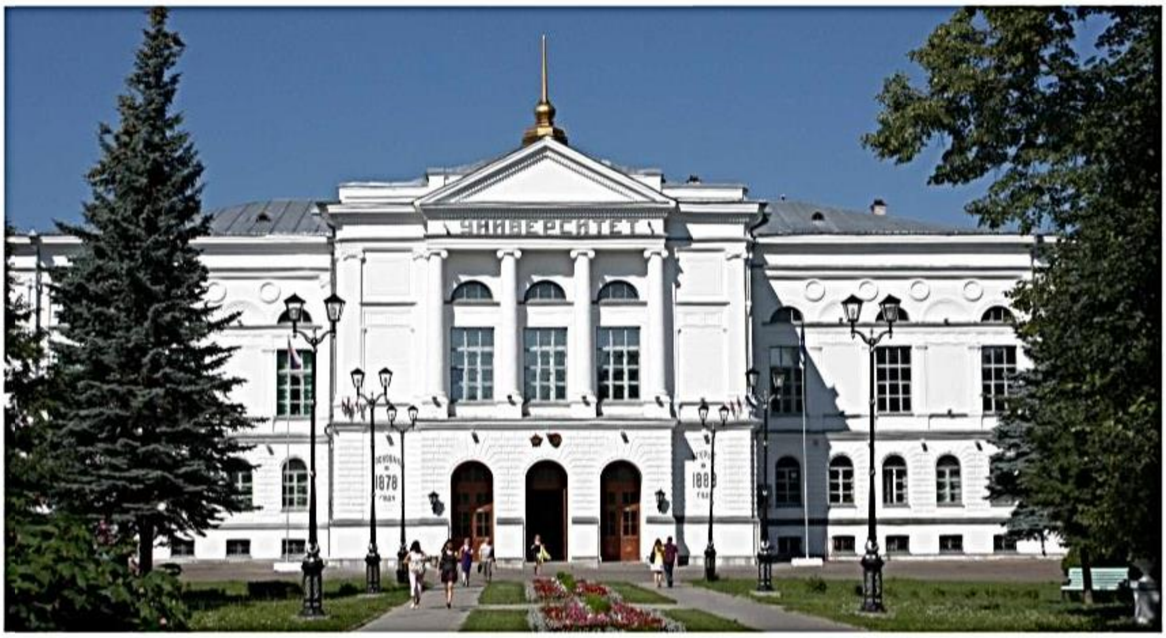
International Workshop

Strong Field Problems in Quantum Theory

6–11 June 2016, Tomsk State University



Program and Abstracts

National Research Tomsk State University

P.N.Lebedev Physical Institute

National Research Tomsk State University
P.N. Lebedev Physical Institute of RAS

International Workshop

Strong Field Problems in Quantum Theory

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Tomsk State University

Program and Abstracts

SCIENTIFIC TECHNOLOGY PUBLISHING HOUSE

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GENERAL INFORMATION

Organizers:

1. National Research Tomsk State University, Laboratory of Quantum Theory of Intense Fields, https://sites.google.com/site/dmgitman0/
2. Tamm Theory Department of the P.N.Lebedev Physical Institute of RAS, Moscow, http://td.lpi.ru/index1.html

Sponsors:

1. The Ministry of Education and Science of Russian Federation
2. The Federal Agency for Scientific Organizations (FASO Russia)
3. Russian Academy of Sciences
4. Russian Foundation for Basic Research

Topics:

- Quantum field theory with unstable vacuum. General methods and approaches
- Strong fields effects in astrophysics, cosmology and neutrino physics
- Superstrong Coulomb field in quantum electrodynamics
- Particles and fields under the influence of external conditions
- General problem of quantum theory and QFT

Workshop Site: http://www.tamm.lpi.ru/confs/sfp/

SCOPE OF WORKSHOP

Even though the complete quantum theory admits a semiclassical description of intense fields when treated as external, or background, fields, the presence of such fields turns out to produce nontrivial quantum effects, such as the Klein paradox, the Hawking black-hole radiation, and the creation from vacuum of electron-positron pairs by external electric and supercritical Coulomb fields. These effects require a nonperturbative consideration for their description within relativistic quantum mechanics, and sometimes also within quantum field theory involving background fields.

The foundation for these theories was laid in the works by the outstanding physicists P.A.M. Dirac, R. Feynman, J. Schwinger, as well as by many others. In recent years, significant attention has been attached to the application of these theories and their corresponding quantum effects to high-energy physics, astrophysics, and condensed matter physics, especially the physics of graphene and other nanostructures.

Even though all these effects and their applications are discussed at various meetings on a regular basis, many important problems of the theory remain untouched, and we believe it is timely to discuss the existing unsolved problems of the nonperturbative approach to theories with background fields, for instance, the problems associated with spontaneous creation of electron-positron pairs by supercritical Coulomb fields, the problems involving the range of applicability of nonperturbative QFT methods to neutrino and nanostructure physics, etc. Any other contributions devoted to these problems and special effects associated with strong fields are certainly welcome.

It is worth noting that the organizing bodies of the Workshop, namely, Lebedev Institute and Tomsk State University (together with Tomsk State Pedagogical University) were among the pioneers of the work on quantum effects in strong fields in the former USSR and Russia. In this respect, one can mention the works of A.I. Nikishov, V.I. Ritus, E.S. Fradkin, A.E. Shabad, I.A. Batalin, D.M. Gitman, V.G. Bagrov, Sh.M. Shwartsman, J.L. Buchbinder, S.P. Gavrilov, as well as their numerous students.

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Shapovalov Alexander
Tchaikovskaya Olga
Zhevlakov Alexey

SCIENTIFIC PROGRAM

Monday, June 06

Tomsk State University
Large Conference Hall of Scientific Library, Lenin Ave. 34a
Old Building

9:00–10:00	Registration
10:00–10:15	Opening
10:15–10:45	*Gitman D.M.* Opening speech
10:45–11:15	**Coffee break**

M o r n i n g S e s s i o n
Quantum Field Theory with Unstable Vacuum (A. Shabad)

11:15–11:45	*Di Piazza A.* Recollision processes in strong-field QED
11:45–12:15	*Kim S.P.* In-out formalism for effective actions in QED and gravity
12:15–12:45	*Schubert C.* Multiloop Euler-Heisenberg Lagrangians, Schwinger pair creation, and the photon S-matrix
12:45–13:05	*Adorno T.C.* Particle creation from the vacuum by a peak electric field
13:05–14:45	**Lunch**

E v e n i n g S e s s i o n
Superstrong Field in Quantum Electrodynamics (A. Barvinsky)

14:45–15:15	*Shabaev V.M.* Quantum electrodynamics of heavy ions and atoms
15:15–15:45	*Sinyukov Yu.M.* Entanglement of scales as a possible mechanism for decoherence and thermalization in relativistic heavy ion collisions
15:45–16:15	*Lewkowicz M.* Signature of Schwinger's pair creation rate via radiation generated in graphene by strong electric current
16:15–16:45	**Coffee break**
16:45–17:15	*Shabad A.E.* Quantum electromagnetic nonlinearity affecting charges and dipole moments
17:15–17:35	*Krachkov P.A.* Quasiclassical approach and high energy QED processes in the field of a heavy atom

17:35–17:55 *Juchnowski Ł.K.* Nonequilibrium meson production in strong fields
17:55–18:25 *Smirnov A.G.* Reduction by symmetries in singular quantum-mechanical problems

Tuesday, June 07

Tomsk State University
Large Conference Hall of Scientific Library, Lenin Ave. 34a
Old Building

Morning Session
General Problems of Quantum Theory and QFT (V. Man'ko)

9:00–9:30 *Fulling S.A.* Curved-space quantum field theory of the 1970s elucidates boundary "Casimir" energy today
9:30–10:00 *Barvinsky A.O.* Holography beyond conformal invariance and AdS isometry?
10:00–10:30 *Berezin V.A.* Towards understanding conformal gravity
10:30–10:50 *Sushkov S.V.* Cosmology with nonminimal kinetic coupling and a Higgs-like potential
10:50–11:20 Coffee break
11:20–11:50 *Brodsky S.J.* New insights into color confinement and hadron dynamics from light-front holography and superconformal quantum mechanics (Skype)
11:50–12:20 *Lyubovitskij V.E.* Hadron structure in holographic QCD
12:20–12:50 *Dorokhov A.E.* Status of the muon g-2 problem
12:50–13:10 *Kulikova A.V.* Classical aspect of anomalous magnetic moment of electron
13:10–15:00 Lunch

Evening Session
Quantum Field Theory with Unstable Vacuum (S. Shvartsman)

15:00–15:30 *Smolyansky S.A.* Vacuum particle creation in strong fields as a field induced phase transition
15:30–16:00 *Gitman D.M.* QFT treatment of processes in strong external backgrounds
16:00–16:30 *Gavrilov S.P.* Radiative processes in graphene and similar nanostructures at strong electric fields
16:30–17:00 Coffee break

17:00–17:20	*Maltsev I.A.* Electron-positron pair production in slow collisions of bare nuclei
17:20–17:40	*Fillion-Gourdeau F.* Dynamical pair production in graphene
17:40–18:00	*Aleksandrov I.A.* Electron-positron pair production in space-time varying external electric fields
18:00–18:20	*Dvornikov M.S.* Creation of neutrino-antineutrino pairs in dense matter moving with acceleration

Wednesday, June 08

Cultural Program
TSU Main Entrance

Tours in English

10:00–10:50 Visiting TSU Department of Rare Books
11:00–11:50 Visiting Museum of History of TSU

Tours in Russian

10:00–10:50 Visiting Museum of History of TSU
11:00–11:50 Visiting TSU Department of Rare Books

Tour around Tomsk
in English and Russian (16:30-18:30)

Thursday, June 09

Tomsk State University
Large Conference Hall of Scientific Library, Lenin Ave. 34a
Old Building

Morning Session
General Problems of Quantum Theory and QFT (S. Lyakhovich)

9:00–9:30	*Man'ko V.I.* Conventional quantum mechanics with probability instead of wave function
9:30–10:00	*Assirati J.L.M.* Covariant operator orderings in curved space
10:00–10:20	*Jafarov R.G.* Landau pole problem in quantum field theory: from N.N. Bogolyubov to the present days

10:20–10:40	*Kazinski P.O.* Large mass expansion of the one-loop effective action of a scalar field on the two dimensional Minkowski space with non-trivial (1+1) splitting
10:40–11.00	*Ahmadiniaz N.* Multiphoton amplitude and generalized LKF transformation in scalar QED
11:00–11:30	**Coffee break**
11:30–12:00	*Lyakhovich S.L.* Involutive form of field equations and consistency of interactions
12:00–12:30	*Sharapov A.A.* Variational tricomplex and BRST theory
12:30–12:50	*Kaparulin D.S.* Higher derivative extensions of 3d Chern-Simons models: symmetries, conservation laws and stability
12:50–13:10	*Fellah M.A.* Strong field problems in Horava-Lifshitz gravity
13:10–14:45	**Lunch**

E v e n i n g S e s s i o n
Particles and Fields under the Influence of External Conditions
(V. Berezin)

14:45–15:15	*Vassilevich D.V.* Casimir effect with graphene
15:15–15:45	*Karbstein F.* Optical probes of quantum vacuum nonlinearity in strong electromagnetic fields
15:45–16:15	*Shelepin A.L.* Orientable objects in relativistic quantum theory
16:15–16:45	**Coffee break**
16:45–17:15	*Reshetnyak A.A.* Electronic properties of AB-bilayer graphene in the magnetic and electric fields with general gap energy
17:15–17:35	*Palesheva E.V.* Casimir energy for 3-dimensional Riemann caps
17:35–17:55	*Satunin P.S.* Particle decays in external field: the “Worldline Instanton” approach
17:55–18:15	*Kalinichenko I.S.* Non-perturbative corrections to the one-loop thermodynamical potential from massive fields in a constant magnetic background

Friday, June 10

Tomsk State University
Large Conference Hall of Scientific Library, Lenin Ave. 34a
Old Building

Morning Session
Strong Fields in Astrophysics, Cosmology and Neutrino Physics
(D. Vassilevich)

9:00–9:30	*Starobinsky A.A.* Inflation: determination of details from observational data
9:30–10:00	*Dvornikov M.S.* New model for the generation of strong large-scale magnetic fields in neutron stars
10:00–10:20	*Lobanov A.E.* Neutrino oscillations in matter
10:20–10:40	*Tanaka O.* (*Konstantinova O.A.*) The review of the elementary particles physics in the external electromagnetic fields studies at KEK
10:40–11.00	*Grokhovskaya A.A.* Construstion and identification of curvature radiation profiles from pulsars
11:00–11:30	**Coffee break**
11:30–12:00	*Weigel H.* Cosmic strings stabilized by quantum fluctuations
12:00–12:30	*Morozumi T.* Creation and evolution of particle number asymmetry in an expanding universe
12:30–12:50	*Okane H.* Constraint on seesaw model parameters with electroweak vacuum stability
12:50–13:10	*Zaripov F.* Modified equations in the theory of induced gravity. Cosmological solutions and constant evolution
13:10–14:45	**Lunch**

Evening Session
Particles and Fields under the Influence of External Conditions / General Problems of Quantum Theory and QFT (V. Shabaev)

14:45–15:05	*Loginov A.S.* Polarization and angular distribution structure of synchrotron radiation in non-relativistic approximation
15:05–15:25	*Zlatev S.* Two-photon emission by a charged particle in a magnetic field
15:25–15:45	*Lebedev S.L.* Spin radiation corrections to probability and power of radiation in classical and quantum electrodynamcs

15:45–16:05	*Karlovets D.V.* Scattering of wave packets and non-plane-wave particles in the Wigner formalism
16:05–16:35	**Coffee break**
16:35–16:55	*Markov Yu.A.* Higher order wave equation within the Duffin-Kemmer-Petiau formalism,
16:55–17:15	*Shapovalov A.V.* Symmetry of nonlocal Gross-Pitaevskii equation
17:15–17:35	*Breev A.I.* Non-commutative integration of (2+1) Dirac equation
17:35–17:55	*Zyryanova O.V.* On Gribov horizon in linear gauge
17:55–18:15	*Moshin P.Yu.* Finite field-dependent BRST-anti-BRST transformations: Jacobians and application to the Standard Model

Saturday, June 11

Morning Session
Large Conference Hall of Scientific Library, Lenin Ave. 34a, Old Building
Round Table "Theoretical Physics in Tomsk" (O.N. Tchaikovskaya)

9:30–9:40	*Tchaikovskaya O.N.* (Dean of Physics Dept.) Opening speech
9:40–10:00	*Bagrov V.G.* Tomsk State University as the progenitor of theoretical physics in Tomsk
10:00–10:30	*Gitman D.M.* History of the group of theoretical physics at TSPU
10:30–12:30	Reminiscences of the members of the theoretical group

Evening Session
Tomsk State University (venue to be confirmed)
Lectures for Students and Young Scientists (in Russian)

14:00–15:00	*Starobinsky A.A.* A brief history of the Universe: four ages and four cosmological constants
15:15–16:45	*Man'ko V.I.* New quantum information-entropic inequalities in probability representation of quantum mechanics and applications of entanglement and other quantum correlations in quantum technologies
17:00–18:30	*Barvinsky A.O.* To be announced later

If possible, the following talks will also be included:

1. *Kuleshov V.M.* Two- and three-dimensional Coulomb problem with supercritical charge.
2. *Meireles dos Santos M.* Entanglement in a system of two interacting spins.

Cultural Program

Visiting Museum of Physics of TSU
Rendezvous: Entrance of TSU Center of Culture
(behind the TSU Main Building)

14:00–15:00 Tour in English
15:30–16:30 Tour in Russian

BANQUET

Dancing Hall, TSU Center of Culture (18:30)
Rendezvous: Entrance of TSU Center of Culture
(behind the TSU Main Building)

ADDITIONAL SCIENTIFIC PROGRAM

June 13–15

Tomsk State University
(time and venue to be confirmed)

Lectures for Students and Young Scientists (in Russian)

Shabad A.A. Nonlinear effects in quantum electrodynamics
Dvornikov M.S. Neutrino oscillations in external fields

ABSTRACTS

Particle creation from the vacuum by a peak electric field

T.C. Adorno[1], S.P. Gavrilov[1,2], and D.M. Gitman[1,3,4]

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[2] Department of General and Experimental Physics,
Herzen State Pedagogical University of Russia, St. Petersburg, Russia
[3] P.N. Lebedev Physical Institute, Moscow, Russia
[4] Instituto de Física, Universidade de São Paulo, Brazil

In the framework of quantum electrodynamics (QED) with t-electric potential steps, we study particle creation from the vacuum by the peak electric field, unprecedented in the literature until now. The electric field, characterized by the existence of a peak at a well-defined time instant, is considered as a new two-parameter regularization for a constant electric field. With the exact solutions of the Dirac equation, non-perturbative characteristics of the effect are discussed in detail and, in particular, compared with the well-known one-parameter regularizations of the constant field, namely, the Sauter-type and the T-constant electric fields. The results show that the most significant contribution for differential and total quantities happen when the fields under consideration switch on and off adiabatically, whose influence in vacuum is maximal. In such a case, the total number of pairs created and the vacuum-vacuum probability are similar to estimations of a Sautertype and constant electric fields.

Multiphoton amplitude and generalized LKF transformation in scalar QED

N. Ahmadiniaz

Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju, Korea

We apply the worldline formalism to amplitudes in scalar quantum electrodynamics (QED) involving open scalar lines, with an emphasis on their non-perturbative gauge dependence. At the tree-level, we study the scalar propagator interacting with any number of photons in configuration space as well as in momentum space. At one-loop, we rederive, in an efficient way, the off-shell vertex in an arbitrary dimension and any covariant

gauge. Generalizing the Landau-Khalatnikov-Fradkin transformation (LKFT) to the non-perturbative propagator, we find simple non-perturbative transformation rules for arbitrary x-space amplitudes under a change of the covariant gauge parameter in terms of conformal cross ratios.

Electron-positron pair production in space-time varying external electric fields

I.A. Aleksandrov[1,2], G. Plunien[3], and V.M. Shabaev[1]

[1] *Department of Physics, St. Petersburg State University, Russia*
[2] *ITMO University, Saint Petersburg, Russia*
[3] *Institut für Theoretische Physik, TU Dresden, Germany*

The Schwinger mechanism of electron-positron pair production in the presence of strong external electric fields is discussed. Although exact expressions for the number density of pairs created can be derived for very few one-dimensional (1D) configurations where the external field depends on one variable (e.g., time *t* or spatial coordinate *x*), it is possible to analyze more realistic space- and time-dependent backgrounds by means of numerical calculations. Our approach is based on solving the Dirac equation in momentum representation. The number of particles created in different 2D configurations is obtained numerically and compared with the analytical results for several exactly solvable 1D models. It was found that the switch on and off effects may play a very important role, especially if one considers a “sharp” time- or space-dependent switching function. Finally, it was demonstrated that similar calculations can be easily performed in the case of scalar QED. The method designed can be subsequently applied to a variety of different problems.

Covariant operator orderings in curved space

J.L.M. Assirati

Instituto de Física, Universidade de São Paulo, Brazil

The ambiguities due to the problem of operator orderings that arise in quantum mechanics are shown to be substantially reduced if one takes covariance considerations into account both in flat and curved space. Operational rules for ordering in flat and curved space in general coordinates

are presented. It is shown that additional ambiguities arise for a particle in curved space in the form of a potential that depends on curvature.

Holography beyond conformal invariance and AdS isometry?

A.O. Barvinsky

P.N. Lebedev Physical Institute, Moscow, Russia
Department of Physics, National Research Tomsk State University, Russia

We suggest that the principle of holographic duality can be extended beyond conformal invariance and AdS isometry. Such an extension is based on a special relation between functional determinants of the operators acting in the bulk and on its boundary. This relation holds for operators of general spin-tensor structure on generic manifolds with boundaries irrespective of their background geometry and conformal invariance, and it apparently underlies numerous $O(N^0)$ tests of AdS/CFT correspondence, based on direct calculation of the bulk and boundary partition functions, Casimir energies and conformal anomalies. The generalized holographic duality is discussed within the concept of the "double-trace" deformation of the boundary theory, which is responsible in the case of large N CFT coupled to the tower of higher spin gauge fields for the renormalization group flow between infrared and ultraviolet fixed points. A possible extension of this method beyond one-loop order is also briefly discussed.

Towards understanding conformal gravity

V.A. Berezin

Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

Postulating the conformal invariance of the theory, we construct a phenomenological model of scalar particle creation in strong gravitational fields. It appears that such a model intrinsically contains the conformal gravity, i.e., the square of the Weyl tensor, C^2, in the action integral, as well as the General Relativity, i.e., the scalar curvature R and the φ^4 self-interaction term for the scalar field. The latter property provides the possibility, through the Brout-Englert-Higgs mechanism, for the spontaneous symmetry breaking of conformal invariance and for the acquisition of non-zero rest masses by the created particles.

Non-commutative integration of (2+1) Dirac equation

A.I. Breev and A.V. Shapovalov

Department of Physics, National Research Tomsk State University, Russia

A non-commutative reduction and new exact solutions of the Dirac equation with external electromagnetic fields in (2+1) dimensions are considered. The integrability of the Dirac equation on curved backgrounds is investigated.

New insights into color confinement and hadron dynamics from light-front holography and superconformal quantum mechanics

S. Brodsky

SLAC National Accelerator Laboratory, Stanford University, USA

Light-front holography provides a precise relation between the bound-state amplitudes in the fifth dimension of AdS space and the boost-invariant light-front wavefunctions describing the internal structure of hadrons in physical space-time. The resulting valence Fock-state wavefunctions of the light-front QCD Hamiltonian satisfy a relativistic equation of motion with an effective confining potential. If one requires the effective action which underlies the QCD Lagrangian to remain conformally invariant and extends the formalism of de Alfaro, Fubini and Furlan to light-front Hamiltonian theory, the potential has the unique form of a harmonic oscillator potential, and a mass gap arises. The result is a nonperturbative relativistic light-front wave equation – the Light-Front Schroedinger Equation – which incorporates color confinement and other essential spectroscopic and dynamical features of hadron physics, including a massless pion for zero quark mass and linear Regge trajectories with the same slope in the radial quantum number n and orbital angular momentum L. One can also construct an effective QCD light-front Hamiltonian for both mesons and baryons based on superconformal algebra. The resulting baryon trajectories have the same slope in n and L as the mesons. The superconformal construction is shown to be equivalent to a semi-classical approximation to light-front QCD and its embedding in AdS space.

The specific breaking of conformal invariance uniquely determines the effective confinement potential. The generalized supercharges connect the baryon and meson spectra to each other in a remarkable manner. The mesons and baryons have the same mass if one identifies the relative orbital angular momentum L_M of the mesons with the relative internal orbital angular momentum L_B of the quark-scalar diquark baryons, where $L_M = L_B + 1$. We also show how the mass scale underlying confinement and hadron masses determines the scale controlling the evolution of the perturbative QCD coupling. The relation between scales is obtained by matching the nonperturbative dynamics, as described by an effective conformal theory mapped to the light-front and its embedding in AdS space, to the perturbative QCD regime computed to four-loop order. One derives a running QCD coupling $\alpha_s(Q^2)$ defined at all momenta which is consistent with the measured effective couping defined from the Bjorken sum rule and the measured perturbative scale Λ_{MSbar}.

Recollision processes in strong-field QED

A. Di Piazza

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Two oppositely-charged particles created within a microscopic space-time region can be separated, accelerated over a much larger distance and brought to a recollision by a laser field. Consequently, new reactions become feasible, where the energy absorbed by the particles is efficiently released. By investigating the laser-dressed polarization operator, we identify a new contribution describing high-energy recollisions experienced by an electron-positron pair generated by pure light when a gamma photon impinges on an intense, linearly-polarized laser pulse [1]. The energy absorbed in the recollision process corresponds to a large number of laser photons and can be exploited to prime high-energy reactions. Thus, the recollision contribution to the polarization operator differs qualitatively and quantitatively from the well-known one describing the annihilation of a virtual electron-positron pair within the microscopic formation region.

REFERENCES

[1] S. Meuren, K.Z. Hatsagortsyan, C.H. Keitel, and A. Di Piazza, High-energy recollision processes of laser-generated electron-positron pairs, Phys. Rev. Lett., **114**, 143201 (2015).

Status of the muon g-2 problem

A.E. Dorokhov[1,2,3], A.E. Radzhabov[4], and A.S. Zhevlakov[2]

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[2] Department of Physics, National Research Tomsk State University, Russia
[3] N.N. Bogoliubov Institute of Theoretical Problems of Microworld, M.V. Lomonosov Moscow State University, Russia
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In this report, we briefly review the theoretical and experimental status of the muon anomalous magnetic moment g-2 problem, which becomes still more intriguing due to a new experiment planned at Fermilab in 2017.

Creation of neutrino-antineutrino pairs in dense matter moving with acceleration

M.S. Dvornikov

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, IZMIRAN, Moscow, Russia
Department of Physics, National Research Tomsk State University, Russia

I study the evolution of neutrinos in a background matter moving with acceleration. First I recall how neutrinos interact with polarized background fermions, moving with a constant velocity, by electroweak forces in the approximation of the Fermi model. Then I generalize the Dirac equation for a massive neutrino interacting with a background matter to account for the matter acceleration. This Dirac equation is formulated in the comoving frame where matter is at rest and exactly accounts for the noninertial effects. I solve the Dirac equation for ultrarelativistic neutrinos in a particular case when matter moves with a linear acceleration. The neutrino quantum states in the linearly accelerated matter are obtained. I demonstrate that the neutrino electroweak interaction with an accelerated matter leads to the vacuum instability, which results in the neutrino-antineutrino pairs creation. I rederive the temperature of the Unruh radiation and find a correction to the Unruh effect due to the specific neutrino interaction with background fermions. As a possible application of the obtained results, I discuss the

neutrino pair creation in a core-collapsing supernova. The astrophysical upper limit on the neutrino masses is obtained.

REFERENCES

[1] M. Dvornikov, JHEP 08 (2015) 151, arXiv:1507.01174.
[2] M. Dvornikov, Mod. Phys. Lett., **A 30**, 1530017 (2015), arXiv:1503.01431.
[3] M. Dvornikov, JHEP 10 (2014) 053, arXiv:1408.2735.

New model for the generation of strong large-scale magnetic fields in neutron stars

M.S. Dvornikov

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, IZMIRAN, Moscow, Russia
Department of Physics, National Research Tomsk State University, Russia

I propose a new model for the generation of strong magnetic fields in magnetars, which are highly magnetized neutron stars with magnetic fields $B > 10^{15}$ G. This model is based on magnetic field instability in matter composed of electrons and nucleons interacting with parity-violating electroweak forces. Using an exact solution of the Dirac equation for an electron in dense matter under the influence of an external magnetic field, I obtain a correction to the chiral magnetic effect caused by the electroweak interaction. I obtain a set of kinetic equations for the spectra of magnetic helicity and magnetic energy, as well as for the chiral imbalance. Based on a numerical solution of these equations, I obtain the growth of a seed magnetic field $B_0 = 10^{12}$ G, typical for a pulsar, up to the values predicted in magnetars. The magnetic fields being generated are of large scale, comparable with a neutron star radius. The time of magnetic field growth is 10^3–10^5 yr, which is comparable with the age of young magnetars. I also consider a possible energy source to power magnetic field growth.

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Strong field problems in Horava-Lifshitz gravity

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In this report, we aim to conduct an in-depth study of a novel gravitational theory which goes under the name of Horava-Lifshitz gravity. The main thrust of the research will be to exhibit the claimed renormalizability of this theory explicitly, either in renormalized perturbation theory or using the non-perturbative renormalization group. The second goal is to formulate cosmological models, as well as quantum cosmology, based on this new theory of gravity, and to pin down precisely the relationship of this gravity to Lifhsitz field theory. We will also try to formulate Horava-Lifshitz gravity in 2 and 3 dimensions and investigate their connections to topological field theory and matrix models.

Dynamical pair production in graphene

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The mechanism of electron-hole production is studied for intrinsic graphene immersed in a time-dependent homogeneous electric field. Owing to the formal analogy between relativistic quantum mechanics and the description of graphene quasiparticles in terms of the massless Dirac equation, this mechanism is interpreted as the Schwinger and the multiphoton pair production processes. The pair density is evaluated for many field configurations. At zero transverse momentum, it is shown that the Fermi bound in the electron-hole momentum spectrum is saturated in a certain momentum window and the pair density depends only on the potential difference between asymptotic potentials before and after the interaction. For nonzero transverse momenta, the pair density is evaluated using numerical methods. Different regimes are studied, and it is demonstrated that many phenomena known in QED pair production from strong fields, such as quantum interference, can also be observed in the behavior of graphene quasi-cosmological models as well as quantum cosmology based on particles.

Curved-space quantum field theory of the 1970s elucidates boundary “Casimir” energy today

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Ideal conductors induce divergent surface energies. Analytic regularization methods remove them by fiat; detailed modeling of materials loses the simplicity and charm of the Casimir theory. A middle way is to take seriously a finite ultraviolet cutoff (on a scalar field) as a model, but that leads to two inconsistent values for the force on a boundary. Generalizing the cutoff in a Lorentz-invariant way reveals this phenomenon to be a variant of the direction dependence of point-splitting discovered by DeWitt and Christensen in the '70s, and a satisfactory ad hoc resolution results. A more realistic model replaces the sharp wall by a power-law potential and promises nonanomalous predictions. Explicit calculations have been done in the exterior of the wall and are under way in the interior, where a Christensen-Wald type of renormalization of the potential is necessary. This work has been carried out over several years at Texas A&M University and the University of Oklahoma.

Radiative processes in graphene and similar nanostructures at strong electric fields

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Low-energy single-electron dynamics in graphene monolayers and similar nanostructures is described by the Dirac model, being a 2+1 dimensional version of massless QED with the speed of light replaced by the Fermi velocity $v_F = c/300$. Methods of strong-field QFT are relevant for the Dirac model, since any low-frequency electric field requires a nonperturbative treatment of massless carriers in case it remains unchanged for a sufficiently long time interval. In particular, the effect of particle creation is crucial for understanding the conductivity of graphene, especially in the so-called nonlinear regime. In this case, the effects of creation and annihilation of electron-hole pairs produced from vacuum by a slowly varying and small-gradient electric field are relevant, thereby substantially affecting the radiation pattern. For this reason, the standard QED text-book theory of photon emission cannot be of any assistance. We construct an appropriate Fock-space representation of the Dirac model, which takes exact account of the effects of vacuum instability caused by external electric fields, and in which the interaction between electrons and photons is taken into account perturbatively, following the general theory (the generalized Furry representation). We consider the effective theory of photon emission and absorption in the first-order approximation, taking into account the unitarity relation and constructing the corresponding total probabilities. We apply this theory to the calculation of total probabilities for emission and absorption of a photon by an electron in a constant electric field. We also suggest recommendations for experimental observations of this phenomenon.

QFT treatment of processes in strong external backgrounds

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Study of e^+e^- pair creation in strong electric fields, Klein paradox, and open roblems with superstrong Coulomb field have led us to a clear understanding that these are many-particle quantum processes. A relativistic quantum mechanics cannot in the general case provide their adequate nonperturbative with respect to external backgrounds treatment. Here one needs a consistent QFT of the matter field in the external background. We recall already existing theories of such kind, as well as some recently constructed theories, and describe existing open problems.

Construstion and identification of curvature radiation profiles from pulsars

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In this report, we use a universal kinematic method of constructing periodic profiles of pulsar radiation [1] based on the model expounded by Radhakrishnan & Cooke [2], according to which the radiation source is a stream of very fast particles (jets) flowing from the magnetic poles in the direction of the lines of magnetic field strength. The idea of this method is that the profile of the pulsar emission can be found as an intersection of the indicatrix surface rotating together with the neutron star magnetosphere with a line stationary in space from the viewpoint of the observer. The indicatrix equation is a surface of the instantaneous output power given by the exact theory of radiation for relativistic charged particles.

Essentially, this is the reverse problem, which does not depend initially on any given model of the pulsar magnetosphere and can help to find the actual configuration of existing emission sources location in the pulsars observed experimentally. It is proposed to use a set of fixed parameters, such as the angle of differing magnetic/rotation axes and the angle formed by the line of sight to the pulsar's rotation axis and by the direction of its magnetic axis, in order to identify the pulsar's profiles constructed in this way with the experimentally observed profiles. In addition, this model allows one to vary the parameters of radiation, e.g., the number and energy of emitted particles (gamma factor), the magnetic field strength and the radius of curvature of a trajectory. This technique allows one to construct the profiles of gross power radiation from pulsars that provide a good approximation of some observed pulsar radiation profiles. The parameters of the kinematic model have been determined from the calculated values of radiation power on a basis of the experimental profiles of pulsars [3] under the nonlinear least square problem, which is solved numerically by the Gauss-Newton method [4].

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Landau pole problem in quantum field theory: from N.N. Bogolyubov to the present days

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The oldest problem of quantum field theory, being the asymptotic behavior at large momenta (or at short-distances), is discussed and results of our investigation for the asymptotical behavior of the amplitude at short distances in four-dimensional scalar field theory are presented. To formulate, in our calculation model, the two-particle approximation of mean-field expansion, we use an iteration scheme of solving the Schwinger-Dyson equations with a fermion bilocal source. We have considered nonlinear integral equations in the deep-inelastic region of momenta. As a result, we obtain a non-trivial behavior of the amplitude at large momenta, as we search for the location of non-physical poles (Landau poles) in the amplitude at different coupling constants.

Nonequilibrium meson production in strong fields

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We develop a kinetic equation approach to nonequilibrium pion and sigma meson production in a time-dependent, chiral symmetry breaking field according to the inertial mechanism [1]. We investigate the question to what extent the low-momentum pion enhancement observed in heavy-ion collisions at CERN-LHC can be addressed within this formalism. As a first step [2], we consider the inertial mechanism for nonequilibrium production of σ–mesons and their simultaneous decay into pion pairs for two cases of σ mass evolution. A complete description of the σ-π system requires the solution of the relativistic Boltzmann equation including π-π rescattering effects with a condensate component in the pion distribution function. We present the solution of the kinetic equation for a rapidly expanding hadronic fireball (Hubble flow). We employ techniques that have been developed for studying kinetic processes in the expanding Universe [3].

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Non-perturbative corrections to the one-loop thermodynamical potential from massive fields in a constant magnetic background

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Explicit expressions for the one-loop non-perturbative corrections to the thermodynamical potential are derived at both the strong and weak magnetic field limits. A complete form of the high-temperature expansion for the perturbative part of thermodynamical potential is presented. Bosonic and fermionic cases are considered, as well as a nonzero chemical potential.

Higher derivative extensions of 3d Chern-Simons models: symmetries, conservation laws and stability

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We consider a class of 1-form field $A = A_\mu dx^\mu$ models on 3d Minkowski space with the action

$$S = \frac{1}{2\chi^2}\int * A \wedge (a_0 A + a_1 (*\chi d) A + a_2 (*\chi d)^2 A + a_3 (*\chi d)^3 A + \ldots + a_n (*\chi d)^n A),$$

where χ is a constant with the inverse dimension of mass, $a_0, \ldots, a_n$ are some real dimensionless coefficients, $*$ is Hodge conjugation, and the signature is $(+,-,-)$. For the generic theory of order n we suggest a procedure of constructing n-parametric family of the Noether symmetries and related second-rank conserved tensors whose structure is explicitly identified. In the gauge invariant case $a_0 = 0$, one of the symmetries trivializes, and the corresponding families include $n-1$ parameters. In some cases, depending on the values of the coefficients $a_0, \ldots, a_n$, the positive tensors exist among the conserved quantities, while in the other cases, none of the conserved quantities is positive. Once a positive conserved tensor exists, the theory is classically stable, even though the canonical energy is unbounded.

Optical probes of quantum vacuum nonlinearity in strong electromagnetic fields

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We discuss various optical probes of quantum vacuum nonlinearity in strong electromagnetic fields. Our focus is particularly on signatures of quantum vacuum nonlinearity in inhomogeneous field profiles, as attainable in the focal spots of realistic high-intensity laser experiments.

Scattering of wave packets and non-plane-wave particles in the Wigner formalism

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We develop a perturbative approach to the 2→2 scattering of wave packets and particles, whose wave functions do not represent plane waves, where the wave packet width in momentum representation serves as a small parameter, while all the incoming and outgoing particles are described by their Wigner functions. By using a family of such functions describing, in particular, electrons with the orbital angular momentum (so-called vortex electrons) and the Airy ones, we obtain general formulas for the scattering probability when the incoming particles bear some complex phases. The role of these phases is studied. Possible generalizations of processes in external fields are discussed.

Large mass expansion of the one-loop effective action of a scalar field on the two dimensional Minkowski space with non-trivial (1+1) splitting

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A large mass expansion of the one-loop effective action of a scalar field on the two dimensional Minkowski space is found in the system of coordinates where the metric $g_{\mu\nu}(t,x) \neq \eta_{\mu\nu} = \mathrm{diag}(1,-1)$ and $g_{\mu\nu}(t,x)$ tends to $\eta_{\mu\nu}$ at the spatial and temporal infinities. It is shown that, apart from the Coleman-Weinberg potential, this expansion contains the terms analytic and non-analytic in $1/m^2$, where m is the mass of a scalar field. A general unambiguous expression for the one-loop correction to the effective action on non-stationary backgrounds is derived.

In-out formalism for effective actions in QED and gravity

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Recently, quantum field theory in strong background fields such as electromagnetic fields or curved spacetimes has raised not only theoretical interest but also experimental interest. Intense lasers, for instance, ELI or IZEST, open a window for possible observations of nonperturbative quantum effects, such as the spontaneous pair production from the Dirac sea and the birefringence, photon-photon scattering and photon splitting from the nonlinear vacuum polarization. An intense electromagnetic field or a matter field in a curved spacetime can probe the quantum structure of the Dirac sea or the spacetime. The Schwinger effect and the Hawking radiation have been the most prominent nonperturbative phenomena for many decades. For this purpose one needs quantum field theoretical methods to find the one-loop effective action or the pair-production rate in electromagnetic fields or black holes.

More than six decades ago, Schwinger introduced the in-out formalism based on the variational principle, which has been further elaborated by DeWitt. In the in-out formalism, the one-loop effective action is obtained from the scattering matrix between the in-vacuum and the out vacuum, which in turn is expressed in terms of Bogoliubov coefficients. Remarkably, the Bogoliubov coefficients for exactly solvable field theoretical models could be expressed in terms of gamma functions with complex arguments, which leads to one-loop effective actions via the zeta-function regularization. The gamma-function regularization recovers the Heisenberg-Euler and Schwinger one-loop QED action in a constant electromagnetic field and leads to new QED actions in some localized electric or magnetic fields. The one-loop effective action and, more interestingly, QED action are found in an (anti-) de Sitter space. The Schwinger effect and the Hawking radiation compete with each other. The one-loop QED action and the pair production exhibit a strong intertwinement between the Maxwell theory and gravity. Further, there is a gauge-gravity relation for the one-loop action and pair-production rate.

Quasiclassical approach and high energy QED processes in the field of a heavy atom

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QED processes at high energies in the field of a heavy nucleus or an atom are classical examples of processes in strong fields. They are exhibited in numerous experimental setups, including those designed for completely different purposes, being quite unrelated to an observation of these processes. Their investigation, therefore, has an obvious practical value. From a theoretical point of view, these processes are interesting, since they provide an important insight into the structure of higher-order effects in perturbation theory.

A general approach to strong-field calculations is the use of the Furry picture. In this approach the wave functions and propagators of a particle are replaced by exact solutions and Green functions of wave equations in external fields. The general feature of an exact Green function of a relativistic equation is the existence of a sum of angular momentum which cannot be expressed in a closed form. At high energies of initial particles, the final particle momenta usually have small angles with respect to the incident direction. In this case the typical angular momenta that provide the main contribution to the cross section are large, $l \sim \varepsilon/\Delta >> 1$, where ε is energy and Δ is momentum transfer. The sum of angular momentum converges slowly. Due to such complications, computations based on this expression become rapidly intractable with the growth of particle energy. Fortunately, this is the reason for the quasiclassical approximation based on large angular momenta contributions to come into play. In this approximation, the wave functions and Green functions of the Dirac equation in external fields acquire a very simple form, which simplifies the calculations drastically. The quasiclassical Green functions have been derived for a localized field which generally exhibits no spherical symmetry. One of the main features of the quasiclassical approach is a possibility to calculate not only the leading order term but also the next-to-leading order quasiclassical correction. This approach provides a possibility to investigate numerous QED processes in the field of a heavy atom.

Two- and three-dimensional Coulomb problem with supercritical charge

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A closed-form equation is derived for the critical nucleus charge $Z = Z_{cr}$ at which a discrete level with the Dirac quantum number (κ) touches the lower continuum of Dirac equation solutions. For Coulomb potential which is cut off rectangularly at a short distance $r_0 = R\hbar/(mc)$, $R<<1$, the critical nucleus charge values are obtained for several values of κ and R. It is shown that the partial scattering matrix of elastic positron-nucleus scattering, $S_\kappa = \exp(2i\delta_\kappa(\varepsilon_p))$, is also unitary for $Z > Z_{cr}$. For this range of Z, the scattering phase $\delta_\kappa(\varepsilon_p)$ is calculated as a function of the positron energy $E_p = \varepsilon_p mc^2$, as are the positions and widths of quasidiscrete levels corresponding to the poles of the scattering matrix. The implication is that the single-particle approximation for the Dirac equation is valid not only for $Z < Z_{cr}$, but also for $Z > Z_{cr}$, and that there is no spontaneous creation of e^+e^- pairs from the vacuum.

The properties of carriers in SiC graphene doped with an impurity with charge Z are also studied. For Coulomb potential modified at short distances, closed-form equations for the carriers spectrum are derived. The critical charges Z_{cr} at which a discrete level with given quantum numbers touches the valence bound are obtained. For $Z < Z_{cr}$ and low values of orbital momenta, the energy-charge dependence is also obtained.

Classical aspect of anomalous magnetic moment of electron

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The general methods of covariant integration of the energy-momentum density tensor of electromagnetic field created by an arbitrarily moving point-like charge [1,2] are used to evaluate the self-action force of a charge which is affected by convective field, radiation field and their interference. Besides the standard formula for radiation reaction force, the electromagnetic mass of an electron, $\tilde{m}_0 = e^2/2\varepsilon c^2$, where ε is an external radius of spherically symmetric electromagnetic field produced by a charge in its rest frame, naturally arises in the equations of motion. At $\varepsilon = \lambda_c/2 = \pi\hbar/m_0 c$, this value is known to be an indicator of quantum interactions in terms of microphysics [3]. Assuming that the total mass is represented as $M_0 = m_0 + \tilde{m}_0 = m_0(1+\alpha/2\pi)$, where $\alpha = e^2/\hbar c$ is the fine-structure constant, and the proper magnetic moment of an electron is equal to the Bohr magneton $\mu_0 = e\hbar/2m_0 c$, it appears that, considering the electromagnetic mass of an electron, the observed magnetic moment of an electron is

$$\mu = \frac{e\hbar}{2M_0 c}\left(1+\frac{\alpha}{2\pi}\right) = \tilde{\mu}_0\left(1+\frac{\alpha}{2\pi}\right) = \mu_0 + \mu_a .$$

Thus we have obtained a well-known expression for the anomalous magnetic moment of an electron, which was first found by J. Schwinger in 1948 [4] by using the methods of quantum electrodynamics. Further, it was found that this equation acquires a more complicated form in extremely intense magnetic fields.

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Spin radiation corrections to probability and power of radiation in classical and quantum electrodynamics

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The spin radiation effects in the one-particle sector of QED have a twofold origin and can be understood in terms of the Frenkel classical model of "rotating electron". In the parameter domain examined here, the imaginary part of the mass shift and the radiation power acquire spin contributions of two kinds. The first one is related to the fermion magnetic moment which constitutes an additional source of electromagnetic radiation; the contributions of the second kind have the opposite sign and arise owing to a small alteration in the particle acceleration which results from the Frenkel addition to the mass of the particle. The contributions of the second kind into the above-mentioned quantities are dominant over the first one, thereby explaining the "wrong" sign of the full spin contributions.

We show that not only the sign but also the coefficients can be explained with required accuracy within classical electrodynamics if one calculates spin additions to the mass shift and those to the power of radiation with the use of canonical variables, i.e., at fixed values of velocities and momenta, respectively. These results can be considered as a demonstration of the correspondence principle for spin radiation effects, and even further as a correspondence between classical and quantum theories at the tree level (with respect to external fields). At $a_e = (g - 2)/2$ the equations of the Frenkel model result in a generalization of the Lorentz-BMT system of equations with the Frenkel mass addition taken into account. Some features of experimental observation of spin light are discussed.

Signature of Schwinger's pair creation rate via radiation generated in graphene by strong electric current

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Electron-hole pairs are copuously created by an applied electric field near the Dirac point in graphene or similar 2D electronic systems. It was shown recently that for sufficiently large electric fields and ballistic times the $I-V$ characteristics become strongly nonlinear due to Schwinger's pair creation. Since there is no energy gap, the radiation from the pairs annihilation is enhanced. The spectrum of radiation is calculated. The angular and polarization dependence of the emitted photons with respect to the graphene sheet is quite distinctive. For very large currents, the recombination rate becomes so large that it leads to the second Ohmic regime due to radiation friction.

Neutrino oscillations in matter

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A modification of the Standard Model is constructed in such a way that the neutrinos are combined in a multiplet. The same is done for the charged leptons and the down- and up-type quarks. In this model the action determined by the Lagrangian of free fields is invariant with respect to $SU(3)$, so when quantizing, the multiplets can be considered as a single particle. The one-particle states in the Fock space are defined as usual; the creation and annihilation operators satisfy the standard commutation relations. In so doing, these operators carry an additional discrete quantum number which is associated with the mass of a state.

The Lagrangian of interaction between the fermion fields, the vector boson fields, and the Higgs field formally coincides with the Lagrangian of the Standard Model. However, the fermion wave functions generally describe multiplets, rather than individual particles. In such a model the phenomenon of neutrino oscillations arises.

In the framework of this model, it is possible to obtain a relativistically covariant equation describing the neutrino interaction with dense matter due to forward elastic scattering. The procedure is the same as the one used in deriving the Dirac equation for an electron in external electromagnetic field. This equation can be completed by a phenomenological term of the Dirac-Pauli type which describes the neutrino interaction with electromagnetic field due to anomalous magnetic moment.

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Polarization and angular distribution structure of synchrotron radiation in non-relativistic approximation

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In the first non-zero non-relativistic approximation, the structure of angular distribution and the polarization degree of synchrotron radiation calculated by classical methods are shown to coincide with the corresponding values calculated by quantum methods. Quantum corrections to this approximation affect only the total radiated power.

Involutive form of field equations and consistency of interactions

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A universal method is proposed for constructing consistent interactions between the fields being based on the idea of involutive closure of field equatoions. The method equally well applies to the Lagrangian and non-Lagrangian equations and it is explicitly covariant. The method allows one to explicitly control degree of freedom number in covariant form when the interactions are included, without Hamiltonian constrained analysis and irrespectively to existence of gauge symmetry.

Hadron structure in holographic QCD

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We develop an effective field approach: soft-wall AdS/QCD [1] based on gauge/gravity duality [2] with softly broken conformal invariance, which incorporates confinement through the presence of a background dilaton field. The underlying AdS/QCD action is built for a description of hadrons and exotic states in five-dimensional AdS space. Using the Kaluza-Klein decomposition, we derive the bulk profiles in the extra fifth dimension, which are equivalent to hadronic wave functions. As an application we calculate hadronic mass spectrum with the Regge-behavior and hadronic form factors consistent with quark counting rules [3] at large Euclidean momentum squared. The approach gives a unique opportunity to extend our analysis from simple hadronic systems to exotic states and many-body systems such as nuclei.

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Electron-positron pair production in slow collisions of bare nuclei

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A method for calculation of pair production in slow heavy-ion collisions is presented. The approach is based on numerical solution of the time-dependent Dirac equation in the monopole approximation. Using the developed approach, calculations of pair-production probabilities have been performed for different values of the impact parameter and the nuclear charge.

Conventional quantum mechanics with probability instead of wave function

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A new formulation of usual quantum mechanics is given. Quantum states are described by fair probability distributions. A relation to other approaches and equations for the states is presented.

Higher order wave equation within the Duffin-Kemmer-Petiau formalism

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Within the framework of the Duffin-Kemmer-Petiau (DKP) formalism, a consistent approach to the derivation of the third order wave equation is suggested. For this purpose an additional algebraic object, the so-called *q*-commutator (*q* is a primitive cubic root of unity) and a new set of matrices η_μ, instead of the original matrices β_μ of the DKP algebra, are introduced. It is shown that in terms of these η-matrices we have succeeded in reducing a

procedure of the construction of cubic root of the third-order wave operator to a few simple algebraic transformations and to a certain operation of the passage to the limit $z \to q$, where z is some complex deformation parameter entering into the definition of the η-matrices. A corresponding generalization of this result to the case of interaction with an external electromagnetic field introduced through the minimal coupling scheme is carried out. A detailed analysis of the general structure for a solution of the first-order differential equation for the wave function $\psi(x; z)$ is performed and it is shown that the solution is singular in the $z \to q$ limit. An application to the problem of construction, within the DKP approach, of a path integral representation in parasuperspace for the propagator of a massive vector particle in a background gauge field is discussed.

Entanglement in a two interacting spins system

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From exact solutions of the Schrödinger equation for two interacting spins systems which obey the Heisenberg model, it is possible to obtain the so-called Schmidt and Information Entanglement measures of these systems and, therefore, to carry out an exact theoretical analysis of entanglement dependence on the system parameters, i.e., its dependence on the external magnetic fields B, on the Heisenberg interaction functions J, as well as on the initial states (entangled and not-entangled ones). In fact, in this study we have obtained analytical solutions for some different configurations of interaction between the particles.

Creation and evolution of particle number asymmetry in expanding Universe

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We introduce a model which generates particle number asymmetry in expanding Universe through CP violating and particle number violating interactions. The model consists of a real scalar field and a complex scalar field. Applying nonequilibrium field theory, starting with an initial condition specified by density matrix, we show how the asymmetry is created through the interaction and how it evolves at later time. We study the following cases. The evolution of the asymmetry is studied with scale factor of Universe when its time dependence is explicitly given. For another case, the time dependence of the scale factor itself is determined by Einstein equation.

Finite field-dependent BRST-anti-BRST transformations: Jacobians and application to the Standard Model

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The Jacobians induced by finite BRST-anti-BRST transformations linear in functionally-dependent parameters, as well as those induced by finite BRST-anti-BRST transformations with arbitrary functional parameters, are explicitly calculated. The calculations cover the cases of gauge theories with a closed algebra, dynamical systems with first-class constraints, and general gauge theories. The resulting Jacobians in the case of linearized transformations are different from those in the case of polynomial dependence on the transformation parameters. The finite BRST-anti-BRST transformations with arbitrary parameters induce an extra contribution to the quantum action, which cannot be absorbed into a change of the gauge. These

transformations include an extended case of functionally-dependent parameters that implies a modified compensation equation, which admits non-trivial solutions leading to a Jacobian equal to unity. The finite BRST-anti-BRST transformations with functionally-dependent parameters are applied to the Standard Model. An explicit $Sp(2)$-doublet of functionally-dependent parameters is obtained providing the equivalence of path integrals in arbitrary R_ξ-like gauges. The Gribov-Zwanziger theory is extended to the case of the Standard Model, and a form of the Gribov horizon functional is suggested in Landau gauge and R_ξ-like gauges, in a gauge-independent way using field-dependent finite BRST-anti-BRST transformations, as well as in R_ξ-like gauges using transverse-like non-Abelian gauge fields.

Constraint on seesaw model parameters with electroweak vacuum stability

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Within the standard model, the electroweak vacuum is metastable. We study how heavy right-handed neutrinos in seesaw model have impact on stability through their loop effect for Higgs potential. Requiring that the lifetime of the electroweak vacuum be larger than the age of the Universe, we find a constraint on parameters such as their masses and the strength of Yukawa couplings.

Casimir energy for 3-dimensional Riemann caps

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We consider a particular case of 3-dimensional time-dependent Riemann cap

$$ds^2 = dt^2 - R^2 d\eta^2 - R^2 \cos^2\eta \, d\Omega^2,$$

where $\eta[\eta_0(t), \pi/2]$, $R = R(t)$ and $d\Omega^2$ represents the line element of the two-sphere. The function $\eta_0(t)$ decreases from $\pi/2$ to $-\pi/2$. We compute the vacuum energy of the massive scalar field with Dirichlet boundary condition.

It is assumed that $R(t)$ is a slowly varying function so the quasi-stationary approach is applicable. After separation of variables in the Klein-Gordon equation, eigenfunctions of the Laplace operator are expressed via associated Legendre functions. The zeta function is constructed in terms of a contour integral and its analytic continuation is found using the uniform asymptotic expansion of the Legendre function [1]. Explicit analytic expressions for heat kernel coefficients are obtained. Thereby an expression for the Casimir energy is provided and can be calculated numerically.

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Magnetic monopoles in the early Universe as the reason of formation of photons with the orbital angular momentum

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It is shown that one of the reasons for the formation of photons with non-zero orbital angular momentum in the early Universe may be magnetic monopoles. As one assumes the presence in an expanding Universe region of a space with photons having nonzero orbital angular momentum, the expansion rate of these regions in the Universe increases. Consequently, a region of the Universe in which there existed magnetic monopoles will expand more rapidly, resulting in an uneven spatial distribution of matter. Comparison is made between the present-day uneven distribution of matter and a possible distribution of magnetic monopoles.

Electronic properties of AB-bilayer graphene in the magnetic and electric fields with general gap energy

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The results of theoretical analysis concerning the influence of various types of ground state energy gaps at the K and K' Dirac points in the quasiparticle spectrum on the Hall and longitidunal optical conductivities of graphene AB-bilayers on the basis of QFT in a (2+1)-dimensional space-time are presented. Exact analytical expressions for optical conductivities in electric (determining a gap of the order 5–20 meV) and magnetic fields (3−10 Tesla) are obtained using a 4-band microscopic Hamiltonian. A $U(1)$-gauge-invariant Dirac-type Hamiltonian linear with respect to covariant derivatives, including a magnetic field potential perpendicular to bilayer sheets, is suggested. To obtain the conductivities, an exact Green function for the Schrödinger equation is derived as a matrix sum with respect to the Landau levels. The current-current correlation tensor function is constructed on a basis of this Green function. The resulting conductivities are derived using the Kubo formula and take into account the dependence on temperature and chemical potential. They provide analytically the basic optical transitions between the Landau levels with the selection rule $\Delta n=1$, while neglecting the trigonal warping of the carriers spectrum. The limiting cases for direct current conductivities are studied and relations between the Hall conductivities, as well as the Faraday and Kerr angles when radiation transmits through bilayer samples on substrates in electric and magnetic fields, are derived in a form consistent with experiment, depending on particular realizations of energy gaps. The results predict some regimes of ground states realized under control of external fields which may be used in nano and microoptoelectronic devices on a basis of graphene.

Particle decays in external field: the "Worldline Instanton" approach

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The semiclassical "Worldline Instanton" method has been applied to processes of particle decay in external electromagnetic fields kinematically forbidden in the absence of the field. The non-perturbative regime of a relatively weak field is considered. The method shows a deep analogy between neutral particle decay and vacuum particle creation (Schwinger effect) in external fields. The width of astrophysically relevant processes – photon decay to electron-positron pair and neutrino decay to electron and W-boson in the external magnetic field – has been calculated. It is emphasized that the method is general and is applicable to the decay of an arbitrary neutral particle into charged ones in external electromagnetic fields. Possible astrophysical applications including the possibility of generalizations to external gravitational fields are discussed.

Multiloop Euler-Heisenberg Lagrangians, Schwinger pair creation, and the photon S-matrix

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Although the perturbation series in quantum electrodynamics has been studied for eighty years, concerning its high-order behavior our present understanding is still poorer than for many other field theories. An interesting case is Schwinger pair creation in a constant electric field, which may possibly provide a window to high loop orders; simple non-perturbative closed-form expressions have been conjectured for the pair creation rate in the weak field limit, for scalar QED in 1982 by Affleck, Alvarez and Manton, and for spinor QED by Lebedev and Ritus in 1984. Using Borel analysis, these can be used to obtain non-perturbative information on the physically renormalized N-photon amplitudes at large N and low energy. This line of reasoning also leads to a number of nontrivial predictions for the

QED effective Lagrangian in either four or two dimensions at any loop order, and I will present preliminary results of a calculation of the three-loop Euler-Heisenberg Lagrangian in two dimensions.

Quantum electromagnetic nonlinearity affecting charges and dipole moments

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Owing to the virtual electron-positron pair creation, quantum electrodynamics (QED) may be effectively treated as a nonlinear classical theory of electromagnetic fields. The corresponding mutual and self-interaction of electromagnetic fields is important where these are as strong as magnetic fields of magnetars, electric fields of quark stars, and fields in close vicinity of elementary particles generated by their charges and/or electric and magnetic dipole moments.

We claim that the electromagnetic self-coupling of the dipole moments makes it necessary to subject their values to a sort of renormalization after being calculated following one or another method of strong interaction theory, say QCD or lattice approach. This correction is estimated to be at the brink of the present-day experimental possibilities.

We also report on two magneto-electric effects of nonlinearity. The first is that the nonlinear response of the vacuum with a strong constant magnetic field in it to an applied Coulomb field of an electric monopole turns it into a magnetic dipole in QED and into a magnetic monopole in a theory with violated parity, the Coulomb field itself certainly undergoing a correction, too. The second is that if there are two, mutually non-orthogonal, strong constant fields in the vacuum, electric and magnetic, then already in QED an electric charge produces magnetic monopole field under certain boundary conditions.

We also state that a point-like electric charge possesses a finite electrostatic self-energy due to the self-interaction, if its field is treated within classical electrodynamics nonlinearly extrapolated to its close neighborhood via quantum QED corrections.

Quantum electrodynamics of heavy ions and atoms

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The present-day status of the QED theory of heavy ions is considered. Theoretical predictions for the Lamb shift, the hyperfine splitting, and the *g* factor in highly charged ions are compared with recent experiments. Special attention is given to verifications of QED at strong fields and determination of fundamental constants. Parity nonconservation effects in heavy atoms and ions are also discussed.

Symmetry of the nonlocal Gross-Pitaevskii equation

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We consider a generalization of the Gross-Pitaevskii equation (GPE) whose local (cubic) nonlinear term is subject to a complicated modification by a nonlinear nonlocal term. In the semiclassical approximation formalism, the original equation yields a reduced equation characterizing the leading term of an asymptotic expansion and a dynamical system describing the evolution of moments of an unknown function. We associate the reduced equation with a class of nearly linear integro-differential equations. An approach is proposed which allows one to construct a class of symmetry operators (mapping any solution to another solution of the equation) for the semiclassically reduced nonlocal GPE.

Variational tricomplex and BRST theory

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By making use of the variational tricomplex, a covariant procedure is proposed for deriving the classical BRST charge of the BFV formalism from a given BV master action.

Orientable objects in relativistic quantum theory

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We suggest an approach to quantum-mechanical description of relativistic orientable objects, which extends Wigner's ideas on the treatment of nonrelativistic orientable objects (in particular, nonrelativistic rotator) by using two reference frames (space-fixed and body-fixed). It turns out that such an extension amounts to introducing wave functions on the Poincare group $M(3,1)$ which depend on Minkowski space $M(3,1)/Spin(3,1)$ points x, as well as on orientation variables given by the elements z of a matrix Z from the group $Spin(3,1)$. A field $f(x,z)$ is a generating function of conventional spin-tensor multicomponent fields and admits a number of symmetry operations. A classification of orientable objects is given using a maximal set of 10 commuting operators (generators of left and right transformations) in the space of functions on the Poincare group. In addition to the usual 6 quantum numbers related to external symmetries (given by left generators), there arise some additional quantum numbers related to internal symmetries (given by right generators). The assumption that the internal symmetries in the theory of orientable objects are gauge ones allows one to obtain some important features of the fundamental interactions.

Designing gradient coils for magnetic resonance imaging

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A method is presented for designing transverse gradient coils for magnetic resonance imaging. This method is based on the set of Z intercepts of the coils' current patterns with the z axis in the unfolded z-arc plane. We show that the set of Z intercepts combined with a description of the coil topology, as defined by the necessary azimuthal harmonics, the axial symmetry and the directions of the current flow, is sufficient for designing a practical gradient coil. The theory and design of transverse coils with Z intercepts is illustrated with examples of a symmetric unshielded insert gradient coil for small animal imaging, a human head unshielded symmetric insert gradient coil with shoulder cutouts, and a self-shielded short whole-

body gradient coil. The *Z*-intercept method has also been extended to design higher-order transverse shims. This is illustrated with the design of a *ZX* shim. Additional design capabilities of the *Z*-intercepts.

Entanglement of scales as a possible mechanism for decoherence and thermalization in relativistic heavy ion collisions

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Despite the fact that a system created by relativistic heavy ion collisions is an isolated quantum system which cannot increase its entropy in the course of unitary quantum evolution, a hydrodynamical analysis of experimental data seems to indicate that the matter formed during the collisions is thermalized very rapidly. Based on common considerations of hydrodynamics as an effective theory in the domain of slow and long-length modes, we discuss the physical mechanisms responsible for the decoherence and emergence of a hydrodynamic behavior in such collisions and demonstrate the action of such physical mechanisms in the case of a scalar field model. We obtain an evolution equation for the Wigner function of a long-wavelength subsystem which describes its decoherence, isotropization and approximation to thermal equilibrium, induced by interaction with short-wavelength modes. Our analysis supports the idea that decoherence, quantum-to-classical transition and thermalization in isolated quantum systems are attributed to experimental context and are related to a specific procedure of decomposition of the entire quantum system into subsystems being “relevant” and “irrelevant” from an observational viewpoint.

Reduction by symmetries in singular quantum-mechanical problems

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We develop a general technique for finding self-adjoint extensions of a symmetric operator that respect a given set of its symmetries. Problems of this type naturally arise when considering two- and three-dimensional

Schrödinger operators with singular potentials. The approach is based on constructing a unitary transformation diagonalizing the symmetries and reducing the initial operator to the direct integral of a suitable family of partial operators. We prove that symmetry preserving self-adjoint extensions of the initial operator are in a one-to-one correspondence with measurable families of self-adjoint extensions of partial operators obtained by reduction. The general scheme is applied to the three-dimensional Aharonov-Bohm Hamiltonian describing the electron in the magnetic field of an infinitely thin solenoid. We construct all self-adjoint extensions of this Hamiltonian, invariant under translations along the solenoid and rotations around it, and explicitly find their eigenfunction expansions.

Vacuum particle creation in strong fields as a field induced phase transition

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Vacuum particle production by the Sauter-Schwinger effect under the action of time-dependent strong fields of diverse nature exhibits some general properties which, at the qualitative level, are independent of the nature of a specific system. They include a quasiparticle stage of excitation during the field action, a transient stage of rapid oscillations in the period of external field degradation, a change of symmetry in the system, and an emergence of strong non-equilibrium out-states. Examples can be taken from the physics of condensed matter and stongly correlated systems, as well as from the theories of relativistic phase transitions and early cosmology, etc. The universal character of such phenomena makes it possible to unify them in a general class of field-induced phase transitions, being a concept adopted from [1–3]. The general foundation for this is the mathematical similarity of the corresponding kinetic equations describing the process of particle creation. In the present report we consider in detail an example from strong field QED, where the kinetic equation is well known for the linearly-polarized spatially-homogeneous time-dependent external-electric field model [4,5]. We also discuss possible experimental manifestations of strong oscillations in the transient domain of electron-positron plasma.

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Inflation: determination of details from observational data

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With the recent Planck and other observational data, one can tell much more about the physical properties of an inflationary stage in the early Universe (e.g., curvature, its rate of change, inflaton mass). In particular, these data typically imply the Hubble parameter $H \sim 10^{14}$ GeV in the range about 60 e-folds before the end of inflation and the inflaton mass $m \sim 10^{13}$ GeV after the end. Detection of primordial quantum gravitational waves generated during inflation remains the most fundamental discovery expected in the future. It can be argued that the measured value of the slope $n_s - 1$ of the primordial spectrum of scalar (density) perturbations, under some natural additional assumptions, implies some small, but not quite so small amount of those, $r > 10^{-3}$, which is similar to the original $R+R^2$ inflationary model (1980). Therefore, perspectives of their discovery seem to be promising. In addition, the features of the CMB temperature anisotropy power spectrum in the multipole range $\ell = (20,40)$ may point to some new physics during inflation, including the existence of new elementary particles whose mass exceeds that of the inflaton.

Cosmology with nonminimal kinetic coupling and a Higgs-like potential

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We consider cosmological dynamics in the theory of gravity with a scalar field possessing a nonminimal kinetic coupling to the curvature, given by $\kappa G^{\mu\nu}\phi_{,\mu}\phi_{,\nu}$, and the Higgs-like potential $V(\phi) = \lambda/4(\phi^2 - (\phi_0)^2)^2$. Using the dynamical system method, we analyze stationary points, their stability, and all possible asymptotical regimes of the model under consideration. We show that the Higgs field with the kinetic coupling provides the existence of accelerated regimes in the Universe evolution. There are three possible cosmological scenarios with acceleration:

(i) *The late-time de Sitter epoch* when the Hubble parameter tends to a constant value: $H(t) \to H_\infty = (2\pi G\lambda(\phi_0)^4/3)^{1/2}$ as $t \to \infty$, while the scalar field tends to zero, $\phi(t) \to 0$, so that the Higgs potential reaches its local maximum $V(0) = \lambda/4(\phi_0)^4$*;*

(ii) *The Big Rip* when $H(t)\infty$ and $\phi(t)\infty$ as;

(iii) *The Little Rip* when $H(t)\infty$ and $\phi(t)\infty$ as ∞.

We also obtain modified slow-roll conditions for the Higgs field and demonstrate that they lead to the Little Rip scenario.

The review of the elementary particles physics in the external electromagnetic fields studies at KEK

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The High Energy Accelerator Research Organization is currently running 6 accelerator projects: J-PARC, SuperKEKB, PF, PF-AR, ILC, and cERL [1]. In this review, I intend to discuss the light sources PF, PF-AR, LUCX, and cERL in detail.

Two synchrotron radiation sources of KEK, the Photon Factory (PF) Ring and the Photon Factory Advanced Ring (PF-AR), continue their user operation with various improvements. A wide range of radiated light, from visible light to X-ray, is provided for material science, biology, and life science [2–3].

The LUCX facility at KEK is used as a high brightness pre-bunched electron beam source for radiation experiments. The characterization of the pre-bunched beam (THz sequence of a hundred femtosecond bunches) properties opens up a possibility to establish a detailed simulation of the THz FEL radiation yield and continuously improve the pre-bunched beam dynamics insight [4].

The Compact Energy Recovery Linac (cERL) at KEK is a test accelerator intended to develop the key components used to realize a remarkable ERL performance as a future light source. We currently perform improvements of electron gun performance, high bunch charge operation, mitigation of beam losses, LCS optics tuning and bunch compression for THz radiation [5].

The state of the art in the above projects with respect to elementary particles physics in external electromagnetic fields is emphasized in this review.

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Casimir effect with graphene

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We shall overview an approach to the Casimir interaction of graphene bases on Quantum Field Theory and the Dirac model. Notably, this is the only approach that has been confirmed by experiment. We shall describe in detail the effects of Casimir interaction enhancement due to finite temperature and due to doping. We shall conclude by discussing some future prospects. This talk is based on the following publications:

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Cosmic strings stabilized by quantum fluctuations

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In the standard model, stabilization of a classically unstable cosmic string may occur through the quantum fluctuations of a heavy fermion doublet. In a reduced version of the standard model we investigate the realization of this mechanism within a semi-classical expansion. Then the leading quantum corrections emerge at one loop level for many internal fermion degrees of freedom. Previously [1] we considered quite a limited space for the string configurations. Here we study more general configurations that come at the expense of a very intricate scattering problem for the quantum fluctuations [2]. A symmetry among the one-particle energies exists that is not manifestly maintained in the regularization and renormalization procedure. By numerical simulation we verify that the particular procedure based on the identification of the Born series for scattering data with Feynman diagrams indeed reproduces the symmetry.

The vacuum polarization energy and the binding energy of occupied fermion levels are of the same order in this expansion and must thus be treated on equal footing. Populating these bound states adds charge to the string and lowers the total energy compared to the same number of free fermions. Numerically we find that charged strings are already stabilized for a fermion mass only somewhat larger than the top quark mass. Though obtained in a reduced version these results suggest that neither extraordinarily large fermion masses nor unrealistic couplings are required to bind a cosmic string in the standard model. Furthermore we also review results for a quantum stabilization mechanism that prevents closed Nielsen-Olesen type strings from collapsing [3].

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Modified equations in the theory of induced gravity. Cosmological solutions and constant evolution

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This study is an extension of the author's article [1], in which a conformally invariant generalization of string theory to higher-dimensional objects was suggested. Special cases of the theory in question are the Einstein theory of gravity and string theory. The present work is devoted to the formulation of self-consistent equations of induced gravity in the presence of matter as a perfect fluid interacting with scalar fields. This study is carried out to solve these equations in the case of a certain cosmological model. The model contains some time-evolving gravitational and cosmological "constants", which are determined by the square of scalar fields, whose values can be matched with experiment. The equations describing the theory contain solutions that may be identical with solutions in the standard theory of gravity and may also be different from those. This is caused by the fact that the fundamental "constants" of the theory, such as the gravitational and cosmological ones, may evolve over time and may also depend on coordinates. Therefore, the theory describes two systems (stages): the Einstein stage and the "evolving" or "restructuring" stage. This process is similar to the phenomenon of phase transition, where different phases (Einstein gravity, albeit with different constants) transfer into each other.

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Two-photon emission by a charged particle in a magnetic field

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A technique is proposed for the calculation of the (tree) amplitude for two-photon emission by an electron in a constant magnetic field. Based on the Schwinger proper time representation for the propagator, the technique avoids summation over intermediate states. As a result, the algebraic properties of the Dirac matrices can be used more efficiently, especially in case a suitable set of one-fermion states is used. Since the integral over the proper time cannot be expressed in elementary functions, the final expression is a series representing the amplitude. It is known that the spin degeneracy of electron states is lifted when the anomalous magnetic moment is taken into account, and, therefore, the choice of one-fermion states is not simply a matter of convenience. However, all the other quantum numbers (except the spin variable) being fixed, the degeneracy spaces for the Dirac electron are two-dimensional, and the transition between the base in which the calculations have been done and any other relevant base can be carried out by the application of two-by-two matrices. The proposed technique can be applied straightforwardly to multi-photon processes, e.g., to the two-photon Compton scattering in a constant magnetic field.

On Gribov horizon in linear gauge

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The Gribov-Zwanziger (GZ) theory is an attempt to formulate a non-perturbative approach to quantum theory of non-Abelian gauge fields as one takes into account the Gribov copies. Notice that the original formulation of the GZ theory is only used in the Landau gauge. The gauge dependence problem within the GZ theory has not been considered until quite recently. The study of this problem in Yang-Mills theories assuming the existence of the Gribov horizon functional beyond the Landau gauge was given in [P.M. Lavrov, O. Lechtenfeld and A.A. Reshetnyak, JHEP 1110 (2011) 043]. It was shown that, in general, the vacuum functional, as well as the effective action (even on its extremals), does depend on gauges. It was found that there is a strong restriction on the gauge dependence of the Gribov horizon functional when the effective action on its extremals does not depend on gauges. This leads to an expectation to formulate the GZ theory in a consistent way as a physical theory. We would like, once again, to draw attention to the gauge dependence problem, which is manifest in the original GZ theory. We have also carried out an explicit construction of the Gribov horizon functional in linear gauges, leading to the gauge independence of the partition function in the GZ theory.

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