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V. V. Voronov

REPORT OF ACTIVITY 2003–2009

BOGOLIUBOV LABORATORY OF THEORETICAL PHYSICS

Report to the 107th Session
of the JINR Scientific Council
February 18–19, 2010

Dubna 2010

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The Bogoliubov Laboratory of Theoretical Physics carried out research in several fundamental areas of theoretical physics: quantum field theory and elementary particle physics, theory of atomic nuclei, condensed matter physics and methods of mathematical physics. Theoretical studies were closely connected with the physics programs of major international projects at CERN, GSI, JLab, etc, as well as by Dubna based experimental programs of JINR laboratories.

Inherent features of research at BLTP are the interdisciplinary character of investigations, their direct integration into international projects in cooperation with scientists from the world leading research centres, close coordination of theoretical investigations with experimental programs of JINR. Around ten specialized seminars have worked on a regular basis at which new results of scientists from both BLTP and other research centers of theoretical physics were discussed. The Laboratory maintains and develops the traditions of the famous scientific schools founded by the prominent Russian scientists N.N. Bogoliubov, D.I. Blokhintsev, and M.A. Markov, thus creating a fruitful atmosphere for everyday research work.

Much attention was paid to strengthening of international contacts. A number of permanent scientific programs supported a direct collaboration of Dubna theorists with scientists from Bulgaria, Germany, Italy, Poland, Romania, Slovakia, France, Czech Republic, the South African Republic, People's Republic of China as well as International research centers - CERN, APCTP (countries of Asia and Pacific region), and KEK (Japan). Traditionally, the Laboratory has lasting scientific contacts with the leading Russian research centres (Institute for High Energy Physics, Alikhanov Institute for Theoretical and Experimental Physics, Landau Institute for Theoretical Physics, Lebedev Physical Institute, Steklov Mathematical Institute, Institute for Nuclear Research, Budker Institute of Nuclear Physics, etc.) and research organizations of the FSU countries.

The Laboratory has become a popular site for organization of international conferences, workshops, schools for young scientists in various fields of theoretical physics. In 2003-2009, more than 70 international conferences and workshops, and 23 schools were organized at the Laboratory. Such a high activity is specified by the necessities of investigations carried out at the Laboratory and reflects in full measure the level of

their integration into the world science.

Traditionally, the Laboratory played also the role of the training center for young scientists and students from many countries. This activity became even more pronounced during the last several years due to launching the scientific and educational project "Dubna International Advanced School of Theoretical Physics" (DIAS-TH), as well as opening the new departments of theoretical physics at Moscow Physical Technical University and Dubna International University closely associated with the Laboratory and JINR University Center. The education and training of young scientists and students became an integral part of the Laboratory's activities. The Laboratory established eight grants named after famous physicists to support post-graduates and young researchers. Systematic efforts to attract students and young scientists from the JINR Member States resulted in an optimistic tendency of increasing the fraction of young resarchers working at BLTP. Currently, about one third of scientific personnel are young scientists and PhD students.

Scientists of the Laboratory actively participated in research and educational projects supported by grants of RFBR (Russia), DFG (Germany), INTAS, Helmholtz Foundation, DAAD, etc. More than 120 projects were executed during the years 2003-2009.

Scientific research was carried out in accordance with the themes and projects:

- *Theory of Elementary Particles and Fields*
  (01-3-1028-2003/2008, 01-3-1070-2009/2013): Standard Model and Its Extension, QCD Parton Distributions for Modern and Future Colliders, Physics of Heavy and Exotic Hadrons, Mixed Phase in Heavy-Ion Collisions;

- *Nuclear Theory, Nuclear Structure and Dynamics*
  (01-3-1029-99/2008, 01-3-1071-2009/2013): Nuclear Structure far from Stability Valley, Nucleus-Nucleus Collisions and Nuclear Properties at Low Energies, Exotic Few-Body Systems, Nuclear Structure and Dynamics at Relativistic Energies;

- *Theory of Condensed Matter and New Materials*
  (01-3-1030-99/2008, 01-3-1072-2009/2013): Physical properties of complex materials and nanostructures, Mathematical problems of many-particle systems;

- *Modern Mathematical Physics*
  (01-3-1047-2003/2008, 01-3-1073-2009/2013): Quantum groups and integrable systems, Supersymmetry, Quantum gravity, cosmology and strings;

- *Research and Education Project "Dubna International School of Theoretical Physics (DIAS-TH)"*
  (01-3-1053-2004/2008, 01-3-1074-2009/2013).

The scale and level of the research is well-illustrated by the number of publications during the years 2003-2009: total number of publications – 3150 papers, monographs – 19, journal articles – 1830. It should be noted that every year 4-5 articles were published in the Physical Review Letters which illustrates the high level of research. Most of the results were obtained in cooperation with scientists from JINR Member States, Germany, Italy, France, Spain, China, Republic of Korea and other countries. The main part of the report is devoted to a brief description of the results and lines of research at BLTP which have got significant development during the last several years.

1 Scientific research

1.1 Fields and Particles

Theoretical investigations were carried out within the following projects:

- Standard Model and Its Extensions;
- QCD Parton Distributions for Modern and Future Colliders;
- Physics of Heavy and Exotic Hadrons;
- Mixed Phase in Heavy-Ion Collisions

Much attention was paid to the study of fundamental problems of quantum field theory as well as to the analysis and theoretical support of current and future experiments.

New results were obtained in the Supersymmetric Yang-Mills theories. The three-loop universal anomalous dimension of Wilson twist-2 operators in the $N = 4$ Supersymmetric Yang-Mills model was calculated by extracting the most complicated contributions from the three loop non-singlet anomalous dimensions in QCD. The obtained asymptotics of universal anomalous dimension at large j is in agreement with the expectations based on an interpolation between weak and strong coupling regimes in the framework of the AdS/CFT correspondence. [1] The conditions under which the full Leigh-Strassler deformation of the N=4 Supersymmetric Yang-Mills (SYM) theory would be conformally invariant and finite were discussed. A family of theories which are conformal up to 3 loops in the nonplanar case and up to 4 loops in the planar one was constructed by virtue of the algorithm of perturbative adjustments of the couplings [2].

Fundamental aspects of QCD structure at large distances were studied within the analytic perturbation theory (APT). The reasonableness of the use of perturbative QCD notions in the region close to the scale of hadronization was studied. The interplay between higher orders of pQCD expansion and higher twist contributions in the analysis of recent Jefferson Lab (JLab) data on the Bjorken Sum Rule function $\Gamma_1^{p-n}(Q^2)$

at $0.1 < Q^2 < 3\text{GeV}^2$ was considered. It was shown that the inclusion of the higher-order pQCD corrections could be absorbed, with good numerical accuracy, by change of the normalization of the higher-twist terms. The issue of unphysical singularity (Landau pole at $Q = \Lambda \sim 400MeV$) was avoided by the use of the ghost-free Analytic Perturbation Theory (APT) that has recently proved to be an intriguing candidate for a quantitative description of light quarkonium spectra within the Bethe-Salpeter approach. The values of the twist coefficients μ_{2k} extracted from the mentioned data by using the APT approach gave a better convergence of the higher-twist series than with the common pQCD. As the main result, a good quantitative description of the JLab data down to $Q \simeq 350$ MeV was achieved [3]. The strong running coupling $\alpha_s(Q^2)$ was studied in the low energy domain below 1 GeV. The combination of the Bethe-Salpeter (BS) formalism with the APT algorithm was employed. This combined BS+APT approach enables one to extract values of $\alpha_s(Q^2)$ for the momentum transferred Q range between 200 MeV and 1 GeV. The values agree with the APT curve normalized at its current world average value $\alpha_s(M_Z^2) \simeq 0.118$. This indicates that an analytic-type modification of perturbative QCD at low energies has a chance for providing one with a theoretically consistent and numerically correct description of hadron physics in the energy range from a few hundred MeV up to a few hundred GeV [4].

On the eve of launching of the LHC and within the preparation for SUSY search the parameter space of the Minimal Supersymmetric Standard Model was reanalysed with taking account of recent astrophysical data on the amount of Dark matter. The interpretation of the flux of diffuse gamma rays was given as a signal of annihilation of Dark matter in the halo of our galaxy. It was shown that this interpretation was consistent with supersymmetry and an estimate on the mass of the lightest supersymmetric particle of the order of 60 GeV [5]. The possibility of existence of relatively light charged superparticles in the framework of the Minimal supersymmetric Standard Model (MSSM) was analyzed. Long-lived superpartners of tau-leptons were predicted in the so called coannihilation region of the MSSM parameter space. Production cross-sections of this sort of particles at the Large Hadronic Collider can reach a few per cent of picobarn for tau-sleptons and a few tens of picobarn for top-squarks and charginos [6]. Prospects for observing a signal from

two gluinos were investigated within a certain region of the mSUGRA parameter space. In this region, the lightest stable neutralinos can serve as cold dark matter particles and present a natural explanation of the excess of diffuse galactic gamma rays observed by the EGRET space apparatus. The event selection relies on a very clear signature when decay products of each gluino contain one $b\bar{b}$ pair, one or two $\ell\bar{\ell}$ pair(s), and a neutralino. It was found that the clear signatures of the selected processes demonstrate good prospects for discovering gluinos at the LHC [7].

The Collins fragmentation function was extracted from HERMES data on azimuthal single spin asymmetries in semi-inclusive deeply inelastic scattering, and BELLE data on azimuthal asymmetries in electron positron annihilations. It was found that the HERMES and BELLE data yielded a consistent picture of the Collins fragmentation function which was compatible with COMPASS data and with the information previously obtained from analysis of DELPHI data. On the basis of a fit to the Sivers effect in deep-inelastic scattering, predictions for single-spin asymmetries in the Drell-Yan process at RHIC were made [8]. The studies of transverse spin and momentum dependent parton distributions which are objects of investigations in many current and planned experiments (including spin program at NICA) were continued. The parton distribution function of the leading twist $h_{1T}^{\perp}$ (so-called "pretzelosity") was studied. The Collins fragmentation function was extracted from the data of HERMES and BELLE for the first time. Predictions for the asymmetry $A_{UL}^{\sin 2\phi}$ as well as for the azimuthal asymmetry connected with pretzelosity $A_{UT}^{\sin(3\phi-\phi_S)}$ were given for future experiments CLAS12 and COMPASS [9]. The world data on inclusive polarized DIS, in both NLO and LO QCD, including the new HERMES and COMPASS data on g_1 structure function were analyzed. The updated NLO polarized densities were given in both the $\overline{\text{MS}}$ and JET schemes and presented at HEPDATA web site [10].

High precision theoretical predictions for processes to be investigated at LHC were obtained. In particular, radiative corrections to Drell-Yan like processes (single Z- and W-boson production) were evaluated. Complete one-loop electroweak radiative corrections to the differential distribution of semi-leptonic top-quark decays were presented for the first time. For the conditions of the COMPASS experiment at CERN,

one-loop corrections to the leptonic tensor in bremsstrahlung of high energy leptons on heavy nuclei were calculated [11].

The cross section for polarized and unpolarized electron-proton scattering was calculated by taking into account radiative corrections in leading and next-to-leading logarithmic approximation. The calculation of radiative corrections can bring into agreement the conflicting experimental results on proton electromagnetic form factors [12].

The constraints on the pion distribution amplitude (DA) available from perturbative QCD, nonlocal QCD sum rules and light cone sum rules were analyzed. Good agreement between obtained results and recent high-precision lattice calculations of the second moment of the pion DA was established. It was shown which regions in the space of the first two nontrivial Gegenbauer coefficients a_2 and a_4 of all the constraints overlap, thus tagging the pion structure to the highest degree possible at present [13].

The reactions of quasielastic production of Λ, Σ^-, and Σ^0 hyperons in antineutrino interactions with nucleons crucial for studies of neutrino iscillations were investigated. The most general formulae connecting the structure functions for quasielastic νN and $\overline{\nu} N$ scattering off nucleons with the (complex) hadronic-current form factors accounting for the final lepton mass and nonstandard (G parity violating) second-class currents were derived. Statistical analysis of all available accelerator data on the total and differential cross sections was performed. The world-averaged value of the axial mass of the nucleon $M_A = 0.999 \pm 0.011$ GeV/c^2 was obtained. This result is concordant with the results obtained by fitting the data on exclusive and inclusive νN and $\overline{\nu} N$ reactions [14].

In the dispersive approach to the amplitude of the rare decay $\pi^0 \to e^+e^-$ the nontrivial dynamics is contained only in the subtraction constant. In the leading order in $(m_e/\Lambda)^2$ perturbative series, this constant was expressed in terms of the inverse moment of the pion transition form factor given in symmetric kinematics. In asymmetric kinematics, the lower bound of the decay branching ratio was found using the CELLO and CLEO data on the pion transition form factor. The QCD restrictions lead to the quantitative prediction for the branching $B(\pi^0 \to e^+e^-) = (6.2 \pm 0.1) \cdot 10^{-8}$ which is 3σ below the recent KTeV measurement [15]. The Mellin-Barnes representation was employed in order to improve the theoretical estimate of mass corrections to the

width of light pseudoscalar meson decay into a lepton pair, $P \to l^+l^-$. The full resummation of the terms $\ln(m_l^2/\Lambda^2)(m_l^2/\Lambda^2)^n$ and $(m_l^2/\Lambda^2)^n$ to the decay amplitude was performed. It was demonstrated that the total effect of mass corrections for the e^+e^- channel was negligible and it is of an order of a few per cent in the case of the $\mu^+\mu^-$ channel. This work is a continuation of a series of papers devoted to accurate calculations of strong interaction contributions to low energy processes which play an important role in the Standard Model tests [16].

The infrared behavior of gluon and ghost propagators in Landau-gauge QCD was investgated by means of functional renormalization group equation. It was demonstrated how, in general, the infrared momentum structure of Green functions can be extracted within this approach. An optimization procedure was devised to remove residual regulator dependences. In Landau-gauge QCD this framework was used to determine the infrared leading terms of the propagators. The results support the Kugo-Ojima confinement scenario [17].

High precision results on the bound state formation were obtained. The $O(\alpha)$ and $O(\alpha^3 \ln(\alpha))$ corrections to the total decay width of orthopositronium were obtained in a closed analytic form, in terms of basic transcendental numbers, which can be evaluated numerically to arbitrary precision. The results reproduce the best numerical evaluations within their accuracy. Orthopositronium is the system suitable for precision tests of the validity of electrodynamics, it plays an important role in atomic and particle physics. The results of this work are of fundamental importance [18]. The hyperfine splitting of the states of H_2^+ and HD^+ was calculated with accuracy of an order of $m\alpha^6(m_e/M_N)$ [19]. The data on the antiprotonic helium atom spectroscopy and determination of the $m_{\bar{p}}/m_e$ ratio was included in the 2006 year adjustment of CODATA recommended values for fundamental constants.

The nature of a couple of scalar mesons with rather different masses (observed experimentally) was discussed within the instanton model of QCD vacuum. It was shown that the mass splitting in the scalar sector of meson spectrum could be unexpectedly strong due to the effects of instanton liquid excitations [20]. Physics aspects of a JINR project to reach the planned 5 A GeV energy for the Au and U beams and to increase the bombarding energy up to 10 A GeV was discussed. The project aims to search for a possible formation of a strongly interacting mixed quarkhadron phase. The relevant problems were exemplified. The need for scanning heavy-ion interactions in bombarding energy, collision centrality, and isospin asymmetry is emphasized [21]. Magnetic fields created in noncentral heavy-ion collision were studied within the microscopic transport model, the Ultrarelativistic Quantum Molecular Dynamics model (UrQMD). Simulations were carried out for different impact parameters in the SPS energy range ($E_{\rm lab} = 10 - 158$ A GeV) and highest energies accessible for RHIC. It is demonstrated that magnetic field emerging in heavy-ion collisions has values of an order of $eB_y\ 10 - 1m_p^2$ for the SPS energy range and $eB_y\ m_p^2$ for RHIC energies. The estimated value of the magnetic field strength for the LHC energy amounts to $eB_y\ 15m_p^2$ [22].

1.2 Modern Mathematical Physics

The topics of main focus in the theme were:

- Supersymmetry and Superstrings;
- Quantum Groups and Integrable Systems;
- Quantum Gravity and Cosmology.

An overview of recent progress in constructing and studying superextensions of the Landau problem of a quantum particle on a plane in the uniform magnetic field and its Haldane's S^2 generalization was presented. The main attention was paid to the planar super Landau models. These models are invariant under the inhomogeneous supergroup $ISU(1|1)$, a contraction of the supergroup $SU(2|1)$, and can be seen as minimal superextensions of the original Landau model. Their common notable feature is the presence of hidden dynamical worldline N=2 supersymmetry. It exists at the classical and quantum levels and is revealed most naturally while passing to the new invariant inner products in the space of quantum states [23].

A new superfield approach to N=4 supersymmetric mechanics based on the concept of biharmonic superspace (bi-HSS) was develped. It is an extension of the N=4,d=1 superspace by two sets of harmonic variables associated with the two SU(2) factors of the R-symmetry group

SO(4) of the N=4, d=1 super Poincaré algebra. There are three analytic subspaces in it: two of the Grassmann dimension 2 and one of the dimension 3. They are closed under the infinite-dimensional "large" N=4 superconformal group, as well as under the finite-dimensional superconformal group $D(2,1;\alpha)$. The main advantage of the bi-HSS approach is that it gives an opportunity to treat N=4 supermultiplets with finite numbers of off-shell components on equal footing with their "mirror" counterparts [24].

The most general N=4 superconformal 3-particle systems with translation invariance were constructed. In the basis with decoupled center of mass the supercharges and Hamiltonian possess one arbitrary function which defines all potential terms. With the proper choice of this function one may describe the standard, A_2 Calogero model as well as BC_2, B_2, C_2 and D_2 Calogero models with N=4 superconformal symmetry. The main property of all these systems is that even with the coupling constant equal to zero they still contain nontrivial interactions in the fermionic sector. In other words, there are infinitely many nonequivalent N=4 supersymmetric extensions of the free action depending on one arbitrary function [25].

Hierarchical relations for the Bethe vectors were formulated as inverse generating series, taking values in quantum algebra of currents. In the framework of these investigations a new type of the hierarchical relations for the universal Bethe vectors was found. This type of relations allows one to address the question of the universal Bethe equations or, in other words, to formulate the rule about the structure of the universal Bethe vectors when their parameters satisfy the universal Bethe equations. This rule is algebraic justification of the nested Bethe ansatz [26].

A new construction of the primitive idempotents of the Hecke algebras associated with the symmetric groups was given. The idempotents were found as evaluated products of certain rational functions, thus providing a new version of the fusion procedure for the Hecke algebras. The normalization factors which occur in the procedure are related to the Ocneanu-Markov trace of the idempotents [27].

The noncanonical ghosts and anti-ghosts for non-linear algebras, like W-algebras, were introduced. In terms of these ghosts the BRST operator (for the W_3 and $W_3^{(2)}$ algebras) with the conventional cubic form was constructed. The important feature of this construction is the use of noncanonical ghost algebra which in general is represented as Nichols algebra defined by the special elements (shuffle elements) in the braid group ring. Multiplicative analogues of the shuffle elements of the braid group rings are obtained; in local representations they give rise to new graded associative algebras (b-shuffle algebras)[28].

Generalized dimensional reductions of an integrable 1+1-dimensional dilaton gravity coupled to matter down to one-dimensional static states (black holes in particular), cosmological models and waves was introduced. An unusual feature of these reductions is the fact that the wave solutions depend on two variables - space and time. They are obtained both by reducing the moduli space and a generalized separation of variables. A class of solutions for which the matter fields are finite everywhere in space-time including infinity was found among these new wave-like solutions. This relation between static states, cosmologies, and waves was extended to a new class of integrable two-dimensional dilaton gravity theories in which scalar matter satisfies the Toda equations. The simplest cases of the Toda system were considered in detail, and it was shown how the wave-like solutions of the general Toda systems can be simply derived. In the dilaton gravity theory these solutions describe nonlinear waves coupled to gravity [29].

It was shown explicitly that in dynamics of theories with higher derivatives there arises exponential instability with respect to an external dissipative force. This fact should be taken into account in any extension of standard field theory models by making use of higher derivatives [30].

The three-string vertex coefficients in light-cone open string field theory were found to satisfy the Hirota equations for the dispersionless Toda lattice hierarchy. The Hirota equations allow one to calculate the correlators of an associated quantum system where the Neumann coefficients represent the two-point functions. The three-string vertex coefficients of the light-cone string field theory on a maximally supersymmetric pp-wave background were also considered. These Neumann coefficients were shown to satisfy the Hirota equations for the full Toda lattice hierarchy at least up to the second order in the 'string mass' [31].

It was proved that the field equations of supergravity for purely time-dependent backgrounds admited a Lax pair representation and were fully integrable. In the case where the effective sigma model was on a maximally split non-compact coset U/H, an explicit analytic integration algorithm could also be constructed. The properties of the general integral were particularly suggestive. Initial data were represented by a pair C_0, h_0 where C_0 was in the CSA of the Lie algebra of U and h_0 in H/W was in the compact subgroup H modded by the Weyl group of U. At asymptotically early and asymptotically late times the Lax operator was always in the Cartan subalgebra and due to the isospectral property the two limits differed only by the action of some element of the Weyl group. Hence the entire cosmic evolution could be seen as a billiard scattering with quantized angles defined by the Weyl group. The solution algorithm realized a map from H/W into W[32].

New nontoric Lagrangian fibrations of smooth quadric were found in terms of pseudotoric structures. A new method of constructing toric and nontoric Lagrangian fibrations of toric Fano manifolds was proposed [33].

Kinks and bounce-type solutions of the plane wave matrix model and a matrix analog of the ϕ^4 kink model were constructed. Explicit instanton, dyon, monopole, and monopole-antimonopole chain solutions of pure Yang-Mills theory on $\mathbf{R}^2 \times S^2$ and $\mathbf{R} \times S^3$ were obtained by symmetry reduction to the above-mentioned matrix models [34].

When constructing quantum field theory with allowance for the space-time curvature the methods of spectral geometry and spectral summation were widely used. This technique was applied to calculate the vacuum effects in nanophysics problems. The Casimir force was investigated between two dissimilar plane mirror material the properties of which were described by the Drude or Lorentz models. The short and long distance asymptote of the force was calculated analytically and related to the influence of interacting surface plasmons. Conditions needed for obtaining the Casimir repulsion in this case were also discussed [35].

1.3 Nuclear Structure and Dynamics

Within 2003-2009 nuclear theorists published the monographs [36, 37, 38, 39, 40] and almost 600 (591) papers in peer reviewed journals. The

whole area of nuclear physics studies at BLTP was divided into four projects

- Nuclear Structure Far from Stability Valley
- Nucleus-Nucleus Collisions and Nuclear Properties at Low Excitation Energies
- Exotic Few-Body Systems
- Nuclear Structure and Dynamics at Relativistic Energies

Nuclear structure theory

Two methods to separabelize realistic effective nuclear interaction of the Skyrme type were developed and applied to calculate spectra of heavy nuclei. Both the methods combine the self-consistency with the capability to perform calculations with extremely large model spaces. The first one uses a numerical procedure of the finite rank approximation. It was applied to calculate the properties of heavy spherical nuclei taking into account the coupling of one- and two-RPA-phonons. The properties of low-lying 2^+ states in neutron-deficient nuclides in the mass range $A \sim 120 - 140$ near the closed shells $Z = 50$ or $N = 82$ were predicted and the fragmentation of isoscalar quadrupole resonance was studied [41]. Within the other method the approximated Skyrme forces were substituted for the systematic expansions into a sum of weighted separable terms at the RPA level. The approach was applied to analyze electric E1-E3 giant resonances in axially deformed heavy nuclei in rare-earth, actinide, and superheavy regions [42].

The DiNuclear System (DNS) model was modified to analyze the cluster features in the structure of heavy well-deformed nuclei. The approach was based on the assumption that cluster type shapes were produced by the motion of the nuclear system in the mass asymmetry coordinate. The yrast superdeformed band termination phenomenon in the mass region $A \sim 190$ was explained. The structure of alternative parity collective bands in actinides and rare-earth nuclei was described. The calculated parity splittings and the electric multipole transitions well agree with the experimental data [43].

The Quasiparticle-Phonon Nuclear model was extended for a systematic study of the low-lying excited $0^+, 2^+$ and 4^+ states observed in

large abundance in some deformed nuclei in the rare-earth and actinide regions. A deep insight into the nature of these states was achieved [44].

The influence of temperature and density of a stellar medium on electron capture rates for nuclei with mass number $A \sim 80$ was studied within a formalism based on the thermo field dynamics. The mechanism of thermal unblocking of GT transitions in the Ge isotopes in stellar environment was explained [45].

Theory of nuclear reactions

The theoretical model allowing one to describe the fusion of heavy nuclei, quasifission, and transfer reactions was developed within the DNS concept. A wide variety of nucleus-nucleus reactions was analyzed. In view of the experiments planned at FLNR JINR the production cross sections of neutron-rich isotopes of the elements from Oxygen till Titanium in diffusive multinucleon transfer reactions at incident energies close to the Coulomb barrier were predicted [46].

The production cross sections and excitation functions for different neutron-deficient isotopes of U, Np, Pu, Am, Cm, and Cf were analyzed. In these nuclei the evaporation of charged particles competes with neutron emission and was properly taken into account [47]. Possibilities to synthesize new superheavies with $Z \geq 114$ exploiting the actinide-based reactions with projectiles heavier than ^{48}Ca were investigated. The obtained dependence of the survival probability of superheavy evaporation residues on Z indicates the next doubly magic nucleus beyond ^{208}Pb at $Z \geq 120$ [48, 49].

The microscopic four-body approach to study the light Borromean nuclei in the distorted wave framework was developed. The method of hyperspherical harmonics was used for a consistent description of specific features of the halo structure of the ground state and the fragment motion in the continuum. The approach was applied to describe breakup reactions of two-neutron halo nuclei in collisions with electrons, nucleons, and complex nuclei [50].

The double-folding microscopic model of an optical nucleus-nucleus potential was suggested, where a dependence on the energy and atomic numbers of colliding nuclei was taken into account. The experimental cross sections of elastic proton scattering off ^{6}He measured at FLNR

JINR and other laboratories were analyzed [51].

Few-body theory

The interaction of few-nucleon systems with exotic particles like Λ-hyperon or η or φ mesons was studied based on the Faddeev equations. Possible bound and resonant states of the systems ΛNN and $\Lambda\Lambda N$ were sought [52]. A possibility of the existence of bound clusters formed by two nucleons and a φ-meson was studied. The φnn and φnp systems were found to be bound. The indications of the possible existence of bigger few-nucleon φ-meson clusters were obtained [53].

It was found that the atom-atom interaction or the scattering of an electron off a fixed impurity can be virtually switched off by the impact of geometrical confinement. By tuning the width of an optical or magnetic trap one can turn off the ultracold atom-atom scattering in the confining trap. This happens if the fundamental atom-atom two-body interaction is rather strong and the two-body s- and p- scattering lengths reach the order of the confinement width [54].

Properties of weakly bound small Helium clusters attract considerable attention, in particular, because of the interest in Bose-Einstein condensation of ultra-cold gases. Advanced calculations based on the hard-core version of the Faddeev differential equations were performed for the scattering length and phase shifts of ^{4}He-^{4}He$_2$ and ^{3}He-^{4}He$_2$ collisions. Refined grids were employed, providing an improvement of about 10% [55].

The rigorous mathematical results were obtained while analyzing the six-dimensional Schrödinger and Faddeev equations for a three-body system with two-body central potentials of a more general type than the Coulomb one. These results are very useful in the analysis of three-particle systems like an ion and two slow electrons or three-atom sp-hybridized molecules [56].

Properties of the lowest 0^+ states in ^{12}C were calculated treating the nucleus as a system of three α-particles with the effective two-body and three-body potentials. The potential parameters were fitted to describe correctly a variety of data on $\alpha-\alpha$ scattering, ^{8}Be and ^{12}C nuclei, etc. A very good description of the energy and width of the Hoyle 0^+ state and

of the monopole $0_2^+ \to 0_1^+$ transition matrix element was obtained [57].

Nuclear dynamics at relativistic energies

The relativistic mean-field model with hadron masses and coupling constants depending on the σ-meson field was generalized to finite temperatures. The high-lying baryon resonances and boson excitations as well as excitations of the σ, ω and ρ fields interacting via mean fields were incorporated into this scheme. The model was applied to describe the heavy ion collisions in a broad collision energy range. It might be especially helpful for studying phase diagram in the region near possible phase transitions [58].

The multirank separable kernels of the neutron-proton interaction for uncoupled S and P partial waves (with J=0,1) and coupled $^3S_1^+$-$^3D_1^+$ state were proposed. Using the constructed kernels the experimental phase shifts at laboratory energy up to 3 GeV as well as low-energy parameters were correctly described [59].

The processes ^{2}H(e, e′p)n, ^{3}He(e, e′p)X, and ^{3}He(e, e′N)2N were theoretically investigated using realistic three body wave functions and treating the final state interaction within the eikonal approximation. The results were compared with JLab experimental data and showed that the left-right asymmetry exhibited a clear dependence upon the multiple scattering in the final state and demonstrated the breaking down of the factorization approximation for values of the missing momentum $\geq$ 300MeV/c [60].

The open charm production in the peripheral reactions $\bar{p}p \to \bar{\Lambda}_c^+\Lambda_c^+$ or $\bar{\Sigma}_c^+\Sigma_c^+$ and $\bar{p}p \to \bar{D}D$ or $\bar{D}^*D^*$ was studied at the energies corresponding to the energy range of FAIR. The consideration was based on the topological decomposition of the planar quark and diquark diagrams. The cross sections and longitudinal double-spin asymmetries for exclusive binary reactions with open charm mesons and baryons in the final state were calculated. The polarization observables have a nontrivial t and s dependence [61].

1.4 Theory of Condensed Matter

Investigations in the Theory of Condensed Matter were organized in the framework of two projects:

- Physical properties of complex materials and nanostructures;
- Mathematical problems of many-particle systems.

The research in the field of **complex materials** was conducted in the following main directions: studies of spin dynamics in new materials within the t-J model, theoretical description of cold atoms trapped in optical lattices, and investigations of transport characteristics in direct bandgap semiconductors.

A relaxation-function theory for the dynamic spin susceptibility in the t-J model was presented. By a sum-rule-conserving generalized mean-field approximation (GMFA), the two-spin correlation functions of an arbitrary range, the staggered magnetization, the uniform static susceptibility, and the antiferromagnetic correlation length were calculated in a wide region of hole doping and temperatures. Good agreement with available exact diagonalization (ED) data was found. The calculated correlation length is in reasonable agreement with neutron-scattering experiments on $La_{2-\delta}Sr_\delta CuO_4$. Going beyond the GMFA, the self-energy was calculated in the mode-coupling approximation. The spin dynamics at arbitrary frequencies and wave vectors was studied for various temperatures and hole doping. At low doping a spin-wave-type behavior was found as in the Heisenberg model, while at higher doping a strong damping caused by hole hopping occurs, and a relaxation-type spin dynamics is observed in agreement with the ED results. The local spin susceptibility and its (ω/T) scaling behavior were calculated in reasonable agreement with experimental and ED data [62].

A self-consistent renormalization theory of spin fluctuaions in the paramagnetic spinel LiV_2O_4 was developed. In the family of transition metal oxides this compound was the only metallic system showing a pronounced heavy fermion behavior. In particular, in the limit of low temperatures T an anomalously large value of the specific heat coefficient $g = 1/T$ and strongly enhanced magnetic susceptibility χ_s were detected. A model has been proposed which allows one to relate such an anoma-

lous behavior to a strong degeneracy of the ground state and a proximity of the system to a magnetic instability as $T \to 0$ [63]. The emergence of a rather peculiar paramagnetic ground state with low-energy "critical" antiferromagnetic fluctuations is a result of strong electron correlations and the geometrical frustration of the V ion lattice. A self-consistent renormalization theory was developed to describe effects of strong coupling between spin fluctuation modes and their evolution with varying temperature and external pressure. The theory was shown to provide a firm basis for quantitative description of experimental data obtained in the inelastic neutron scattering and NMR measurements on LiV_2O_4 [64].

A complete irreversible adiabatic transport of Bose-Einstein condensate (BEC) in a double-well trap was investigated within the mean field approximation. The transfer is driven by time-dependent (Gaussian) coupling between the wells and their relative detuning. The protocol successfully works in a wide range of both repulsive and attractive BEC interaction. The nonlinear effects caused by the interaction can be turned from detrimental into favorable for the transport. The results were compared with familiar Landau-Zener scenarios using the constant coupling. It was shown that the pulsed Gaussian coupling provides a new transport regime where coupling edges are decisive and a convenient switch of the transport is possible [65].

The superfluid properties of a 1D Bose gas in a ring trap based on the model of Lieb and Liniger were examined. It was shown that the Landau critical velocity is zero in the thermodynamic limit due to the first supercurrent state which has zero energy and finite probability of excitation. The energy dissipation rate of ring currents in the presence of weak defects was calculated which should be observable on experimental time scales [66].

The effect of edge-type dislocation wall strain field on the Hall mobility in n-type epitaxial GaN was theoretically investigated through the deformation potential within the relaxation time approximation. It was found that this channel of scattering can play a considerable role in the low-temperature transport at a certain set of model parameters. The low temperature experimental data were fitted by including this mechanism of scattering along with ionized impurity and charge dislocation ones [67].

In the field of **nanostructures** the electronic spectra for double-wall zigzag and armchair nanotubes were found. The influence of nanotube curvatures on the electronic spectra was also calculated. The outer shell were found to be hole doped by the inner shell. The difference between Fermi levels of individual shells originates from the different hybridization of pi-orbital. The shift and rotation of the inner nanotube with respect to the outer nanotube were investigated. Stable semimetal characteristics of the armchair DWNTs as regards the shift and rotation of the inner nanotube were found. The shift of the Fermi vector towards the bigger wave vectors with decreasing of the radius of the armchair nanotube was predicted [68].

The importance of experiments with voltage dependent field emission energy distribution analysis in carbon nanosheets was emphasized. The analysis shows the crucial influence of the band structure on the energy distribution of field emitted electrons in few-layer graphene. In addition to the main peak, characteristic sub-peaks in the energy distribution were found. Their positions strongly depend on the number of layers and the inter-layer interaction. The discovery of these peaks in field emission experiments from carbon nanosheets would be a clear manifestation of the quantum size effect in these new materials [69].

Charge formations on superconducting layers and creation of the longitudinal plasma wave in the stack of intrinsic Josephson junctions were found to change crucially the superconducting current through the stack. Investigation of the correlations of superconducting currents in the neighboring Josephson junctions and the charge correlations in the neighboring superconducting layers allows one to predict additional features in the current-voltage characteristics. The charge autocorrelation functions clearly demonstrate the difference between harmonic and chaotic behavior in the breakpoint region. It was shown that the use of the correlation functions gives a powerful method for the analysis of the current–voltage characteristics of coupled Josephson junctions [70].

Several **mathematical problems of many-particle systems** were solved. A model of semi-vicious walkers, which interpolates between the totally asymmetric simple exclusion process and the vicious walkers model having both of them as limiting cases, was proposed. For this model the asymptotics of the survival probability for m particles were calculated and a scaling function which describes the transition from one

limiting case to another was obtained. Then a fluctuation-dissipation relation was used to allow one to reinterpret the result as the particle current generating function in the totally asymmetric simple exclusion process. Thus, the particle current distribution was obtained asymptotically in the large time limit as the number of particles is fixed. The results were applied to the large deviation scale as well as to the diffusive scale. In the latter, a new universal distribution, which has a skew non-Gaussian form, was obtained [71].

A detailed asymptotic analysis of correlation functions for the two-component spanning tree on the two-dimensional lattice was presented when one component contains three paths connecting vicinities of two fixed lattice sites at large distances apart. The known result for correlations on the plane was extended to the case of the upper half-plane with closed and open boundary conditions. Asymptotics of correlations for distance r from the boundary to one of the fixed lattice sites were found for some special cases [72].

A check of predictions of the logarithmic conformal field theory was undertaken. It is well known that the theory predicts logarithmic corrections to correlation functions for the models with the central charge $c = -2$ and gives numerical values of the coefficients at these corrections. However, there were no exact solutions up to now for the pair correlation functions containing logarithmic terms of leading orders. It was shown that the correlation functions containing the logarithmic terms appear in the Abelian ASM theory for the nonlocal operators. The ASM model belongs to the class of free-fermions models. The obtained correlation functions are in full agreement with the predictions of the logarithmic conformal theory [73].

A lattice model of critical spanning webs is considered for the finite cylinder geometry. Due to the presence of cycles, the model is a generalization of the known spanning tree model which belongs to the class of logarithmic theories with central charge c=-2. We show that in the scaling limit the universal part of the partition function for closed boundary conditions at both edges of the cylinder coincides with the character of symplectic fermions with periodic boundary conditions and for open boundary at one edge and closed at the other coincides with the character of symplectic fermions with antiperiodic boundary conditions [75].

The problem of finding integrals of motion for quantum elliptic Calogero-Moser systems with an arbitrary number of particles extended by introducing spin-exchange interaction was considered [74].

A family of continuous biorthogonal functions related to an elliptic analogue of the Gauss hypergeometric function depending on eight parameters and two base variables was constructed. The elliptic beta integral and the integral analogue of the Bailey chains were used. Relations of this contruction to the elliptic Sklyanin algebra were discovered. Two elliptic analogues of the Faddeev modular double were constructed [76]

1.5 Dubna International Advanced School of Theoretical Physics (DIAS-TH)

The overall objective of the permanently running BLTP project "Dubna International School of Theoretical Physics" (DIAS-TH) is a promotion of educational and training programs at JINR in the field of theoretical physics. The DIAS activities are centered around the main directions of research at BLTP: Particles and Fields; Nuclear Theory; Theory of Condensed Matter; Modern Mathematical Physics. The unique feature of DIAS-TH is its coherent integration into the current scientific life of BLTP which ensures a regular and natural participation of the leading scientists in the education and training activities.

The main forms of the DIAS-TH activities were: systematic organization of schools and workshops on the priority research themes of JINR for young scientists, post-graduate students and students from JINR Member States and other countries; cooperation with the JINR University Centre in training students and postgraduates as well as in organizing schools for students; organization of schools of different levels in Dubna and coordination with similar schools in Russia, Germany, and other European countries; support of the JINR experimental programs by organizing lecture courses and review lectures on new trends in modern physics; organisation of the regular seminar on theoretical and mathematical physics for young scientists; publication of lectures in different forms, in particular, with the use of modern electronic equipment; video archive at the Web-site of DIAS-TH was maintained and replenished with new lectures; participation in the educational process at the

Departments of Theoretical and Nuclear Physics of Dubna International University, as well as at the departments of Moscow State University and Moscow Physical Technical University based in Dubna; ensuring the up-to-date level of computer and demonstration equipment of the DIAS-TH lecture hall; administration of the WEB page of DIAS-TH which became the organizing centre of the programs related to DIAS-TH; cooperation of DIAS-TH with international and Russian Foundations (UNESCO, DAAD, DFG, RFBR, Dynasty, etc.) and government organizations (BMBF, INFN, CNRS).

Twenty three schools for young scientists were organized during the years 2003-2009. The program of the schools covered wide variety of topics in modern theoretical and mathematical physics, as well as the most important trends of modern experiments (theory of nanostructures; supersymmetry, superstrings, gravity and cosmology; Standard Model and its extentions, experimental program of LHC, dense hadronic matter and heavy ion collisions, astrophysics, heavy quark physics, etc). In 2009 the activities within the project DIAS-TH were: VIIth Winter School on Theoretical Physics; XIIIth Research Workshop "Nucleation Theory and Applications"; Helmholtz International School on Calculations for Modern and Future Colliders; Helmholtz International Summer School on Modern Mathematical Physics.

2 Computer facilities

The number of PCs at BLTP has increased in comparison with 2002 approximately 1.5-fold reaching a value of about 180. During 7 years about 120 PCs were acquired. New PCs built in 2009 are 4 times more productive, but cheaper than PCs purchased in 2002. Five servers were installed. The most powerful of them is 3-5 times more productive and has 8 times more memory than the best server at the Laboratory in 2002. The speed of network connections for computers has increased from 10-100 Mbit/s to 100-1000 Mbit/s. The communication in large auditoriums is provided with 5 wireless access points. New digital multimedia projectors gave extended opportunities and improved quality of presentations.

3 Conferences and meetings

More than 70 international conferences and workshops were organized at BLTP during 2003-2009. Two very significant for the Laboratory and the Institute events were the International Bogolyubov Conference "Problems of Theoretical and Mathematical Physics" (dedicated to the 100th anniversary of the birth of N.N. Bogolyubov (1909-1992)) (August 21 - 27, 2009) and XIIIth International Conference "Selected Problems of Modern Theoretical Physics", (dedicated to the 100th anniversary of the birth of D.I. Blokhintsev (1908-1979)) (June 23 - 27, 2008). Several traditional for BLTP series of meetings were successfully continued: International Workshop on High Energy Spin Physics, International Workshop "Supersymmetries and Quantum Symmetries", International Conference "Nuclear Structure and Related Topics", International Conference "Symmetry Methods in Physics", International Workshop "Supersymmetries and Quantum Symmetries", International Baldin Seminar "Relativistic Nuclear Physics and Quantum Chromodynamics", etc. New demands of recent developments in JINR experimental programs and international cooperation programs triggered new series of meetings that appeared during these years: Round Table Discussion "Physics at NICA" (four meetings during 2005 -2009), International Conference "Dubna-Nano", Joint Workshops BLTP-APCTP (Asia Pacific Center of Theoretical Physics), and some others.

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