Physics – Uspekhi **59** (8) 787 – 795 (2016)

70th ANNIVERSARY OF THE A I ALIKHANOV INSTITUTE FOR THEORETICAL AND EXPERIMENTAL PHYSICS

PACS numbers: **01.65.+g**, **11.10.–z**, **12.10.–g**

70 years of ITEP: some theoretical results

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DOI: 10.3367/UFNe.2015.12.037733

Contents

Abstract. Some outstanding results of the 70 years of theoretical research at the Alikhanov Institute for Theoretical and Experimental Physics (ITEP) are reviewed.

1. Introduction

At the time of its establishment in December 1945, Laboratory No. 3 (later renamed into the Alikhanov Institute for Theoretical and Experiment Physics) was assigned to specific tasks related to construction of nuclear reactors. Later, in the late 1950s and early 1960s, the institute was tasked with designing strong-focusing proton accelerators. ITEP theoretical physicists, while making important contributions to solving these problems, always combined applied research with fundamental studies. In this paper, we describe the fundamental results obtained by ITEP theorists

In December 1945, all the theoretical work of Laboratory No. 3 was put under the charge of Lev Davydovich Landau (1908–1968), and in 1946, Isaak Yakovlevich Pomeranchuk (1913–1966), his former student, became the head of the Theoretical Department. Until 1958, Landau collaborated with and was a regular seminar participant at ITEP. Together with Pomeranchuk, Vladimir Borisovich Berestetskii and Aleksei Dmitrievich Galanin were in the Theoretical Department staff at the establishment of ITEP.

In concluding this brief introduction, the ITEP 60th anniversary paper [1] reviewing the institute's theoretical work is worth referencing.

2. Quantum electrodynamics

In 1939–1946, Pomeranchuk developed the theory of radiation of relativistic electrons propagating in a magnetic field (magneto-bremsstrahlung, or synchrotron, radiation) [2, 3]. In application to cosmic rays, this radiation determines the upper energy bound on the electron and positron components of the primary cosmic rays on Earth's surface. The same radiation prevents the construction of very-high-energy e^+e^- colliders: circular e^+e^- colliders currently planned with a total energy of a few hundred GeV (a few TeV) are either linear (International Linear Collider, ILC, or Compact Linear Collider, CLIC) or combine a very large radius with a relatively low energy (Future ee Circular Collider, FCC-ee, with a ring circumference of 100 km). Currently, the use of electron accumulation rings as synchrotron radiation sources is a major factor contributing to the development of such fields as atomic and molecular physics and solid state physics, catalysis, materials science, and biophysics.

To find photon wave functions, Berestetskii developed a theory of spherical vectors in 1947 and used it to explain beta–gamma correlations in nuclear decay [4].

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Received 25 December 2015
Uspekhi Fizicheskikh Nauk **186** (8) 869 – 878 (2016)
DOI: 10.3367/UFNr.2015.12.037733
Translated by E G Strel'chenko; edited by A M Semikhatov

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In 1948, Pomeranchuk noted in [5] that two versions of positronium (e^+e^- atom) — orthopositronium, in which the electron and positron spins sum up to unity, and parapositronium, in which they sum up to zero — should differ greatly in their lifetimes (for the positronium ground state with zero orbital momentum). The reason is that the two-photon annihilation is forbidden for orthopositronium, and the only possible decay is to three photons, resulting in its lifetime being about a thousand times larger than that of its para counterpart. The fact that orthopositronium cannot decay into two photons is easily explained by the charge (C) parity conservation in electromagnetic interactions. The C parity of an e^+e^- pair is $(-1)^{l+s}$, where l is the orbital momentum of the pair and s is the total spin. Because $l = 0$ in the ground state, the para and ortho ground states are C-even and C-odd, respectively. The negative charge parity of the photon prevents the ortho ground state from decaying into two photons. A similar mechanism produces a long-lifetime J/ψ meson, which is a bound state of charmed $c\bar{c}$ quarks. As a spin-1 system, J/ψ cannot decay into two gluons; the decay occurs into three gluons, and its probability is suppressed by the third power of the strong interaction constant α_s. The same mechanism explains the small width of the Υ meson consisting of two bottom $b\bar{b}$ quarks (also of importance is the large mass of the c and b quarks; the 'constant' α_s decreases with increasing the characteristic energy, in this case the mass of the heavy quark).

Pomeranchuk's prediction of the two-photon decay being impossible for the orthopositronium enabled Landau to prove a general theorem in the same year 1948, according to which two photons cannot be in a state with the total momentum equal to unity [6]. In the literature, this statement is referred to as the Landau–Yang theorem: C N Yang came to the same conclusion [7] in 1950. This theorem played an important role in determining the quantum numbers of the 125 GeV mass H boson discovered in 2012 at the Large Hadron Collider (LHC); the detection of the two-photon decay of H showed that its spin cannot be unity (according to experimental data, the spin most likely is zero, as it should for the Higgs boson).

In 1949, Berestetskii and Landau [8] obtained a Hamiltonian describing the e^+e^- system through the order v^2/c^2. In Berestetskii's paper [9] of the same year, this Hamiltonian was used to determine the fine structure of the positronium levels; it was found, in particular, that the ground level of positronium lies above that of parapositronium by $\Delta = (4/3 + 1)\, m\alpha^4/4$ (the second term in parentheses corresponds to the annihilation diagram). The following feature of the Zeeman effect in positronium was also noted in [9]: the level shift linear in the magnetic field is absent, and ortho- and parapositronium mix in a magnetic field. The experimental study of the effect of a magnetic field on positronium decay made it possible to measure the ortho–para splitting [10] in the early 1950s. The theoretical accuracy in the calculation of Δ is currently at the level of corrections proportional to α^7 (which correspond to three-loop diagrams) and is consistent with experimental results of similar accuracy [11].

Berestetskii's 1951 paper [12] established a fundamental theorem concerning the opposite spatial parity of a fermion and an antifermion. This theorem is important not only in the study of positronium but also in determining the spatial parity of mesons, which are bound states of a quark–antiquark pair: the s-wave states with the total spin 0 and 1 (say, π and ρ mesons) are P-odd because $(-1)^{l+1} = -1$.

In 1952, Galanin and Pomeranchuk [13] considered the Lamb shift in muonic hydrogen, i.e., hydrogen in which the

electron is replaced by a muon. Due to its large mass, the muon is $m_\mu/m_e \approx 210$ times closer to the nucleus than the electron. As a result, a qualitative effect occurs, namely, unlike in usual hydrogen, the Lamb shift in a muonic atom is dominated by the variation of the Coulomb potential over small distances due to the increase in the fine structure constant α. Because this increase has a stronger effect on the s levels, the 2s level turns out to be bound more strongly than the 2p one, whereas in usual hydrogen the 2s level climbs above 2p due to the Lamb shift. Another reason for atomic level shifts is the finite charge radius of the proton r_p. The value of r_p extracted from the spectrum of muonic hydrogen by taking the Lamb shift into account differs considerably (by 5–8 standard deviations) from the values obtained from the spectrum of usual hydrogen and measured in ep scattering experiments. This contradiction gives rise to the current problem of the proton charge radius [14].

The cross section for the $e^+e^- \to \mu^+\mu^-$ annihilation calculated by Berestetskii and Pomeranchuk in 1954 is used to normalize the cross section measured in e^+e^- colliders [15].

In a 1956 paper by Sudakov [16], the so-called double logarithmic terms determining the asymptotic behavior of the QED vertex diagrams were separated, calculated for high energy and to an arbitrary order of the perturbation theory, and then summed. These terms occur because the photon, the interaction mediator in QED, is a spin-one particle. According to the Standard Model, the strong and weak interactions are also mediated by spin-one particles, namely, gluons and $W^\pm$ and Z bosons. Therefore, the Sudakov form factor plays an important role not only in QED but also in weak and strong interactions at high energies. To mention a relatively recent application of the quantum-electrodynamical Sudakov form factor, we note the result that the inclusion of virtual and real photons leads to the suppression of the inclusive cross section for the creation of Z bosons in the e^+e^- annihilation process by the factor

$$\exp\left(-\frac{2\alpha}{\pi}\ln\frac{M_Z^2}{m_e^2}\ln\frac{M_Z}{\Gamma_Z}\right) \approx 0.7\,,$$

where Γ_Z is the total width of Z. The small value of the constant α is compensated by the double logarithmic factor due to the large mass of the Z boson, $M_Z \approx 91$ GeV.

According to the solution of the Dirac equation for an electron in the field of a point-like nucleus with a charge Z, the ground-state energy of a hydrogen-like ion, $W = m_e[1-(\alpha Z)^2]^{1/2}$, vanishes for $Z = 137$ and becomes purely imaginary for larger Z. In their 1945 work, Pomeranchuk and Smorodinskii [17] noted that allowing for the finite nuclear size removes the root singularity in the Z dependence of energy. As Z increases, the energy becomes negative and at a certain charge (called critical in [17]) reaches the value $-m_e$. We note that, as Gershtein and Zel'dovich [18] pointed out, the creation of two e^+e^- pairs from a vacuum becomes energetically possible, such that the electrons occupy the atomic level with the energy $-m_e$ and the positrons escape to infinity (see [19]). In [20–22], Popov calculated the critical charge to improve Pomeranchuk and Smorodinskii's result, showed that the wave function of the strongly bound electron concentrates at a distance $\sim 1/m_e$ near the nucleus, and calculated the time it takes for the e^+e^- pair to be created from the vacuum. These and many other results are reviewed by Zel'dovich and Popov [23]. In further work, Popov et al. [24–27] solved the problem of pair creation in a collision of two heavy nuclei when the effective charge increases adiabatically and reaches the critical value. Because $Z_{cr} \approx 175$, collision of two uranium nuclei is usually discussed.

An external magnetic field decreases Z_{cr} because the electron orbit comes closer to the nucleus and thereby increases the electron binding energy. The effect becomes significant for $B \gtrsim B_0 \equiv m_e^2/e$. As shown in [28] by Oraevskii, Rez, and Semikoz of the Pushkov Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation (IZMIRAN), the uranium nucleus becomes critical for $B \approx 100B_0$, and for the nucleus with $Z = 40$, criticality occurs for $B = 3\times 10^4 B_0$. The picture changes qualitatively, however, if the polarization of the vacuum in an ultrahigh magnetic field $B > m_e^2/e^3$ is taken into account; this effect leads to the screening of the Coulomb potential (Usov and Shabad of the Lebedev Physics Institute, RAS) [29]. According to Vysotsky, Godunov, and Machet [30, 31], $Z < 60$ nuclei do not become critical for any B, whereas nuclei in the range $60 < Z < 210$ become critical at significantly higher magnetic fields than when neglecting the screening, and are critical in a finite range of B. At the same time, $Z > 210$ nuclei are critical at any magnetic field. The finite nuclear size is an important factor in determining the region of criticality.

A basis for the analytic description of the ionization of atoms, ions, and solids by laser radiation was provided by the work of Keldysh of the Lebedev Physics Institute [32]. Peremolov, Popov, and Terent'ev [33, 34] developed an imaginary-time method for constructing a theory of the multiphoton ionization of atoms by intense laser light. Popov et al. [35–37] widely used this method in the physics of intense laser fields, in particular when considering e^+e^- pair creation by laser radiation from a vacuum.

We note that Berestetskii's books *Quantum Electrodynamics* [38] (coauthored by Akhiezer) and *Relativistic Quantum Theory* [39] (coauthored by E M Lifshits and Pitaevskii and retitled *Quantum Electrodynamics* for later editions) remain among the best texts on the subject even today. The first edition of book [38] in 1953 prompted F Dyson (USA) to say: "this book is the first good monograph on quantum electrodynamics and it is likely to remain so for a long time."

3. Zero charge and asymptotic freedom

Landau and Pomeranchuk discovered in 1955 that vacuum polarization in quantum electrodynamics fully screens a finite point-like charge [40]. The idea of a disappearing charge was advanced independently by E S Fradkin of the Lebedev Physics Institute. According to the 1955–1956 studies of Pomeranchuk [41] and Pomeranchuk, Sudakov, and Ter-Martirosyan [42], the same behavior is obtained in Yukawa's theories. This phenomenon came to be known as zero charge or Moscow zero. The small value of the fine structure constant results in the zero charge problems starting to arise in QED at very high energies $\sim m_e \exp(1/\alpha)$ (or at very small distances $\sim \exp(-1/\alpha)/m_e$). However, in the case of strong interactions, the large value of the charge makes quantum field theory totally invalid. The discovery of the zero charge had the effect that over the following 15 years most efforts in the field were devoted to developing methods based on general principles such as the unitarity and analyticity of the scattering matrix, with little or no attention paid to Lagrangian field theory. Later, it turned out that, as with many other no-go theorems in physics, there is an exception to the zero-

charge picture: in non-Abelian gauge theories, a charge shows the opposite behavior in that it decreases with increasing energy (decreasing distance), a property known as the asymptotic freedom. As a result, the modern strong interaction theory based on the non-Abelian group SU(3) becomes self-consistent at small distances, where the constant α_s becomes small. It is at large distances, where the charge becomes of the order of unity and perturbative methods break down, that troubles arise. We then have to limit ourselves to a qualitative picture of quark and gluon confinement and use the numerical simulation of hadron properties.

The problem of a charge behaving inconsistently with the zero-charge picture was first encountered in 1965 by Vanyashin of Dnipropetrovsk University and Terent'ev in their 4D electromagnetic treatment [43][1] of massive charged vector bosons. Notably, the first coefficient of the Gell-Mann–Low QED function is predicted in [43] to be -7 due to the contribution from massive $W^{\pm}$ bosons. The amplitude of the two-photon Higgs boson decay observed experimentally in 2012 contains a factor of $-7 + 16/9$, of which the first term is the contribution from $W^{\pm}$ and the second from the t-quark loop. The authors of Ref. [43] attribute the nonrenormalizability of the theory with massive vector bosons to the anomalous charge behavior they discovered (the realization that the Higgs mechanism makes such a theory renormalizable came much later). In 1968, Khriplovich from the Budker Institute of Nuclear Physics (BINP), SB RAS, Novosibirsk, calculated the charge behavior in an SU(2)-based non-Abelian gauge theory with massless vector particles [45]. His result for the first coefficient of the Gell-Mann–Low function was $-22/3$, which becomes -7 if the contribution from the Goldstone mode is taken into account, which makes vector bosons massive (i.e., a charged Higgs boson): $-22/3 + 1/3 = -7$. At about the same time, experiments on deep inelastic scattering showed that if strong interactions are described by quantum field theory, the charge in this theory should decrease with increasing energy. In the early 1970s, the theory based on the non-Abelian group SU(3) and involving colored gluons and quarks (quantum chromodynamics, QCD) was already considered to be a strong interaction theory. In 1972, 't Hooft noted in his remark at a conference in Marseilles that according to his calculations in this theory, the charge decreases as the energy increases. A detailed discussion of these issues, including the analysis of the evolution of the proton structure function in QCD, was given by Politzer [46, 47] and Gross and Wilczek [48–50] in 1973. The Standard Model of elementary particle physics is based on the group $SU(3) \times SU(2) \times U(1)$ with gauge charges g_3, g_2, and g_1. The charges g_3 and g_2 show an asymptotically free behavior, while g_1 shows the zero-charge behavior. One of key principles in constructing theories at high energies is the absence of a Landau pole, which is the recently adopted name for the zero-charge phenomenon.

4. Anomalies

In some cases, a symmetry of a classical theory can be broken by loop corrections. The most widely known example is axial symmetry, which leads to the conservation of the axial current in quantum electrodynamics of massless electrons and which is broken if we introduce triangle diagrams describing the electron-loop-mediated transition of the axial current into two photons. An analysis in [51] of the divergence of a neutral isotriplet axial current yielded the width of the $\pi^0 \to 2\gamma$ decay. A similar analysis by Terent'ev [52] provided the amplitude of the $\gamma \to \pi^+\pi^-\pi^0$ transition in the limit of small pion momenta (see also Ref. [53]). In [54], Terent'ev proposed an experimental test of his result on the photoproduction of a neutral pion in the coherent scattering of a charged pion by a heavy nucleus, a proposal that was later implemented at the IHEP accelerator [55]. Similar processes involving K-mesons were investigated by Wess and Zumino [56] in the limit of a small s-quark mass; the description of these processes in terms of an effective Lagrangian is given by Witten [57]. IHEP is currently running an experiment searching for anomalies in the reaction $K^+\gamma \to K^+\pi^0$ [58]; formulas necessary for the analysis of experimental data were recently derived in Ref. [59].

The reason for the anomalies is the poor convergence of Feynman diagram integrals in the region of large integration momentum. However, as shown by Dolgov and Zakharov [60], the anomalous amplitudes have nonzero imaginary parts $\sim \delta(q^2)$, where q^2 is the momentum entering the axial current vertex. Given this infrared aspect of the anomaly, the presence of anomalous amplitudes allows drawing certain conclusions regarding the hadron spectrum, something which cannot be done with Lagrangian-based QCD because of the strong on-shell coupling. The singularities $\sim \delta(q^2)$ in diagrams with virtual massless u, d, and s quarks should be reproduced by diagrams with inner lines corresponding to hadron propagation. The only way to meet this requirement is to allow the presence in the hadron spectrum of scalar (pseudoscalar) states massless in the limit $m_{u,d,s} \to 0$. Such a state is provided by the octet of pseudogoldstone bosons $\pi^{\pm}$, π^0, $K^{\pm}$, K^0, $\bar{K}^0$, η. This consequence of the infrared aspect of anomalies is noted by Witten and Coleman [61].

5. Weak interactions

To solve the $\theta - \tau$ problem in the decay of charged kaons, Lee and Yang from the US proposed in 1956 that such decays violate P parity. To test this hypothesis in weak interactions, they assumed that the β decays of polarized nuclei can exhibit correlation of the form $\bar{s}\bar{p}$ between the momenta of produced electrons and nuclear spins. Because this correlation is T-even, its experimental observation would also imply, in view of the CPT theorem, the violation of C parity. This would in turn invalidate the well-established decay scenario of neutral K mesons, in which the C-even short-lived K_S decayed into two π mesons, whereas the C-odd K_L had a long lifetime due to its inability to decay into two π mesons. However, as noted by Ioffe, Okun', and Rudik in 1957 [62], the T-parity conservation implies the conservation of C times P, and this is sufficient to prevent $K_L \to 2\pi$ decays because two π mesons in an s wave form not only a C-even but also a CP-even state, whereas K_L is CP odd.

Thus, the observation of the $\bar{s}\bar{p}$ correlation is not inconsistent with the existence of a long-lived K_L, but rather indicates the violation of C parity in weak interactions. At the same time, Lee, Oehme, and Yang from the US pointed out in [63] that the spin–momentum correlation (which was soon discovered experimentally by C S Wu of the US) would indicate the violation of both spatial and charge parities.

[1] The fact that the charge does not vanish in a four-fermion theory in two-dimensional space-time was established by Ansel'm [44] from the Konstantinov Petersburg Nuclear Physics Institute, PNPI. (Here and throughout, we use the present-day names of institutes).

The violation of discrete symmetries in weak interactions prompted Landau's papers [64, 65]. In [64], which, Landau explains, arose from his discussions with Okun', Ioffe, and Rudik, it is argued that the assumption that the P inversion should be accompanied by particle–antiparticle reversal amounts to saying that the laws of nature are invariant under this transformation (which Landau calls combined parity). It is emphasized that this symmetry prevents elementary particles from having electric dipole moments. As we know today, combined parity, or CP parity, is not a fundamental law of nature: in 1964, a long-lived neutral K_L meson was observed to decay into two π mesons, thereby violating CP parity. This notwithstanding, the concept of CP symmetry has proven extremely fruitful, as has the search for its violation in the decay of K and B mesons. The dipole moments of elementary particles in the Standard Model are extremely small, and still remain the subject of huge search efforts (see below).

In Ref. [65] it is noted that the P-parity violation hypothetically imposes new properties on the massless neutrino. In the case of a massless fermion, the Dirac equation decomposes into two decoupled equations, which transform into each other under inversion (Weyl's equations). In the absence of P invariance, a single equation suffices to describe the neutrino; the neutrino is then always longitudinally polarized, whereas the antineutrino is polarized oppositely. Experimental data on the spectra of electrons from muon decay suggest the creation of a $\nu\bar{\nu}$ pair in this decay. The operators of the longitudinal neutrino and those of the antineutrino can only be combined into a four-dimensional vector, whereas for the muon and electron operators, there are two possible combinations: a vector and a pseudovector. The energy and angular distribution of outgoing electrons were found (with the angle referring to that between the electron and muon directions, where the latter direction specifies the polarization of the muon produced in the $\pi \to \mu\nu$ decay). We note that in constructing the Standard Model, all fermion wave functions are chosen to be Weyl spinors. The way in which originally massless fermions acquire masses is via the Higgs mechanism. A theory of a two-component neutrino was advanced simultaneously by Lee and Yang and Salam of Great Britain.

In 1957, Okun' and Pontecorvo from the Joint Institute for Nuclear Research (JINR) noted that the small difference between the K_1^0 and K_2^0 masses implies the absence of $\Delta S = 2$ transitions in the first order in the weak interaction [65]. In 1960, Okun' noted that the second-order contribution is determined by the value of the cutoff Λ, which should be of the order of 1 GeV [67]. That such a low cutoff would be ensured by the strong interactions proved to be a vain hope: Ioffe and Shabalin [68] showed in 1967 that strong interactions do not cut off processes of the second order in weak interactions. As understood today, this cutoff is provided by the relatively small c-quark mass, $m_c \approx 1.3$ GeV, and the corresponding mechanism was proposed in 1970 by Glashow, Iliopoulos, and Maiani (from the US, France, and Italy, respectively) even before the discovery of the c quark (the GIM mechanism).

Following the discovery of the b quark, in 1980, Vysotskii in [69] calculated the amplitude of the $K^0 - \bar{K}^0$ transition in a six-quark model without assuming a small t-quark/W-boson mass ratio (the functions describing this amplitude became known in the literature as Inami–Lim functions [70, 71]) and used the leading logarithmic approximation to obtain the gluon correction to it. The lack of heavy-particle decoupling in electroweak theory is vividly demonstrated by the presence in the $K^0 - \bar{K}^0$ transition amplitude of contributions that increase as m_t^2 for $m_t \gg M_W$. Precisely these contributions determine the CP violation in $K^0 - \bar{K}^0$ mixing within the Kobayashi–Maskawa six-quark model. The same contributions are responsible for the $B^0 - \bar{B}^0$ mixing. The first indication of the anomalously massive t quark came from DESY (Deutsches Electronen-SYnchrotron) in 1986, when an unexpectedly large $B^0 - \bar{B}^0$ mixing was discovered by the ARGUS collaboration with active participation of ITEP experimentalists.

In 1957–1958, Okun' [72] proposed a composite model in which all the then known hadrons (now a commonly accepted term introduced by Okun' in 1962) should be thought of as consisting of three protoparticles. That was a point of difference from Sakata's earlier model in which the hadrons were built from physical particles, namely, a proton, a neutron, and a lambda-hyperon. Based on this model, the existence of a nonet of pseudoscalar mesons was predicted, as were the properties of its two still lacking component particles, η and η' mesons. Selection rules for the semileptonic decays of strange particles were also obtained: $|\Delta S| = 1$, $\Delta Q = \Delta S$, and $\Delta T = 1/2$. In 1962, Kobzarev and Okun' [73] used the SU(3) symmetry of strong interactions to derive implications for leptonic meson decays. A thorough analysis of the leptonic decays of mesons and baryons was performed by Cabibbo from Italy in 1963. Okun' used the model as the basis for his well-known monograph "Weak Interactions of Elementary Particles" [74] (first edition 1963). The model was the immediate precursor of the quark model.

A presentation of the current gauge theory of electroweak interactions can be found in Okun's monograph "Leptons and quarks" [75].

Terent'ev's study [76] proves that there are no corrections to the weak vector current that are linear in the deviation from isotopic symmetry. This statement allows determining the Kobayashi–Maskawa matrix element V_{ud}, numerically by analyzing nuclear β decays due to the vector current. In the literature, this statement is known as the Ademolo–Gatto theorem, a similar statement about the violation of SU(3) symmetry, proved for a strangeness-changing vector field [77].

In 1974, Voloshin, Kobzarev, and Okun' [78] presented the first quantum-field-theory analysis of the false-vacuum problem, whose current importance derives from the fact that given the current values of t-quark and Higgs boson masses, the extrapolation of the Higgs potential of the Standard Model to the Planck values of the Higgs field suggests vacuum metastability in electroweak theory.

In 1978, Vainshtein (from INP), Zakharov, and Shifman [79] developed the leading-logarithmic approximation for the effective Hamiltonian for weak nonleptonic decays with a gluon exchange. A novel enhancement mechanism for $\Delta T = 1/2$ transitions due to the so-called penguin diagrams — gluon-emitting $s \to d$ transitions — was discovered. These results were later extended to the case of six quarks and have numerous applications.

Sikivie (USA), Susskind (USA), Voloshin, and Zakharov, in their study [79] of Technicolor models discovered that the Glashow–Weinberg–Salam model exhibits a global SU(2) symmetry, which remains unbroken by the Higgs field condensate — the so-called custodial symmetry, which is

responsible for the fact the W and Z bosons are close in mass. The importance of custodial symmetry becomes clear in the study of radiative corrections to electroweak theory: the violation of this symmetry by the large t-quark mass made it possible to extract this mass to within ± 30 GeV from precision data on the parameters of W and Z bosons, which facilitated the 1995 discovery of the t quark at the Fermilab Tevatron in the USA.

In 1978, Shabalin [81] considered the neutron dipole moment in the Kobayashi–Maskawa six-quark CP-violation model and showed that its literature estimate was wrong at the time: the total effect of the two-loop diagrams is zero (single-loop result for the dipole moment of the neutron d_n is obviously zero). A nonzero dipole moment arises at the three-loop level and, as calculated by INP's Khriplovich, is many orders of magnitude less than the current experimental constraint [82]. The discovery of a nonzero d_n would provide a strong case for new physics beyond the Standard Model and is therefore currently a highly pursued goal.

In their 1980 paper [83], Kobzarev, Okun', Martem'yanov, and Shchepkin parameterized the neutrino mixing matrix in the most general case with both the Dirac and Majorana mass terms present.

The paper by Vysotskii [84] is one of the first reviews in the world literature on the subject of low-energy supersymmetry.

Voloshin, Vysotskii, and Okun' [85, 86] proposed that the anticorrelation between the solar neutrino flux and solar activity, then a subject of discussion in the literature, can be interpreted as a manifestation of the neutrino magnetic moment, a proposal that stimulated a series of experiments in Russia and elsewhere aimed at searching for the neutrino magnetic moment.

In 1978, it was proposed by Ioffe and Khose from PNPI [87] that the Higgs boson be searched for in the reaction $e^+e^- \to ZH$, which indeed was done at the Large Electron–Positron collider (LEP) at CERN. The search came to nothing, however, yielding the constraint $m_H > 114$ GeV for the Higgs boson mass.

The Z parameter measurements at e^+e^- colliders LEP I (CERN) and SLC (Stanford Linear Collider, SLAC National Accelerator Laboratory) and the W mass measurements at the e^+e^- collider LEP II and the Tevatron were performed with sufficient precision to test electroweak theory, including radiative corrections. The renormalizability of electroweak theory makes these corrections amenable to calculation. Vysotskii, Novikov, Okun', and Rozanov [88–90] obtained the corresponding formulas expressing the experimentally measured parameters in terms of the most precisely measured values of the Fermi constant G_F, the Z-boson mass M_Z, and fine structure constant at the Z-boson mass scale. Originally (1991–1995), these results were used to predict the t-quark mass. After the t-quark was discovered and its mass measured at the Tevatron, the prediction $M_H = 80^{+30}_{-20}$ GeV was obtained for the Higgs boson mass from the Standard Model, later to be confirmed by the LHC 2012 result of $M_H = 125 \pm 1$ GeV.

6. Strong interactions

The scientific glory of ITEP's Theoretical Department is primarily due to the fundamental results obtained by Pomeranchuk in the field of strong interactions. In his 1958 paper [91], Pomeranchuk used dispersion relations to prove that particles and antiparticles have asymptotically equal fixed-target cross sections (Pomeranchuk's theorem). In [92–94], Pomeranchuk and Gribov from PNPI used the quantum-mechanical theory of Regge poles to formulate a consistent theory of processes at asymptotically high energies. In honor of Pomeranchuk, the name 'pomeron' was given abroad to the Regge pole that has vacuum quantum numbers and is responsible for satisfying the Pomeranchuk theorem. Further development of reggistics was pursued by K A Ter-Martirosyan and A B Kaidalov.

Following the creation of QCD and the discovery of the asymptotic freedom in strong interactions, a number of fundamental results, later to become classic, emerged from the efforts of the ITEP Theoretical Department. In particular, a simple quark model for deep-inelastic processes was proposed [95], capable of matching the composite nucleon model with the distribution of quarks and gluons at large momentum transfers, an idea that was later developed by European theoretical physicists.

Also of note is the realization in [96] that the c-quark mass is large on the Λ_{QCD} scale and that strong interactions can be accounted for in heavy-quark processes by expanding in the small parameters $\alpha_s(m_c)$. In this way, significant corrections to the mass difference $K_L - K_S$ and to photo- and electro-creation of charmed particles were calculated.

Following the discovery of the J/ψ meson, the dispersion theory of charmonium was developed in the work of Vainshtein, Voloshin, Zakharov, Novikov, Okun', and Shifman, and famous review papers [97, 98] were written, which are now textbooks for anyone involved in the physics of heavy quarks. Further development of these ideas by Vainshtein, Zakharov, and Shifman [99] led to the famous QCD sum rules that allowed calculating the properties of hadrons composed of light u-, d-, and s-quarks in terms of vacuum condensates. This approach found various applications in the work of Belyaev, Ioffe, Kogan, Eletskii, and Smilga [100–103].

In their 1977 paper [104], Voloshin and Okun' discussed whether quark 'molecules' — bound quark states containing heavy quarks — can exist. In recent years, such states have been discovered in systems of c and b quarks and are being actively discussed in the literature. Voloshin is developing the 'molecular' approach, and there are other approaches to the problem (ITEP researchers on the physics of exotic hadrons include Badalin, Kalashnikov, Kudryavtsev, Nefed'ev, and Simonov [105, 106]).

7. Exact results in quantum field theory

Among the achievements of ITEP theoretical physicists are a number of exact quantum-field-theory results. One example is the discovery by Bogomol'nyi [107] of a new class of solutions of classical equations in gauge field theory with a scalar condensate. These are the so-called Bogomol'nyi–Prasad–Sommerfeld (BPS) monopoles, which play an extremely important role in $N = 2$ and $N = 4$ supersymmetric theories. We also note the derivation of many exact correlation relations and the prediction that the mass scale in strong interactions of glueballs and hybrid states can be several times larger than Λ_{QCD}.

In [109], a supersymmetric formalism for describing superinstantons was developed and a theorem about the absence of corrections to the instanton amplitudes was proved. As a result, the supersymmetric QCD gluon condensate and the so-called Novikov–Shifman–Vainshtein–Zakharov β-functions were exactly calculated. As shown

later by a Princeton group, superinstantons can lead to the dynamic violation of supersymmetry.

8. Gravitation and cosmology

In their 1961 paper [110], Sudakov, Lifshits (IPP), and Khalatnikov (IPP) discussed the singularity arising in cosmological models based on general relativity (GR).

In 1970, Zakharov [111] showed that allowing an arbitrarily small graviton mass is inconsistent with the observational consequences of GR (the so-called Veltman–van Dam–Zakharov singularity). Vainshtein [112] proposed a mechanism to construct a gravity theory that has a continuum limit as the graviton mass tends to zero, a proposal which received some discussion in the literature.

In 1965, Zel'dovich, Okun', and Pikel'ner [113] calculated the cosmological concentration of relic quarks by assuming that they can exist in free form and obtained a result that was inconsistent with the existing constraints on the abundance of quarks in the Universe and thus uniquely favored the confinement of quarks. The kinetic equation that was used in Ref. [113] to calculate the cosmological number density of heavy particles was rediscovered by B Lee and S Weinberg, in 1977, and is currently known by their names.

Kobzarev, Okun', and Pomeranchuk [114, 115] proposed and discussed the idea of mirror matter. This was a pioneering theoretical study about the possible existence of dark matter in the Universe. Later, ideas of mirror dark matter were developed at ITEP by Blinnikov (see Ref. [116] for a review).

The work by Zel'dovich, Kobzarev, and Okun' [117, 118] revealed that the spontaneous CP violation model contradicts the observed data on the isotropy of the Universe, because the huge energy of the wall between the matter and antimatter domains would destroy the isotropy of the microwave background. This work initiated research on the 'dissolution' mechanism of domain walls. Possible solutions to this problem are discussed in the recent literature [119].

The cosmological number density of weakly interacting relic particles was calculated by Vysotskii, Dolgov, and Zel'dovich [120] in 1977; essentially simultaneously, B Lee and Weinberg from the US, Hut from the Netherlands, and K Sato and M Kobayashi from Japan carried out similar studies. The results of this work provided the basis for calculating the density of massive dark matter particles, in particular, neutralinos.

A substantial body of original results was presented in the famous 1980 review "Cosmology and Elementary Particles" by Dolgov and Zel'dovich [121]. The review to a large extent initiated the development of the field; in particular, its title was given as the name to one of the sections of Rochester conferences. The current state of the field is outlined in [122].

The study of the cosmological impacts of the neutrino received major contributions from Dolgov's group. A kinetic equation for the density matrix of oscillating neutrinos was derived [123], which is currently the primary tool for investigating neutrino oscillation effects in the early Universe and in supernovae. Barbieri and Dolgov [124, 125] used the solution of this equation in their pioneering derivation of constraints on the neutrino oscillation parameters from the observed abundances of light elements. This result was later extended [126] to the case where all active neutrinos are mixed. Also, in the work cited above ([124, 125]; also see [127]), a method for calculating the cosmological concentration of sterile neutrinos was developed, which underlies the calculation of the density of warm dark matter if it consists of sterile neutrinos. The method has come to be known as the Dodtlson–Widrow method after the two authors who entered the field later. The observation of a new neutrino heating effect due to the late annihilation of hotter electron–positron pairs was reported in [128–131]. It is now commonly accepted due to this work that the canonical effective number of neutrino types in cosmology is not three, as one could naively expect, but 3.046. Dolgov et al. [132] obtained the strongest possible constraint on the chemical potential of the cosmological neutrino; contrary to what was previously believed, this constraint rules out the influence of neutrino degeneration on the structure of the Universe and the CMB.

Dolgov and coauthors performed pioneering calculations on the heating of the Universe both perturbatively [133] and nonperturbatively [134].

Blinnikov et al. [135] proposed a new method for directly determining the Hubble constant. The method is based on the observation of type-IIn supernovae and is free of nonuniquenesses typical of the classical approach to constructing the spatial distance grid. For a number of known supernovae, the distances obtained with the new method agree remarkably well with those known from reliable conventional methods.

Dolgov's group explored the so-called modified $F(R)$ gravity as a hypothetical mechanism for the accelerating expansion of the Universe. It was found in [136] that a large class of modified theories exhibit a strong instability effect (which has become known in the literature as the Dolgov–Kawasaki instability) and must be modified in order to eliminate the instability. Further analysis of these functions has led to the discovery of a range of new phenomena, including low-frequency oscillations of the curvature scalar R [137, 138], antigravitation (gravitational repulsion) in finite systems [139], and new gravitational instability effects different from the well-known Jeans instability [140]. It is by verifying these predictions that a particular model can be uniquely confirmed or refuted or can be given constraints on its parameters.

9. Kinetics and thermodynamics

After the discovery of CP violation in the K meson decay in 1964, it became clear for all practical purposes that, due to the CPT theorem, the T invariance — i.e., invariance under time reversal — is also violated. But then the question arises as to the validity of the canonical equilibrium distributions in quantum statistics that were derived in a standard way from the detailed balance condition (which follows from the T invariance). Dolgov [141] argues in this connection that "equilibrium kinetics is stronger than the T violation." The unitarity of the S-matrix ensures the validity of standard equilibrium distributions, despite the violation of the detailed balance condition. Equilibrium between the direct and reverse reactions is achieved via several reaction chains. For this reason, the occurrence of T violations has the effect of replacing the detailed balance by what the work cited above refers to as 'cyclic' balance.

Acknowledgements

M I V and V A N are supported by the Russian Foundation for Basic Research (14-02-00995, 16-02-00342), and A D D is supported by the Government of the Russian Federation grant 11.G34.31.0047.

References

1. Okun L B *Phys. Atom. Nucl.* **69** 1759 (2006); *Yad. Fiz.* **69** 1796 (2006)
2. Pomeranchuk I Ya *Sobranie Nauchnykh Trudov* (Collection of Scientific Works) Vol. 1–3 (Moscow: Nauka, 1972)
3. Pomeranchuk I Ya *Izv. Akad. Nauk SSSR Ser. Fiz.* **10** 316 (1946)
4. Berestetskii V *Zh. Eksp. Teor. Fiz.* **17** 12 (1947)
5. Pomeranchuk I *Dok. Akad. Nauk SSSR* **60** 213 (1948)
6. Landau L, in *Collected Papers of L D Landau* (Ed. D ter Haar) (Oxford: Pergamon Press, 1965) p. 471; Translated from Russian: *Dokl. Akad. Nauk SSSR* **60** 207 (1948)
7. Yang C N *Phys. Rev.* **77** 242 (1950)
8. Berestetskii V, Landau L *Guide Russ. Sci. Period Lit. Brookhaven* **4** 33 (1951); *Zh. Eksp. Teor. Fiz.* **19** 673 (1949)
9. Berestetskii V *Zh. Eksp. Teor. Fiz.* **19** 1130 (1949)
10. Deutsch M, Dulit E *Phys. Rev.* **84** 601 (1951)
11. Baker M et al. *Phys. Rev. Lett.* **112** 120407 (2014)
12. Berestetskii V *Zh. Eksp. Teor. Fiz.* **21** 43 (1951)
13. Galanin A D, Pomeranchuk I *Dokl. Akad. Nauk SSSR* **86** 251 (1952)
14. Carlson C E *Prog. Part. Nucl. Phys.* **82** 59 (2015); arxiv:1502.05314
15. Berestetskii V B, Pomeranchuk I Ya *Sov. Phys. JETP* **2** 580 (1956); *Zh. Eksp. Teor. Fiz.* **29** 864 (1955)
16. Sudakov V V *Sov. Phys. JETP* **3** 65 (1956); *Zh. Eksp. Teor. Fiz.* **30** 87 (1956)
17. Pomeranchuk I, Smorodinsky Ya *J. Phys. USSR* **9** 97 (1945)
18. Gershtein S S, Zel'dovich Ya B *Sov. Phys. JETP* **30** 358 (1970); *Zh. Eksp. Teor. Fiz.* **57** 654 (1969)
19. Voronkov V V, Kolesnikov N N *Sov. Phys. JETP* **12** 136 (1961); *Zh. Eksp. Teor. Fiz.* **39** 189 (1960)
20. Popov V S *Sov. J. Nucl. Phys.* **12** 235 (1971); *Yad. Fiz.* **12** 429 (1970)
21. Popov V S *JETP Lett.* **11** 162 (1970); *Pis'ma Zh. Eksp. Teor. Fiz.* **11** 254 (1970)
22. Popov V S *Sov. Phys. JETP* **32** 526 (1971); *Zh. Eksp. Teor. Fiz.* **59** 965 (1970)
23. Zel'dovich Ya B, Popov V S *Sov. Phys. Usp.* **14** 673 (1972); *Usp. Fiz. Nauk* **105** 403 (1971)
24. Popov V S *Phys. Atom. Nucl.* **64** 367 (2001); *Yad. Fiz.* **64** 421 (2001)
25. Marinov M S, Popov V S, Stolin V L *JETP Lett.* **19** 49 (1974); *Pis'ma Zh. Eksp. Teor. Fiz.* **19** 76 (1974)
26. Lisin V I, Marinov M S, Popov V S *Phys. Lett. B* **69** 141 (1977)
27. Lisin V I, Marinov M S, Popov V S *Phys. Lett. B* **91** 20 (1980)
28. Oraevskii V N, Rex A I, Semikoz V B *Sov. Phys. JETP* **45** 428 (1977); *Zh. Eksp. Teor. Fiz.* **72** 820 (1977)
29. Shabad A E, Usov V V *Phys. Rev. D* **77** 025001 (2008)
30. Godunov S I, Machet B, Vysotsky M I *Phys. Rev. D* **85** 044058 (2012)
31. Godunov S I, Vysotsky M I *Phys. Rev. D* **87** 124035 (2013)
32. Keldysh L V *Sov. Phys. JETP* **20** 1307 (1965); *Zh. Eksp. Teor. Fiz.* **47** 1945 (1964)
33. Perelomov A M, Popov V S, Terent'ev M V *Sov. Phys. JETP* **23** 924 (1966); *Zh. Eksp. Teor. Fiz.* **50** 1393 (1966)
34. Perelomov A M, Popov V S, Terent'ev M V *Sov. Phys. JETP* **24** 207 (1967); *Zh. Eksp. Teor. Fiz.* **51** 309 (1966)
35. Popov V S *Phys. Usp.* **47** 855 (2004); *Usp. Fiz. Nauk* **174** 921 (2004)
36. Karnakov B M, Mur V D, Popruzhenko S V, Popov V S *Phys. Usp.* **58** 3 (2015); *Usp. Fiz. Nauk* **185** 3 (2015)
37. Popov V S, Mur V D, Narozhnyi N B, Popruzhenko S V *JETP* **122** 539 (2016); *Zh. Eksp. Teor. Fiz.* **149** 623 (2016)
38. Akhiezer A I, Berestetskii V B *Quantum Electrodynamics* (New York: Interscience Publ., 1965); Translated from 2nd Russian ed.: *Kvantovaya Elektrodinamika* (Quantum Electrodynamics) (Moscow: Gostekhizrat, 1953); *Kvantovaya Elektrodinamika* (Quantum Electrodynamics) 2nd ed. (Moscow: Fizmatgiz, 1959); *Kvantovaya Elektrodinamika* (Quantum Electrodynamics) 3rd ed. (Moscow: Nauka, 1969); *Kvantovaya Elektrodinamika* (Quantum Electrodynamics) 4th ed. (Moscow: Nauka, 1981)
39. Berestetskii V B, Lifshitz E M, Pitaevskii L P *Relativistic Quantum Theory* Vol. 1 (Oxford: Pergamon Press, 1971); Translated from Russian: *Relyativistskaya Kvantovaya Teoriya* Vol. 1 (Moscow: Nauka, 1968); *Quantum Electrodynamics* (Oxford: Butterworth-Heinemann, 1999); Translated from Russian: *Kvantovaya Elektrodinamika* (Moscow: Fizmatlit, 2001)
40. Landau L D, Pomeranchuk I Ya *Dokl. Akad. Nauk SSSR* **102** 489 (1955)
41. Pomeranchuk I Ya *Dokl. Akad. Nauk SSSR* **105** 461 (1955)
42. Pomeranchuk I Ya, Sudakov V V, Ter-Martirosyan K A *Phys. Rev.* **103** 784 (1956)
43. Vanyashin V S, Terent'ev M V *Sov. Phys. JETP* **21** 375 (1965); *Zh. Eksp. Teor. Fiz.* **48** 565 (1965)
44. Ansel'm A A *Sov. Phys. JETP* **9** 608 (1959); *Zh. Eksp. Teor. Fiz.* **36** 863 (1959)
45. Khriplovich I B *Sov. J. Nucl. Phys.* **10** 235 (1970); *Yad. Fiz.* **10** 409 (1969)
46. Politzer H D *Phys. Rev. Lett.* **30** 1346 (1973)
47. Politzer H D *Phys. Rep.* **14** 129 (1974)
48. Gross G J, Wilczek F *Phys. Rev. Lett.* **30** 1343 (1973)
49. Gross D J, Wilczek F *Phys. Rev. D* **8** 3633 (1973)
50. Gross D J, Wilczek F *Phys. Rev. D* **9** 980 (1974)
51. Adler S L *Phys. Rev.* **177** 2426 (1969)
52. Terent'ev M V *JETP Lett.* **14** 94 (1971); *Pis'ma Zh. Eksp. Teor. Fiz.* **14** 140 (1971)
53. Terent'ev M V *Sov. Phys. Usp.* **17** 20 (1974); *Usp. Fiz. Nauk* **112** 37 (1974)
54. Terent'ev M V *Phys. Lett. B* **38** 419 (1972)
55. Antipov Yu M et al. *Phys. Rev. D* **36** 21 (1987)
56. Wess J, Zumino B *Phys. Lett. B* **37** 95 (1971)
57. Witten E *Nucl. Phys. B* **223** 422 (1983)
58. Burtovoy V S *Phys. Atom. Nucl.* **78** 1470 (2015); Translated from Russian: *Yad. Fiz. Inzhiniring* **5** 724 (2014)
59. Vysotsky M I, Zhemchugov E V *Phys. Rev. D* **93** 094029 (2016)
60. Dolgov A D, Zakharov V I *Sov. J. Nucl. Phys.* **13** 345 (1971); *Yad. Fiz.* **13** 608 (1971)
61. Coleman S, Witten E *Phys. Rev. Lett.* **45** 100 (1980)
62. Ioffe B L, Okun' L B, Rudik A P *Sov. Phys. JETP* **5** 328 (1957); *Zh. Eksp. Teor. Fiz.* **32** 396 (1957)
63. Lee T D, Oehme R, Yang C N *Phys. Rev.* **106** 340 (1957)
64. Landau L D *Sov. Phys. JETP* **5** 336 (1957); *Zh. Eksp. Teor. Fiz.* **32** 405 (1957)
65. Landau L D *Sov. Phys. JETP* **5** 337 (1957); *Zh. Eksp. Teor. Fiz.* **32** 407 (1957)
66. Okun' L B, Pontecorvo B M *Sov. Phys. JETP* **5** 1297 (1957); *Zh. Eksp. Teor. Fiz.* **32** 1587 (1957)
67. Okun L B, in *Proc. of the 1960 Annual Intern. Conf. on High Energy Physics at Rochester* (Eds E C G Sudarshan, J H Tinlot, A C Melissinos) (Rochester, N.Y.: Univ. of Rochester, 1960) p. 743
68. Ioffe B L, Shabalin E P *Sov. J. Nucl. Phys.* **6** 603 (1968); *Yad. Fiz.* **6** 828 (1967)
69. Vysotskii M I *Sov. J. Nucl. Phys.* **31** 797 (1980); *Yad. Fiz.* **31** 1535 (1980)
70. Inami T, Lim C S *Prog. Theor. Phys.* **65** 297 (1981)
71. Inami T, Lim C S *Prog. Theor. Phys.* **65** 1772 (1981)
72. Okun' L B *Sov. Phys. JETP* **7** 322 (1958); *Zh. Eksp. Teor. Fiz.* **34** 469 (1958)
73. Kobzarev I Yu, Okun' L B *Sov. Phys. JETP* **15** 970 (1962); *Zh. Eksp. Teor. Fiz.* **42** 1400 (1962)
74. Okun' L B *Weak Interactions of Elementary Particles* (Jerusalem: Israel Program for Scientific Translations, 1965); Translated from Russian: *Slaboe Vzaimodeistvie Elementarnykh Chastits* (Moscow: GIFML, 1963)
75. Okun L B *Leptons and Quarks* (Amsterdam: North-Holland, 1982); *Leptons and Quarks* 2nd ed. (Amsterdam: North-Holland, 1984); Translared from Russian: *Leptony i Kvarki* (Moscow: Nauka, 1981); *Leptony i Kvarki* 2nd ed. (Leptons and Quarks) (Moscow: Nauka, 1990)
76. Terent'ev M V *Sov. Phys. JETP* **17** 890 (1963); *Zh. Eksp. Teor. Fiz.* **44** 1320 (1963)
77. Ademollo M, Gatto R *Phys. Rev. Lett.* **13** 264 (1964)
78. Voloshin M B, Kobzarev I Yu, Okun L B *Sov. J. Nucl. Phys.* **20** 644 (1975); *Yad. Fiz.* **20** 1229 (1974)
79. Vainshtein A I, Zakharov V I, Shifman M A *Sov. Phys. JETP* **45** 670 (1977); *Zh. Eksp. Teor. Fiz.* **72** 1275 (1977)
80. Sikivie P, Susskind L, Voloshin M, Zakharov V *Nucl. Phys. B* **173** 189 (1980)
81. Shabalin E P *Sov. J. Nucl. Phys.* **28** 75 (1978); *Yad. Fiz.* **28** 151 (1978)
82. Khriplovich I B *Phys. Lett. B* **173** 193 (1986)

83. Kobzarev I Yu, Martem'yanov B V, Okun' L B, Shchepkin M G *Sov. J. Nucl. Phys.* **32** 823 (1980); *Yad. Fiz.* **32** 1590 (1980)
84. Vysotskii M I *Sov. Phys. Usp.* **28** 667 (1985); *Usp. Fiz. Nauk* **146**591 (1985)
85. Voloshin M B, Vysotskii M I *Sov. J. Nucl. Phys.* **44** 544 (1986); *Yad. Fiz.* **44** 845 (1986)
86. Voloshin M B, Vysotskii M I, Okun' L B *Sov. Phys. JETP* **64** 446 (1986); *Zh. Eksp. Teor. Fiz.* **91** 754 (1986)
87. Ioffe B L, Khoze V A *Sov. J. Part. Nucl.* **9** 50 (1978); *Fiz. Elem. Chasits At. Yadra* **9** 118 (1978)
88. Novikov V A, Okun L B, Vysotsky M I *Nucl. Phys. B* **397** 35 (1993)
89. Vysotskii M I, Novikov V A, Okun L B, Rozanov A N *Phys. Usp.* **39** 503 (1996); *Usp. Fiz. Nauk* **166** 539 (1996)
90. Novikov V A, Okun L B, Rozanov A N, Vysotsky M I *Rep. Prog. Phys.* **62** 1275 (1999)
91. Pomeranchuk I Ia *Sov. Phys. Usp.* **7** 499 (1958); *Zh. Eksp. Teor. Fiz.* **34**725 (1958)
92. Gribov V N, Pomeranchuk I Ya *Phys. Rev. Lett.* **8** 343 (1962)
93. Gribov V N, Pomeranchuk I Ya *Sov. Phys. JETP* **15** 788 (1962); *Zh. Eksp. Tepr. Fiz.* **42** 1141 (1962)
94. Gribov V N, Pomeranchuk I Ya *Sov. Phys. JETP* **16** 1387 (1963); *Zh. Eksp. Teor. Fiz.* **43** 1970 (1963)
95. Novikov V A, Shifman M A, Vainshtein A I, Zakharov V I *Ann. Physics* **105** 276 (1977)
96. Novikov V A, Shifman M A, Vainshtein A I, Zakharov V I *Phys. Rev. D* **16** 223 (1977)
97. Vainshtein A I, Voloshin M B, Zakharov V I, Novikov V A, Okun' L B, Shifman M A *Sov. Phys. Usp.* **20** 796 (1977); *Usp. Fiz. Nauk* **123** 217 (1977)
98. Novikov V A, Okun L B, Shifman M A, Vainshtein A I, Voloshin M B, Zakharov V I *Phys. Rep.* **41** 1 (1978)
99. Shifman M A, Vainshtein A I, Zakharov V I *Nucl. Phys. B* **147** 385 (1979); *Nucl. Phys. B* **147** 448 (1979); *Nucl. Phys. B* **147** 519 (1979)
100. Ioffe B L *Nucl. Phys. B* **188** 317 (1981)
101. Belyaev V M, Ioffe B L *Sov. Phys. JETP* **56** 493 (1982); *Zh. Eksp. Teor. Fiz.* **83** 969 (1982)
102. Eletsky V L, Kogan Ya I *Z. Phys. C* **28** 155 (1984)
103. Ioffe B L, Smilga A V *Nucl. Phys. B* **232** 109 (1984)
104. Voloshin M B, Okun' L B *JETP Lett.* **23** 333 (1976); *Pis'ma Zh. Eksp. Teor. Fiz.* **23** 369 (1976)
105. Hanhart C, Kalashnikova Yu S, Kudryavtsev A E, Nefediev A V *Phys. Rev. D* **85** 011501(R) (2012)
106. Badalian A M, Simonov Yu A, Bakker B L G *Phys. Rev. D* **91** 056001 (2015)
107. Bogomol'nyi E B *Sov. J. Nucl. Phys.* **24** 449 (1976); *Yad. Fiz.* **24** 861 (1976)
108. Novikov V A, Shifman M A, Vainshtein A I, Zakharov V I *Nucl. Phys. B* **191** 301 (1981)
109. Novikov V A, Shifman M A, Vainshtein A I, Zakharov V I *Nucl. Phys. B* **223** 445 (1983)
110. Lifshitz E M, Sudakov V V, Khalatnikov I M *Sov. Phys. JETP* **13** 1298 (1961); *Zh. Eksp. Teor. Fiz.* **40** 1847 (1961)
111. Zakharov V I *JETP Lett.* **12** 312 (1970); *Pis'ma Zh. Eksp. Teor. Fiz.* **12** 447 (1970)
112. Vainshtein A I *Phys. Lett. B* **39** 393 (1972)
113. Zel'dovich Ya B, Okun L B, Pikel'ner S B *Sov. Phys. Usp.* **8** 702 (1966); *Usp. Fiz. Nauk* **87** 113 (1965)
114. Kobzarev I Yu, Okun L B, Pomeranchuk I Ya *Sov. J. Nucl. Phys.* **3** 837 (1966); *Yad. Fiz.* **3** 1154 (1966)
115. Okun L B *Phys. Usp.* **50** 380 (2007); *Usp. Fiz. Nauk* **177** 397 (2007)
116. Blinnikov S I *Phys. Usp.* **57** 183 (2014); *Usp. Fiz. Nauk* **184** 194 (2014)
117. Zel'dovich Ya B, Kobzarev I Yu, Okun' L B *Sov. Phys. JETP* **40** 1 (1975); *Zh. Eksp. Teor. Fiz.* **67** 3 (1974)
118. Kobsarev I Yu, Okun L B, Zeldovich Ya B *Phys. Lett. B* **50** 340 (1974)
119. Dolgov A D, Godunov S I, Rudenko A S, Tkachev I I *JCAP* (10) 027 (2015)
120. Vysotskii M I, Dolgov A D, Zel'dovich A D *JETP Lett.* **26** 188 (1977); *Pis'ma Zh. Eksp. Teor. Fiz.* **26** 200 (1977)
121. Dolgov A D, Zeldovich Ya B *Rev. Mod. Phys.* **53** 1 (1981); *Usp. Fiz. Nauk* **130** 559 (1980)
122. Dolgov A D *Phys. Usp.* **57** 199 (2014); *Usp. Fiz. Nauk* **184** 211 (2014)
123. Dolgov A D *Sov. J. Nucl. Phys.* **33** 700 (1981); *Yad. Fiz.* **33** 1309 (1981)
124. Barbieri R, Dolgov A *Phys. Lett. B* **237** 440 (1990)
125. Barbieri R, Dolgov A *Nucl. Phys. B* **349** 743 (1991)
126. Dolgov A D, Villante F L *Nucl. Phys. B* **679** 261 (2004)
127. Dolgov A D *Phys. Rep.* **370** 333 (2002)
128. Dolgov A D, Fukugita M *JETP Lett.* **56** 123 (1992); *Pis'ma Zh. Eksp. Teor. Fiz.* **56** 129 (1992)
129. Dolgov A D, Fukugita M *Phys. Rev. D* **46** 5378 (1992)
130. Dolgov A D, Hansen S H, Semikoz D V *Nucl. Phys. B* **503** 426 (1997)
131. Dolgov A D, Hansen S H, Semikoz D V *Nucl. Phys. B* **543** 269 (1999)
132. Dolgov A D et al. *Nucl. Phys. B* **632** 363 (2002)
133. Dolgov A D, Linde A D *Phys. Lett. B* **116** 329 (1982)
134. Dolgov A D, Kirilova D P *Sov. J. Nucl. Phys.* **51** 172 (1990); *Yad. Fiz.* **51** 273 (1990)
135. Baklanov P V, Blinnikov S I, Potashov M Sh, Dolgov A D *JETP Lett.* **98** 432 (2013); *Pis'ma Zh. Eksp. Teor. Fiz.* **98** 489 (2013)
136. Dolgov A D, Kawasaki M *Phys. Lett. B* **573** 1 (2003)
137. Arbuzova E V, Dolgov A D *Phys. Lett. B* **700** 289 (2011)
138. Arbuzova E V, Dolgov A D, Reverberi L *Eur. Phys. J. C* **72** 2247 (2012)
139. Arbuzova E V, Dolgov A D, Reverberi L *Astropart. Phys.* **54** 44 (2014)
140. Arbuzova E V, Dolgov A D, Reverberi L *Phys. Lett. B* **739** 279 (2014)
141. Dolgov A D *JETP Lett.* **29** 228 (1979); *Pis'ma Zh. Eksp. Teor. Fiz.* **29** 254 (1979)