The phenomenology of the neutralization of color and electric charges in jets was discussed in a report by I. M. Dremin and A. B. Leonidov. It was proposed that the screening time of the color current be measured based on the emission of hard photons in e^+e^- annihilation.

A report by É. V. Shuryak entitled "Does stable quark matter exist?" had an interdisciplinary character. The question of whether a minimum in the energy per baryon is realized in ordinary nuclear matter or whether there exists an even more energetically favorable state—stable quark matter (SQM)—was discussed. The fact that the latter possibility is not excluded was recently pointed out by Witten, who showed that in any case SQM cannot be created under laboratory conditions. He proposed a cosmological mechanism for the formation of SQM, which could explain the nature of the "dark matter" in galaxies. A more realistic source of SQM are pulsars, so that this question was raised in connection with the puzzling muonic signal from Cygnus X-3, which cannot be explained by the known elementary particles.

The report entitled "Magnetic moment of the neutrino and time-dependent measurements of the solar neutrino flux" (based on the work of M. B. Voloshin, M. I. Vysotskiĭ, and L. B. Okun') by M. Vysotskiĭ was listened to with great attention. The existence of a neutrino magnetic moment $\mu_\nu \sim 10^{-10}\mu_B$ should lead to variations of the observed solar neutrino flux, which are associated with the solar magnetic activity. For neutrinos forming in pp reactions an 11-year variation of the flux, anticorrelated with the solar activity, should be observed. For boron and beryllium neutrinos half-year variations of the observed neutrino flux, owing to the presence of an equatorial "gap" in the sun's toroidal magnetic field and the inclination of the solar equator relative to the plane of the ecliptic, should be observed during years of maximum solar activity. In Davis's experiment there was indeed a decrease in the neutrino flux at the beginning of March and September in 1979–1982 at the 3σ level.

Neutrino physics was also the subject of a report by V. A. Tsarev. It was shown that terrestrial matter can substantially increase the amplitude of neutrino oscillations $\nu_\mu \to \nu_e$ at accelerator energies ($E_\nu \sim 1$–10^3 GeV) over distances of $l \sim 10^4$ km.

For $\Delta m^2/E_\nu \sim 10^{-3}$ eV^2/GeV $P_{\nu_\mu - \nu_e}$ becomes of the order of unity even for $\theta_\nu \ll 1$. This simplifies the search for oscillations and increases the sensitivity of neutrino sounding of the earth compared with the absorption method by a factor of 10^3–10^7.

The neutrino section was concluded by a report by I. M. Zheleznykh entitled "Experimental and theoretical problems in the detection of neutrinos in the ocean, ice masses, and the earth's atmosphere." The possibility of recording fluxes of natural neutrinos and other particles with superhigh energies ($E_{\nu \text{th}} \sim 10^{12}$ eV) using optical detectors at great depths in the ocean (project DUMAND) and radio detectors monitoring a volume of 10^9–10^{11}m^3 of low-temperture ice ($t \sim -50$ °C) in Antartica ($E_{\nu \text{th}} \sim 10^{14}$ eV) was examined. The problems of studying the upper limit of the neutrino energy spectrum (10^{20}–10^{28} eV) and the problems of neutrino astrophysics and the physics of cosmic rays were discussed. The prospects for utilizing neutrino radiodetectors in ice masses for measuring the $\bar{\nu}_e$ flux at energies near $5 \cdot 10^{15}$ eV based on the resonance reaction $\bar{\nu}_e \, e \to W \to$ hadrons were pointed out.

In spite of the theoretical leaning of the school, a great deal of attention was devoted to experimental investigations. Cosmophysical experiments and experiments on the scale of the earth were already discussed above. Installations for recording extensive air showers continued to play an important role in them. A seminar by D. M. Kotlyarevskiĭ and B. I. Luchkov was devoted to a discussion of the prospects for such studies at Tskhra-Tskharo.

V. A. Nikitin reviewed material from traditional conferences on the interactions of leptons and photons and polarization phenomena in nuclear physics (Japan, 1985). The review reflected the results on the refinement of the properties of $W^\pm$ and Z^0 bosons, creation and decay of particles containing b and c quarks, discovery of a second excited state of the D meson with a mass of 2420 ± 6 MeV/c^2, and the search for supersymmetric particles, excited leptons, and new types of quarks in the assimilated energy range in the center of mass system of up to 900 GeV. Progress in experimental techniques and new types of chambers and devices for reading out information were discussed. It was pointed out that under the conditions of the large installations it becomes necessary to have an excess margin of reliability and excess information about events. Programs for building accelerators at the largest world centers for research in high-energy physics were presented.

The results of experiments at the Serpukhov accelerator, reported at the school, were obtained in antiproton beams on the RISK installation (Joint Institute of Nuclear Research) and the Mirabel bubble chamber (Institute of High-Energy Physics). L. A. Gabuniya presented a comparative analysis of the properties of events with backward emitted protons in interactions of antiprotons with a momentum of 40 GeV/c with nuclei. A discussion of the dependence of the characteristics of such events on the atomic number of the nucleus and the role of cascade processes elicited a lively debate. It was pointed out that at the energies studied antiproton annihilation should play an important role in collisions with nucleons and nuclei.

Models of multiple creation of particles on nuclei were discussed in a report by B. B. Levchenko.

L. N. Smirnova made a detailed analysis and review of the properties of $\bar{p}p$ annihilation compared with nonannihilative interactions based on results of an experiment with antiproton momentum of 32 GeV/c. As a result of an analysis of the characteristics of pairs of neutral strange particles in the same experiment using a strong quark-gluon model and the standard Lund model, N. A. Kruglov gave preference in his report to the first model.

É. P. Kistenev presented the first inclusive spectra of vector D* mesons and ratios of the yields of vector and pseudoscalar charmed mesons in $\pi\bar{p}$ and pp interactions with a momentum of 360 GeV/c.

M. V. Danilov presented in his report a number of recent results obtained by the ARGUS group. The discovery of the decay $D_0 \to \bar{K}^0 \varphi$ was the first experimental proof of the contribution of annihilation diagrams to the decay of charmed particles. Taking this contribution into account makes it possible to explain the difference between the lifetimes of charged and neutral D mesons. The discovery of the inclusive decay $B \to J/\psi + X$ gives new information about the applicability of the color selection rules. The high masses of the system X in this decay indicate the importance of the spectator mechanism in this reaction. Investigation of the properties of the new charmed meson D* (2420) showed that the spectroscopy of excited states of charmed particles gives another opportunity for checking the theory of strong interactions.

As always, in spite of the strenuous program of the school, sufficient time was allotted for questions and discussions, which is of special interest at a school encompassing such a wide spectrum of problems. The excellent organization of the schedule, which was provided by the organization committee headed by J. L. Chkareuli, and the friendly atmosphere encouraged active contacts among physicists and stimulated their further creative involvement.

Translated by M. E. Alferieff