BOGOLIUBOV LABORATORY OF THEORETICAL PHYSICS

At the Bogoliubov Laboratory of Theoretical Physics (BLTP) studies were carried out on the following four themes: Theory of Elementary Particles; Nuclear Structure and Dynamics; Theory of Condensed Matter and New Materials; Modern Mathematical Physics: Gravity, Supersymmetry, Integrability. Important components of BLTP activities are theoretical support of experimental research to be carried out within major international projects with participation of JINR as well as Dubna based experimental programmes of JINR Laboratories, and recruiting of young researchers, students, and post-graduate students to the Laboratory.

SCIENTIFIC RESEARCH

Theory of Elementary Particles

Theoretical investigations were continued in the framework of 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.

Theoretical research in particle physics during the year 2012 reflected the main tendencies in this field: theoretical support of recent results of the LHC including the discovery of the Higgs boson and search for new physics, supersymmetry in particular, multiloop precision calculations in QCD and electroweak theory, analysis of the spin structure of hadrons, physics of heavy quarks and B physics, nonperturbative effects in QCD, neutrino physics and hadron spectroscopy.

A new approach to consider and include both the perturbative and the nonperturbative contributions to the multiplicities of gluon and quark jets is presented. Thanks to this new method, it was possible to include, for the first time, new contributions to these quantities obtaining next-to-next-to-leading-logarithmic (NNLL) resummed formulae. The obtained analytic expressions depend on two nonperturbative parameters with a clear physical interpretation. A global fit of these two quantities shows how new results solve a longstanding discrepancy in the theoretical description of the data [1].

New fragmentation functions (FFs) are extracted from an NLO QCD fit to the preliminary COMPASS data on pion and kaon multiplicities. The new kaon FFs are very different from the result of other research groups (De Florian *et al.*, Hirai *et al.*). The sensitivity of the extracted polarized PDFs to the new FFs was discussed [2].

A comparative theoretical study of the data at spacelike momentum transfer for the pion transition form factor, just reported by the Belle Collaboration, vs. those published before by BaBar, also including the older CLEO and CELLO data, was performed. Various implications for the structure of the distribution amplitude vis-a-vis those data are discussed and the existing theoretical predictions are classified into three distinct categories. It is argued that the actual bifurcation of the data with antithetic trends is artificial, and the reasons that the Belle data are the better option are given [3].

Taking into account the electromagnetic and gravitational form factors, calculated from a new set of t-dependent GPDs, a new model of the nucleons and elastic scattering at high energies was built. In the framework of the model, the quantitative description of all existing experimental data in the broad range of energies, including the Coulomb range and large momentum transfers, was obtained with only 3 parameters. The comparison with the preliminary data of the TOTEM Collaboration at an energy of 7 TeV was made [4].

The photon was explored as an object to test the applications of QCD to the perturbatively calculable collinear parton distributions. The analytic properties of deeply virtual Compton scattering amplitudes and related sum rules of generalized parton distributions of the photon are studied. The relation of these GPDs to the quintessential functions in the framework of the dual parameterization approach was also found [5].

The ATLAS and CMS experiments did not find evidence for supersymmetry using close to 5 fb^{-1} of published LHC data at a center-of-mass energy of 7 TeV. We combine these LHC data with data on $B_s \to \mu\mu$ (LHCb experiment), the relic density (WMAP and other cosmological data) and upper limits on the dark matter scattering cross sections on nuclei (XENON100 data). The excluded regions in the constrained Minimal Supersymmetric SM (CMSSM) lead to gluinos excluded below 1270 GeV and dark matter candidates below 220 GeV for values of the scalar masses m_0 below 1500 GeV. For large m_0 values, the limits of the gluinos and the dark matter candidate are reduced to 970 GeV and 130 GeV, respectively. If a Higgs mass of 125 GeV is imposed in the fit, the preferred SUSY region is above this excluded region, but the size of it strongly depends on the assumed theoretical error. A slight tension between all constraints and the Higgs mass in the MSSM already appears, thus suggesting an extension of the minimal model [6].

The form factors of the $B(B_s) \to P(V)$ transitions in the full kinematic region of momentum transfer were calculated. As an application of our results, we calculate the widths of the nonleptonic B_s decays into $D_s^- D_s^+$, $D_s^{*-} D_s^+$, $D_s^- D_s^{*+}$, and $D_s^{*-} D_s^{*+}$. These modes give the largest contribution to $\delta\gamma$ for the $B_s - \bar{B}_s$ system. The nonleptonic decay $B_s \to \phi J/\psi$ was studied. This decay mode has important implications for the search for possible CP-violating new physics effects in $B_s - \bar{B}_s$ mixing [7].

The light-by-light contribution from the neutral pseudoscalar (π, η, η') and scalar ($a_0(980)$, σ, $f_0(980)$) mesons to the anomalous magnetic moment of muon is calculated in the framework of the nonlocal quark model, based on the instanton liquid vacuum model. Full kinematic dependence of the effective photon–meson vertices is taken into account for the first time. The mixing angles for the η–η' meson mixing in the pseudoscalar channel and for the σ–$f_0(980)$ meson mixing in the scalar channel depend on the meson virtualities. The detailed studies of the sign problem of the scalar meson contribution and of the reduction to the local limit are performed. It is shown that the combined contribution of pseudoscalar and scalar mesons has a smaller model error of relatively separate contributions. The total contribution of pseudoscalar and scalar mesons to the muon g^{-2} reduces to $(6.25 \pm 0.83) \cdot 10^{-10}$ [8].

The deeply virtual Compton scattering (DVCS) off a spin-one particle, as the case for the coherent scattering off a deuteron target, was studied. The role of twist-three contributions for restoring the gauge invariance of the amplitude was discussed. Twist-three contributions and relations, which emanate from the QCD equations of motion, were used for derivation of the gauge invariant amplitude for DVCS off hadrons with spin 1. The derived gauge invariant amplitude was used for the study of the single spin asymmetry effects [9].

Basic features of hot and dense gas of quarks, considered as the quasiparticles of the model Hamiltonian with four-fermion interaction, were studied. Being adapted to the Nambu–Jona-Lasinio model, this approach leads to accommodation of a phase transition similar to the liquid-gas one. The mixed phase of vacuum and baryonic matter appears then as a plausible scenario of chiral symmetry restoration. The transition layer between two phases was also considered [10].

The decay width of the process $\tau \to \pi\omega\nu$ was described in the framework of the extended NJL model. The contribution of intermediate state with vector mesons in the ground and in the first radial excitation states was taken into account. The obtained result is in satisfactory agreement with experimental data without additional parameters [11].

The Sommerfeld–Gamow–Sakharov factor was considered for the general case of arbitrary masses and energies. It has been shown that the scalar triangular one-loop diagram gives the Coulomb singularity in radiative corrections at the threshold. The singular part of the correction is factorized at the complete Born cross section regardless of its partial wave decomposition. Different approaches to generalize the factor are discussed [12].

The production of spin-one mesons in high-energy heavy-ion collisions with peripheral kinematics was studied in the framework of QED. The cross sections of the production of a single vector meson and of two different ones were presented. The explicit dependence on the virtuality of the intermediate vector meson was obtained within the quark model. The effect of reggeization of the intermediate vector meson state in the case of production of two vector mesons was taken into account [13].

A general procedure to evaluate the Bethe logarithm for a general few-body atomic or molecular system was considered. The calculations for the ground states of a helium atom and H_2^+ molecular ion were used as benchmarks. The obtained high precision values are: $\beta_{\rm He} = 4.37016022306(2)$ for the helium atom, and $\beta_{\rm He_2} = 3.012230335(1)$ for the H_2^+. Both results substantially improve the best known values for these quantities [14].

Three-loop gauge field anomalous dimensions are calculated in the background field gauge within the unbroken phase of the Standard Model. The results are valid for the general background field gauge parametrized by three independent parameters. Both quantum and background fields were considered. The former were used to find three-loop anomalous dimensions for the gauge-fixing parameters, and the latter allowed one to obtain the three-loop SM gauge beta-functions. Independence of beta-functions on gauge-fixing parameters served as a validity check of our final results [15].

The procedures for the computation of the analytic images of the strong coupling constant powers in the Minkowski and Euclidean domains at arbitrary energy scales were provided for schemes with a fixed number of active flavours and for the global one with all heavy-quark thresholds taken into account. These singularity-free couplings are inevitable elements of Analytic Perturbation Theory (APT) in QCD and its generalization — Fractional APT needed to apply the APT imperative to renormalization-group improved hadronic observables [16].

Modern Mathematical Physics

The topics of main focus in the theme were:
- Supersymmetry and Superstrings;
- Quantum Groups and Integrable Systems;
- Quantum Gravity and Cosmology.

In the gravitation theory new solutions were constructed which describe extremal multicentre black holes. An important impact of vacuum Yang–Mills condensates on both the inflationary and the hot universe regimes was demonstrated. In the framework of the Galilean cosmology, the new scaling solutions were discovered and investigated. An important problem of observational astronomy is the experimental detection of the black hole parameters. To this end, the interesting technique based on the mechanism of shadows arising in the vicinity of supermassive black holes was proposed. The geometrical and topological properties of the full symmetric Toda systems were analyzed, and their equivalence to the Morse–Smale system was demonstrated. The development of the system is proposed in the framework of the quantum field theory. On the basis of spectral summation method, a rigorous derivation of the Lifshitz formula for the vacuum forces between material bodies was carried out.

The quantum-mechanical systems of particles with extended worldline supersymmetry were studied. These investigations are relevant to a number of hot topics in modern theoretical physics, such as the AdS/CFT correspondence in diverse dimensions, the structure of supersymmetric integrable systems and their multiple relationships with $N = 4$ super-Yang–Mills theory and superstring theory. New one-dimensional systems with extended $N = 4$ supersymmetry were constructed, including those containing couplings with external gauge fields. One of the most important results in this direction became the discovery of the fact that the necessary and sufficient conditions of the existence of $N = 4$ supersymmetry in a wide class of models are equivalent to the famous Nahm equations.

These and some other results are presented in more detail below.

Infrared behavior of the Landau gauge gluon propagators is studied numerically in the $3D$ $SU(2)$ gauge theory on the lattice. Special emphasis was made on the study of the Gribov copy effect. For this study we employ an efficient gauge-fixing algorithm and a large number of gauge copies (up to 280 copies per configuration). It is shown that in the deep infrared region, the Gribov copy effects are very significant. Also we show that in the infinite-volume limit the zero-momentum value of the propagator does not vanish [17].

We study $SU(3)$-invariant integrable models solvable by the nested algebraic Bethe ansatz. Scalar products of the Bethe vectors in these models can be expressed in terms of a bilinear combination of their highest coefficients. We obtain various different representations for the highest coefficient in terms of sums over partitions. We also obtain multiple integral representations for the highest coefficient [18].

It was shown that exotic tori of the Chekanov type can be constructed in terms of pseudotoric structures introduced by the author as a generalization of toric structures on compact manifolds. It follows that exotic Lagrangian tori can be constructed on toric manifolds. As an example, an exotic torus on the del Pezzo surface of degree 6 was construsted [19].

The new general L operator which is intertwined by the $SO(2n)$ spinor R matrix and by the R operator which acts in the tensor product of two infinite-dimensional spaces is constructed. The R operator is built as a product of four factors which satisfy the star-triangle relation. On the base of this L operator, the quantum integrable models which are invariant under $SO(2n)$ and conformal symmetries are formulated [20].

The first example of super-Landau model with both $N = 4$ worldline supersymmetry and nontrivial target space supersymmetry $ISU(2|2)$ is given. The model also reveals the second hidden $N = 4$ supersymmetry which, together with the manifest one, closes on a worldline $SU(2|2)$. At each Landau level $N > 0$, the wave functions are shown to form «atypical» $(2N + 2N)$-dimensional multiplets of the worldline supergroup $SU(2|2)$. We promote the action to the most general form compatible with the off-shell $N = 4$ worldline supersymmetry [21].

The Maxwell-invariant extension of the $D = 4$ relativistic free particle model into the ten-dimensional Maxwell tensorial space was introduced. The new model after first quantization describes in a particular Lorentz frame the planar dynamics providing Landau orbits in the presence of the constant magnetic field [22].

A system of $N = 4$ chiral supermultiplet coupled with an auxiliary $N = 4$ fermionic supermutiplet containing on-shell four physical fermions and four auxiliary bosons is studied. The latter play the role of isospin variables. The resulting component action describes an interaction of the chiral supermultiplet with a magnetic field constant on the pseudosphere $SU(1,1)/U(1)$. The Hamiltonian and supercharges describing the motion of a particle on the sphere S^2 in the background of the constant magnetic field are presented. One of the most important features of this construction is the presence of the isospin group $SU(2)$ in the Hamiltonian and supercharges of all currents [23].

Four-dimensional supergravity theories whose scalar manifold is a symmetric coset manifold $U_{D=4}/H_c$ are arranged into a finite list of Tits–Satake universality classes. Stationary solutions of these theories, spherically symmetric or not, are identified with those of an Euclidian three-dimensional sigma-model, whose target manifold is a Lorentzian coset $U_{D=3}/H^*$ and the extremal ones are associated with H^* nilpotent orbits in the K^* representation emerging from the orthogonal decomposition of the algebra $\mathrm{U}_{D=3}$ with respect to H^*. It is shown that the classification of such orbits can always be reduced to the Tits–Satake projection and it is a class property of the Tits–Satake universality classes. The construction procedure of Bossard *et al.* of extremal multicentre solutions by means of a triangular hierarchy of integrable equations is completed and converted into a closed algorithm by means of a general formula that provides the transition from the symmetric to the solvable gauge. The question of the relation between H^* orbits and charge orbits W of the corresponding black holes is addressed and also reduced to the corresponding question within the Tits–Satake projection. It is conjectured that on the vanishing locus of the Taub-NUT current, the relation between the H^* orbit and the W orbit is rigid and one-to-one. All black holes emerging from multicentre solutions associated with a given H^* orbit have the same W type. For the S^3 model we provide a complete survey of its multicentre solutions associated with all of the previously classified nilpotent orbits of $sl(2) \times sl(2)$ within $g\,[2, 2]$. We find a new intrinsic classification of the W orbits of this model that might provide a paradigm for an analogous classification in all the other Tits–Satake universality classes [24].

Geometric and topological properties of the full symmetric Toda system are investigated. It is shown by a direct inspection that the phase transition diagram for the full symmetric Toda system in dimensions $n = 3$, 4 coincides with the Hasse diagram of the Bruhat order of symmetric group S_3 and S_4. The method we use is based on the existence of a vast collection of invariant subvarieties of the Toda flow in orthogonal groups. We show how one can extend it to the case of general n. The resulting theorem identifies the set of singular points of the $\dim = n$ Toda flow with the elements of the permutation group S_n, so that points will be connected by a trajectory if and only if the corresponding elements are Bruhat comparable. We also show that the dimension of the submanifolds, spanned by the trajectories, connecting two singular points, is equal to the length of the corresponding segment in the Hasse diagramm. This is equivalent to the fact, that the system at hand is in fact a Morse–Smale system [25].

The homogeneous and isotropic cosmological models driven by $SU(2)$ gauge fields were investigated in the framework of Einstein gravity. The conformal invariance of this type of models which usually leads to the radiation dominated universe can be broken due to the quantum corrections or, in the case of the closed universe, by the coupling with the scalar Higgs doublet. It was shown that with quantum corrections in the form of the so-called theta-term in the Lagrangian, the slow-roll inflation with a realistic number of e folds does exist. The advantage of this model is that the field amplitude remains below the Planck energy and the parameter of the model, theta, may be just of an order of ten, which differs from the other models often requiring extra large or small parameter values or trans-Planckian field amplitudes. Also, it was demonstrated that the unique configuration with the YM-doublet Higgs contains an intrinsic mechanism for inflation due to the Higgs potential and admits both the inflationary and the hot universe regimes [26].

Scaling solutions are the well-known solutions which can describe the late time acceleration of the universe in the standard scalar field theory. These solutions arise due to a special form of the scalar field potential. Actually, this model does not contain any modifications of gravity. On the other hand, Galilean gravity is a modified gravity model. It uses a special modification of the scalar field kinetic term. There are five orders in this kind of theory. The second one corresponds to the standard kinetic term, while others are different. The main feature of all these terms is the following: all these terms do not increase the order of equations of motion. A new scaling solution was found. It appears due to the third Galileon term. Stability conditions were obtained for this solution. It was shown that this solution is stable at the dust stage [27].

Formation of shadows around supermassive black holes is simulated. Due to an extremely fast development of observational facilities there is an opportunity to measure a size and a shape of shadows around the supermassive black holes, for the black hole at the Galactic Center, in particular. Black holes with metrics different from the standard Schwarzschild one can exist in theories with extra dimensions, in Randall–Sundrum brane model of the II type, in particular, and the model predicts the existence of black holes with a tidal charge. The shadow size imposes restrictions on the tidal charge [28].

The Lifshitz formula, describing the dispersive forces, is derived by making use of the spectral summation method which is a mathematically rigorous simultaneous application of both the mode-by-mode summation technique and the scattering formalism. The contributions to the Casimir energy of electromagnetic excitations of different types (surface modes, waveguide modes, and photonic modes) are clearly retraced. A correct transition to imaginary frequencies is accomplished with allowance for all the peculiarities of the frequency equations and pertinent scattering data in the complex ω plane, including, in particular, the cuts connecting the branch points and complex roots of the frequency equations (quasinormal modes). The principal novelty of our approach is a special choice of appropriate passes in the contour integrals which are used for transition to imaginary frequencies. As a result, the long standing problem of cuts in the complex ω plane is solved completely. Some subtleties and vague points in previous derivations of the Lifshitz formula are elucidated. For completeness of the presentation, the necessary mathematical facts are also stated, namely, solution of the Maxwell equations for configurations under consideration, scattering formalism for parallel plane interfaces, determination of the frequency equation roots, and some others [29].

Nuclear Structure and Dynamics

In 2012, investigations within the area «Nuclear Structure and Dynamics» were carried out in accordance with the four projects:

• Nuclear Structure Far from Stability Valley;

• Nucleus–Nucleus Collisions and Nuclear Properties at the Low Energies;

• Exotic Few-Body Systems;

• Nuclear Structure and Dynamics at the Relativistic Energies.

The whole area of nuclear physics studies at BLTP is divided into three parts: the theory of nuclear phenomena at low-energies (theory of nuclear structure and low-energy nuclear reactions), theory of few-body systems, and theory of processes with nuclei at relativistic energies.

Seven papers are chosen to present the most interesting results of the studies within the low-energy nuclear physics. In [30], spin-isospin giant resonances in spherical nuclei are treated within the self-consistent approach «Hartree–Fock–Bogoliubov + QRPA» based on Skyrme interaction and separabelization procedure for residual NN interaction. These resonances strongly influence the rates of weak-interaction processes with nuclei (beta decays, electron captures, neutrino–nucleus interactions, etc.). Therefore, theoretical predictions of their properties in unstable nuclei are strongly needed for astrophysical applications. R. Jolos and coauthors [31], analyzing spectra of alternative parity bands in selected nuclei from actinide region, proved that these nuclei change the shapes with increasing angular momenta along the band and suffer the second order phase transition. There are only a few evident examples of such a phase transition in finite quantum systems. In [32], a set of properties of nuclei with $Z > 104$ were calculated and compared with available experimental data. Then, the results were extrapolated to the range of nuclei with $Z \sim 120$. Whereas the theoretical results are in reasonable agreement with experiments, the extrapolation predicts that the next doubly magic nucleus beyond ^{208}Pb is at $Z \geqslant 120$. S. M. Bilenky and F. Šimkovic [33] discussed a possibility of testing theoretical nuclear matrix elements of the neutrinoless double-beta-decay using the data on the corresponding half-lives from the forthcoming experiments where the rate of this rare decay supposedly will be measured. S. Ershov and coauthors [34] confronted the unusually large matter radius of the ^{22}C nuclide recently extracted from experimental data with the theoretically calculated binding energy of the nucleus (its experimental value is unknown). Some inconsistency between the two was found and a way to check the data in the experiment where the soft dipole mode in ^{22}C should be excited was proposed. The works [35, 36] are devoted to theoretical studies of heavy ion collisions at intermediate energies. In [35], the effect of the shell structure of colliding nuclei on the fusion–fission process was analyzed and its sizeable influence on the probability of evaporation-residue formation was shown. In [36], a possibility of studying experimentally the dynamics of quasifission process is discussed.

One of the problems which are under study in the few-body theory group of BLTP is the few-body physics at low dimensions. New pathways for the study of low-dimensional few-body systems were opened by recent progress of the physics of ultracold quantum gases. Specifically, it was shown that the $\gamma\gamma$ confining geometry of atomic traps can drastically change the scattering properties of ultracold atoms and induce resonances in the collisions. In [37], V. S. Melezhik with coauthors developed a theoretical model to calculate the shifts and widths of Feshbach resonances in an atomic waveguide. The model opens possibilities for quantitative studies of the scattering processes in ultracold atomic gases in waveguides.

The work [38] is devoted to relativistic collisions of heavy nuclei. The authors intended to clarify how the interplay of quark and hadron degrees of freedom is changed with increasing bombarding energy. To this aim, they studied the azimuthal anisotropies of the collective transverse flow of hadrons in the energy range of colliding nuclei from the AGS to the top RHIC energy regime. The history of the study of e^+e^- production in $\gamma\gamma'$ interaction is quite long. If one identifies the external electromagnetic (em) field with a laser pulse, then most of the early works considered long lasting pulses where the temporal shape can be neglected. The next generation of optical laser beams is expected to be essentially short (femtosecond duration) with only a few oscillations of the em field in the pulse. This requires the generalization of the previous theory of multiphoton process. Just this generalization is provided in [39]. The two-nucleon density distribution in a nucleus strongly deviates from the mean-field prediction due to the short-range correlations (SRC) which play a crucial role at a relative nucleon–nucleon distance $r < 1.3{-}1.5$ fm. The study of SRC could provide decisive answers to long-standing fundamental questions, such as the formation and structure of cold dense nuclear matter, the origin of the EMC effect, and the role of quark–gluon degrees of freedom in nuclei. In work [40], several universal features of SRC are found. In the following, the results obtained in the cited papers are presented in more detail.

The finite rank separable approximation of Skyrme-type forces to the case of charge-exchange excitations, and more specifically to the spin-isospin channels was extended. The approximation enables one to reduce considerably the dimensions of the matrices that one needs to diagonalize performing QRPA calculations in very large configuration spaces. It was shown that the approximation reproduces reasonably well the charge-exchange RPA results on the spin-dipole resonances in the ^{90}Zr and ^{132}Sn nuclides obtained with a standard diagonalization procedure. Then Gamow–Teller and spin-dipole strength distributions of the parent nuclei ^{126,128,130}Cd in the T_+ and T_- channels were studied with the Skyrme parameterization SGII. The peak energies of the spin-dipole distributions in these Cd isotopes obey the energy hierarchy $E(2^-) < E(1^-) < E(0^-)$ [30].

Shape phase transitions in finite quantal systems are very interesting phenomena. The analysis of experimental data on the ground state alternating parity bands of the nuclides ^{232}Th, ^{238}U, and ^{240}Pu indicated the second order phase transition from reflection-symmetric to reflection-asymmetric shapes in these bands. In the analysis, the mathematical techniques of supersymmetric quantum mechanics, two-centre octupole wave function ansatz, and the Landau theory of phase transitions were used. The approach was based on the assumption that the main role in the description of the properties of the alternating parity bands is played by the octupole mode, preserving the axial symmetry. The phase transition takes place at some value of the angular momentum, which plays the role of the control parameter [31].

The shell structure of heavy nuclei with $Z > 104$, which can be produced in the actinide-based complete fusion reactions, was studied with a modified two-centre shell model. Using the microscopic-macroscopic approach, the mass excesses and Q_α values were calculated and compared with available experimental data. The predicted properties of superheavy nuclei show that the next doubly magic nucleus beyond ^{208}Pb is at $Z \geqslant 120$. It was shown that the production cross sections of new superheavy nuclei decisively depend on the position of proton shell closure [32].

The main way to investigate the problem of the Majorana nature of neutrinos with definite masses is to study the $0\nu\beta\beta$ decay of selected even–even nuclei. The measurement of half-lives of the $0\nu\beta\beta$ decay allows one to determine only the product of the effective Majorana mass and the nuclear matrix element (NME). Results of different NME calculations differ by a factor of 2–3. A possible test of the calculations of the relevant NMEs was proposed. This test is based on the assumption that in future experiments sensitive to the inverted mass hierarchy, half-lives of the $0\nu\beta\beta$ decay will be measured. Moreover, it was assumed that the light Majorana neutrino mass mechanism is the dominant mechanism of the $0\nu\beta\beta$ decay and information about the lightest neutrino mass will be available from future high-precision cosmological measurements [33].

An unusually large value of the ^{22}C matter radius which recently was extracted from the measured reaction cross sections was analyzed within the three-body cluster model. The sensitivity of the s-motion-dominated ^{22}C geometry to the two-neutron separation energy was explored. A low energy of a few tens of keV is required to reach the alleged experimental lower value of the matter radius, while the experimental mean radius requires an extremely tiny binding. The dependence of the ^{22}C charge radius on the two-neutron separation energy was also calculated. The soft dipole mode in ^{22}C was shown to be strongly affected by the loose binding and should be studied in the process of Coulomb fragmentation [34].

The fusion–fission processes within a nucleus–nucleus collision were studied using the two-stage reaction model. In the first stage (the approach phase), the properties of the system at the touching point were calculated. In the second stage, the evolution of the compact system was described. It was assumed that in the approach process, the symmetry axes of the colliding ions coincide. The distributions at the touching point obtained at the first step were used as the initial conditions for the evolution of a compact system. Both the approach phase and the evolution of the compact system were described in terms of Langevin equations for the collective coordinates (deformation parameters). At both stages, the shell structure of the colliding ions and that of the compound nucleus were taken into account. When colliding nuclei are spherical in their ground state, the shell effects in the deformation energy of the nuclei have a substantial influence on the characteristics of the combined system at the touching point as well as on the probability of evaporation-residue formation [35].

In nucleus–nucleus collisions at energies near the Coulomb barrier, a complete fusion and a quasi-fission are the competing processes. This competition strongly reduces the value of the fusion cross section. The nucleus–nucleus reactions at deep sub-barrier energies, which are lower than the ground-state energies of the compound nuclei, were proposed to be used for thorough investigations of the dynamics of quasi-fission. At these energies, the capture cross section is very small and the unique quasi-fission can be studied experimentally. The capture cross sections for selected pairs of colliding nuclei were calculated within the quantum diffusion approach taking into account the coupling of relative motion of nuclei with their intrinsic degrees of freedom. The optimal combinations of colliding nuclei suitable for studying the «pure» quasi-fission process were proposed [36].

A theoretical model was developed that yields the shifts and widths of Feshbach resonances in an atomic waveguide. The model is based on a multichannel approach for confinement-induced resonances (CIRs) and atomic transitions in the waveguides in the multimode regime. As the interatomic interaction, the four-channel tensorial potential modeling resonances of different structure were used. Shifts and widths of s-, d- and g-wave magnetic Feshbach resonances of Cs atoms emerging in harmonic waveguides as CIRs were calculated as well as the resonant enhancement of the transmission at zeros of the free space scattering length. It was found that there is a linear dependence of the width of the resonance on the longitudinal atomic momentum and quadratic dependence on the waiveguide width [37].

The azimuthal anisotropies of the collective transverse flow of hadrons were investigated in a large range of heavy-ion collision energy within the parton-hadron-string dynamics (PHSD) microscopic transport approach which incorporates explicit partonic degrees of freedom in terms of strongly interacting quasiparticles (quarks and gluons) in line with an equation-of-state from lattice QCD as well as dynamical hadronization and hadronic dynamics in the final reaction phase. The experimentally observed increase of the elliptic flow v_2 with bombarding energy was successfully described in terms of the PHSD approach in contrast to a variety of other kinetic models based on hadronic interactions. The analysis of higher-order harmonics v_3 and v_4 shows a similar tendency of growing deviations between partonic and purely hadronic models with increasing bombarding energy. This signals that the excitation functions of azimuthal anisotropies provide a sensitive probe for the underling degrees of freedom excited in heavy-ion collisions [38].

The rapidly evolving laser technology can provide the laser power which is sufficient for the formation of positrons from cascade processes in the photon–electron–positron plasma generated by photon–laser, electron–laser, or laser–laser interactions. A method was elaborated to calculate the total cross section in the subthreshold (multiphoton) region accounting for the effect of finite laser–pulse duration in e^+e^- pair production off a probe photon. A nontrivial dependence of the e^+e^- production probability on the pulse duration was found. Just below the threshold of the weak-field Breit–Wheeler process, the short laser pulses increase the cross section up to two orders of magnitude relative to a monochromatic plane wave [39].

Using realistic wave functions, the proton–neutron and proton–proton momentum distributions in ^{3}He and ^{4}He were calculated as a function of the relative, $k_{\rm rel}$, and center of mass, $K_{\rm c.m.}$, momenta and the angle between them. For large values of $k_{\rm rel} \gtrsim 2^{-1}$ and small values of $K_{\rm c.m.} \lesssim 1.0$ fm^{-1}, both distributions are angle independent and decrease with increasing $K_{\rm c.m}$. At the same time the pn distribution is factorizing into the deuteron momentum distribution times a rapidly decreasing function of $K_{\rm c.m.}$, in agreement with the two-nucleon $(2N)$ short-range correlation (SRC) picture. When $K_{\rm c.m.}$ and $k_{\rm rel}$ are both large, the distributions exhibit a strong angle dependence, which is an evidence of three-nucleon $(3N)$ SRC. The predicted centre-of-mass and angular dependence of $2N$ and $3N$ SRC should be observable in two-nucleon knock-out processes $A(e,e'pN)$ [40].

Theory of Condensed Matter

Theoretical investigations within the theme «Theory of Condensed Matter and New Materials» were continued in the framework of the following projects:

- Physical Properties of Complex Materials and Nanostructures;
- Mathematical Problems of Many-Particle Systems.

A microscopic theory of the electrical conductivity $\sigma(\omega)$ within the $t{-}J$ model was developed. An exact representation for $\sigma(\omega)$ was obtained using the memory-function technique for the relaxation function in terms of the Hubbard operators, and the generalized Drude law was derived. The relaxation rate due to the decay of charge excitations into particle-hole pairs assisted by antiferromagnetic spin fluctuations was calculated in the mode-coupling approximation. Using results for the spectral function of spin excitations, we calculated the relaxation rate and the optical and statistical conductivity in a wide range of alloy temperatures. The reasonable agreement of the theory with experimental data for cuprates proves the important role of spin-fluctuation scattering in the charge dynamics [41].

In the low doping regime, the ground-state energy of the $t{-}J$ model for $J/t \ll 1$ was shown to separate into hole-rich ferromagnetic and hole-depleted antiferromagnetic regions. This picture holds true up to a threshold concentration $\delta = \sqrt{J(2\pi t)}$ [42].

A precise numerical study of phase dynamics in high-temperature superconductors under electromagnetic radiation was performed. The charging of superconducting layers in the bias current interval corresponding to the Shapiro step was observed. A remarkable change in the longitudinal plasma wavelength at parametric resonance was shown. Double resonance of the Josephson oscillations with radiation and plasma frequencies leads to additional parametric resonances and the non-Bessel Shapiro step [43, 44].

Upper and lower bounds on the fidelity susceptibility were derived in terms of macroscopic thermodynamic quantities, such as the susceptibilities and thermal average values. The quality of the bounds was checked against the exact expressions for a single spin in an external magnetic field. Their usefulness was illustrated by two examples of many-particle models which were exactly solved in the thermodynamic limit: the Dicke superradiance model and the single-impurity Kondo model. It was shown that when divergent behavior is considered, the fidelity susceptibility and the thermodynamic susceptibility are equivalent for a large class of models exhibiting critical behavior [45].

A theoretical model for interpretation of mobility collapse as a function of the concentration of free carriers in GaN-based films was suggested. The calculations were performed based on the traditional approach of

Read cylinders. Along with phonon and impurity scattering mechanisms, electron scattering due to charged dislocations embedded into the walls was taken into account in the model. An expression was obtained for the height of the drift barrier depending on the concentration of free carriers. Based on the derived equations, the dependence of the location of the mobility minimum on the dislocation structure was interpreted [46].

The low-temperature thermal conductivity in polycrystalline graphene was theoretically studied. The contributions from three branches of acoustic phonons were calculated by taking into account scattering on sample borders, point defects, and grain boundaries. Phonon scattering due to sample borders and grain boundaries was shown to result in a T^n-behaviour in the thermal conductivity where n varies between 1 and 2. This behaviour was found to be more pronounced for nanosized grain boundaries [47].

The Green functions play an important role in the calculation of the local density of states of the carbon nanostructures. Their nature for the variously oriented and disclinated graphene-like surfaces was investigated. The case of a small perturbation generated by two heptagonal defects was studied, and from the character of the local density of states in the border sites of these defects their minimal and maximal distances on the perturbed cylindrical surface were derived. For this purpose, the given surface was transformed into a chain using the Haydock recursion method [48].

Effects of decoherence in an open quantum dot coupled with its environment at a fixed temperature were investigated. The motion of electrons in the quantum dot was assumed to be confined by a two-dimensional parabolic potential, and the interaction between electrons was approximated by the effective potential of the Johnson–Payne type. The degradation of entanglement of the electron orbital motion (charge entanglement) depending on the temperature of environment and the QD parameters (quantum dot shapes and the strength of electron interaction) was analyzed [49, 50].

A theory of neutron scattering by statistical medium was developed on the basis of general principles of quantum statistical mechanics. The theory of scattering of particles (e.g., neutrons) by statistical medium was reformulated and generalized for a nonequilibrium statistical medium. The correlation scattering function of the relevant variables gives rise to a very compact and entirely general expression for the scattering cross section of interest. The formula obtained by Van Hove provides a convenient method of analyzing the properties of slow neutron and light scattering by systems of particles such as gas, liquid or solid in the equilibrium state. In our study, a new method of quantum-statistical derivation of the space and time Fourier transforms of the Van Hove correlation function was formulated. Thus, in place of the usual Van Hove scattering function, a generalized one was deduced and the result was shown to be of greater potential utility than those previously given in the literature. The feasibility of light- and neutron-scattering experiments to investigate the appropriate problems in real physical systems was analyzed and discussed [51].

The one-dimensional Bose gas is an unusual superfluid. In contrast to higher spatial dimensions, the existence of nonclassical rotational inertia is not directly linked to the dissipationless motion of infinitesimal impurities. Recently, experimental tests with ultracold atoms have been started and quantitative predictions for the drag force experienced by moving obstacles have become available. This topical review discusses the drag force obtained from a linear response theory in relation to Landau criterion of superfluidity. Based upon improved analytical and numerical understanding of the dynamical structure factor, results for different obstacle potentials were obtained, including single impurities, optical lattices, and random potentials generated from speckle patterns. The dynamical breakdown of superfluidity in random potentials was discussed in relation to Anderson localization and the predicted superfluid–insulator transition in these systems [52].

The evolution of a quasi-isolated finite quantum system from a nonequilibrium initial state was considered. The condition of quasi-isolation allows for the description of the system dynamics on the general basis, without specifying the system details and for arbitrary initial conditions. The influence of surrounding results in (at least partial) equilibration and decoherence. The resulting equilibrium state bears information on initial conditions and is characterized by a representative ensemble. It has been shown that the system average information with time does not increase. The partial equilibration and nonincrease of average information explain the irreversibility of time [53].

An effective method for ultrafast magnetization reversal of nanoclusters was suggested. The method is based on coupling of a nanocluster to a resonant electric circuit. This coupling causes the appearance of a magnetic feedback field acting on the cluster, which drastically shortens the magnetization reversal time. The influence of the resonator properties, nanocluster parameters, and external fields on the magnetization dynamics and reversal time was analyzed. The magnetization reversal time can be made many orders shorter than the natural relaxation time. The reversal was studied for both the cases of a single nanocluster as well as for the system of many nanoclusters interacting through dipole forces [54].

The totally asymmetric exclusion process in discrete time with generalized updating rules was considered. A control parameter into the interaction between particles was introduced. Two particular values of the parameter correspond to known parallel and sequential updates. In the whole range of its values, the interaction varies from repulsive to attractive. In the latter case the particle flow demonstrates an apparent jamming tendency not typical for the known updates. The master equation for N particles on the infinite lattice by the Bethe ansatz was solved. The nonstationary solution for arbitrary initial conditions was obtained in a closed determinant form [55].

The joint exit probabilities of particles in the totally asymmetric simple exclusion process (TASEP) from space-time sets of a given form were studied. Previous results on the space-time correlation functions of the TASEP, which correspond to exits from the sets bounded by straight vertical or horizontal lines, were extended. In particular, our approach allows us to remove ordering of time moments used in previous studies so that only a natural space-like ordering of particle coordinates remains. Sequences of general staircase-like boundaries going from the northeast to southwest in the space-time plane were considered. The exit probabilities from the given sets were derived in the form of a Fredholm determinant defined on the boundaries of the sets. In the scaling limit, the staircase-like boundaries were treated as approximations of continuous differentiable curves. The exit probabilities with respect to points of these curves belonging to an arbitrary space-like path were shown to converge to the universal $Airy_2$ process [56].

The helix-coil transition in a double-stranded homopolynucleotide was considered. The new approach to the melted loops account was proposed. The relative distance between the corresponding monomers of two polymer chains was modelled by the two-dimensional random walk on the square lattice. Returns of the random walk to the origin describe the formation of hydrogen bonds between complementary units. To take into account the interaction of monomers inside the chains, various regimes of return to the origin were considered. One of them involves two competing interactions and demonstrates a nontrivial sharp denaturation transition. The rich phase behavior of the double-stranded homopolynucleotide was discussed in terms of the proposed approach [57].

DUBNA INTERNATIONAL ADVANCED SCHOOL OF THEORETICAL PHYSICS (DIAS-TH)

In 2012, the research and education project DIAS-TH was successfully continued. There were the following activities in the framework of DIAS-TH:

• X Winter School on Theoretical Physics (January 30–February 6);

• XVI Research Workshop «Nucleation Theory and Applications» (April 1–30);

• Helmholtz International Summer School–Workshop «Calculations for Modern and Future Colliders (CALC-2012)» (July 23–August 2);

• Helmholtz International School «Dense Matter in Heavy-Ion Collisions and Astrophysics» (August 28–September 8);

• Regular seminars for students and postgraduates were organized;

• Computer processing of videorecords of lectures was continued;

• Web-site of DIAS-TH was supported.

Preliminary Plans for 2013

• XI Winter School on Theoretical Physics (January 28–February 3);

• XVII Research Workshop «Nucleation Theory and Applications» (April 1–30);

• Helmholtz International Summer School–Workshop «Physics of Heavy Quarks and Hadrons» (July 15–28);

• Helmholtz International School «Cosmology, Strings, and new Physics» (September 2–14).

CONFERENCES AND MEETINGS

• International Conference «Classical and Quantum Integrable Systems», January 23–27, Dubna;

• NICA/JINR–FAIR Bilateral Workshop «Matter at Highest Baryon Densities in the Laboratory and in Space», April 2–4, Frankfurt, Germany;

• XX International Colloquium «Integrable Systems and Quantum Symmetries», June 17–23, Prague, Czech Republic;

• International Workshop «Few-Body System», June 27–29, Dubna;

• Advanced Study Institute «Symmetries and Spin», July 1–8, Prague, Czech Republic;

• International Conference «Nuclear Structure and Related Topics (NSRT12)», July 2–7, Dubna;

• International Conference «Dubna–Nano2012», July 9–14, Dubna;

• KLFTP/CAS–BLTP/JINR Workshop on Nuclear Problems, August 2–6, Dubna;

• V International Conference «Precision Physics and Fundamental Physical Constants», September 10–14, Stara Lesna, High Tatras, Slovakia;

• XXI International Baldin Seminar «Relativistic Nuclear Physics and Quantum Chromodynamics», September 10–15, Dubna;

• XX International Symposium «Spin Physics (SPIN2012)», September 16–23, Dubna;

• III South Africa–JINR Symposium «Few to Many Body Systems: Models, Methods and Applications», November 27–30, Stellenbosch, South Africa;

• Round Table «France–Italy–Russia, Dubna», December 16–18, Dubna;

• Armenia–Dubna Workshop on «Problems of Integrable (Supersymmetric) Systems», December 24–25, Dubna.

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