Quantum theory of gravitation (based on the Proceedings of the Second International Seminar on the Quantum Theory of Gravitation, Moscow, October 13–15, 1981)

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The second seminar Quantum Theory of Gravitation was held from 13 through 15 October, 1981 in Moscow at the House of Scientists. Like the first seminar in 1978, it was organized by the Department of Nuclear Physics of the USSR Academy of Sciences in conjunction with the Institute of Nuclear Research of the USSR Academy of Sciences. It continued the series of seminars devoted to topical problems of theoretical physics and elementary-particle physics organized by the Department of Nuclear Physics. Earlier seminars in the series were, in particular entitled The μ–e Problem and Quarks and Partons.

At the present seminar, attention was mainly concentrated on discussion of the following problems: 1. Quantum gravity (new approaches and unsolved problems); 2. Quantum effects in cosmology and origin of the Universe; 3. Quantum effects in black holes; 4. Supergravity (latent advances). Besides Soviet specialists, a number of well-known foreign physicists participated, including S. Hawking (Great Britain), W. Unruh (Canada), J, Hartle (USA), and others.

During the three days, 30 lectures (lasting between 30 and 40 min) were given, and these covered a large proportion of the new results obtained in recent years in the subject covered by the seminar. The participants therefore received a fairly full picture of the new developments in the quantum theory of gravitation during the last two or three years.

Before turning to a discussion of the main scientific results presented at the seminar, it is appropriate to say a few words about the present status of quantum gravity and its problems. Quantum gravity is the branch of theoretical physics which studies the quantum features of the gravitational interaction. Although a theory of quantum gravity is still far from completion, it appears that at the present time almost all specialists share the conviction that only when quantum-gravity effects have been taken into account fully will it be possible to complete the process of constructing a unified theory of all interactions and eliminate the fundamental difficulties inherent in quantum field theory (in particular, its infinities). Although this point of view is now widely accepted, it was by no means always the case. The change in the general opinion of theoretical physicists, which occurred during the last decade, was evidently brought about by the construction of Grand Unification theories (in which the strong, weak, and electromagnetic interactions are unified) and the stormy development of supergravity. [Supergravity is a theory constructed on the basis of Einstein's theory of gravitation and includes in a natural manner a description of not only the gravitational field but a complete set of other fields (bosons and fermions) unified in a single set on the basis of the supersymmetry principle (i.e, the symmetry that relates fields of integral and half-integral spin).]

Because the gravitational coupling constant is so weak, quantum gravity effects can be significant either at extremely short space-time distances (of order 10^{-33} cm, which corresponds to an interaction energy of particles of order 10^{28} eV) or in strong gravitational fields. Such strong fields arise naturally in the early stages in the evolution of the Universe and in the formation of black holes (i.e., compact massive objects whose strong gravitational field confines matter and light and thus prevents any information escaping outward). Study in the framework of classical (nonquantum) gravitational theory of the structure of space-time in the presence of strong gravitational fields showed that the occurrence of such fields is necessarily (under the most general assumptions) associated with the formation of singularities, i.e., irremovable singularities in space-time, in the neighborhood of which the classical theory of gravitation is insufficient and ceases to work. In cosmology, this singularity was present (in the framework of the classical description) at the initial time of expansion of the Universe (Big Bang). In black holes, the singularity develops as a result of the contraction (collapse) of matter. Although the singularity, being hidden within the black hole, cannot be seen by an external observer, the very existence of this singularity challenges the theoreticians. Investigation of the cosmological singularity is necessary, since it was shown that the nature of the processes that occur near it can essentially determine the further evolution of the Universe and, in particular, explain the formation of galaxies.

Although hopes that quantum gravity could cure these "chronic diseases" of classical theory were expressed long ago, the beginning of definite investigations aimed at understanding quantum phenomena under such extremal conditions is an achievement of the last decade.

It was these key problems, listed above, in quantum gravity that shaped the program of the seminar. Below, we briefly report the new results communicated at the seminar on these fundamental problems.

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1. QUANTUM GRAVITY (NEW APPROACHES AND UNSOLVED PROBLEMS)

In his introductory lecture "Some problems of the general theory of relativity," M. A. Markov reviewed the main directions in the development of quantum gravity and formulated a number of problems and questions whose investigation appears most topical and important for the understanding of quantum gravity itself as well as its cosmological and astrophysical applications. These problems include, in particular, the part played by gravity in the self-energy problem of elementary particles. It is well known that all attempts to calculate the masses of elementary particles lead to infinities, whereas in classical theory it has been shown that the classical divergences of the self-energy can be satisfactorily eliminated when allowance is made for the gravitational interaction. It is therefore important to establish whether gravity keeps its regularizing role in quantum theory. Another important problem discussed by Markov was the hypothesis of the existence of stable elementary black holes with the Planck mass (10^{-5} g) (maximons). This question became acute after Hawking's proof that if the CPT theorem holds a final state containing stable maximons cannot arise from a state that initially does not contain maximons. Markov pointed out that this theorem does not prohibit the existence of stable maximons in a world whose initial conditions are such that maximons are present from the beginning. This remark is particularly important, since the attractive possibility of constructing a scenario of the Universe in which the maximon component plays the fundamental part remains open. If stable maximons exist, then they play the role of elementary particles of the largest possible mass, determining the scale and upper limit of the elementary-particle mass spectrum. However, even if elementary black holes are unstable, they must nevertheless participate in intermediate states in quantum processes as virtual (short-lived) formations.

The problem of virtual black holes is intimately related to that of the structure of the vacuum in quantum gravity. According to modern ideas, the physical vacuum, i.e., the state in which there are no real particles, is a complicated formation generated by the quantum fluctuations of all the physical fields which exist in nature. Because the gravitational constant is a dimensional quantity, quantum gravity differs from the remaining interactions in that the amplitude of the quantum fluctuations is greater, the smaller the region they occupy. As was already noted by the American theoretician Wheeler, this, in particular, has the consequence that at scales of 10^{-33} cm the fluctuations of the metric are comparable with unity, and it is possible to have virtual changes in the topology and the formation of virtual black holes. In other words, space-time in the small resembles foam rather than smooth water. A theory of the foam structure of space-time has been intensively developed in recent years by one of the leading English theoreticians, S. Hawking, Professor at Cambridge University. In the lecture he gave at the seminar he discussed the question of how such a foam structure could influence physical processes and, in particular, the propagation of physical particles. A fundamentally new feature here is the possibility of loss of quantum coherence as a result of interaction of a particle with a virtual black hole. As a consequence, any quantum system must be described by a density matrix rather than a state vector. The system of axioms of quantum field theory and the mathematical formalism for describing processes such as the decay and scattering of elementary particles is modified accordingly. This results in the possible violation of many conservation laws, including those for the baryon and lepton charges. The characteristic lifetime of the proton with respect to such quantum-gravity processes is 10^{50} years, which is almost 20 orders of magnitude greater than the characteristic time discussed at present in the framework of Grand Unification theories. Although the lifetime of particles as a result of such decays is extremely long and cannot be measured at the present time, the fundamental possibility of nonconservation of the baryon and lepton numbers in gravitational interactions is of undoubted interest and may be extremely important for cosmology.

The dimensional gravitational coupling constant responsible for the features of the vacuum described above simultaneously has the consequence that quantum gravity constructed in the standard manner is a nonrenormalizable theory, i.e., a theory in which one cannot eliminate divergences by formal redefinition of unrenormalized quantities. Therefore, the renormalizability property of the quantum theory of gravity based on the modification of Einstein's theory by the addition of small terms quadratic in the curvature is very attractive. This possibility was considered by E. S. Fradkin (together with A. A. Tseĭtlin). He showed that such a theory is asymptotically free, i.e., the gravitational coupling constant at energies above the Planck energy (10^{28} eV) tends to zero, so that in this region calculations based on perturbation theory can be made. Moreover, the interaction of other fields with the gravitational field in such a theory leads to the appearance of asymptotic freedom in cases when it was not previously present (including supergravity) and does not eliminate the asymptotic freedom of interactions that have this property in their own right. Similarly, an analysis of the variants of extended supergravity (i.e., the generalizations of standard supergravity by the inclusion of additional particles on the basis of an additional group of internal symmetries) showed that the initially absent property of asymptotic freedom arises on the transition to the conformal generalization of this theory. And although it has not yet proved possible to overcome in the variants considered by Fradkin the difficulties inherent in all theories with higher derivatives (it has not been established that the considered theory is unitary), the presented results appear very promising.

Several contributions developed the idea that the gravitational field is a composite entity and that general relativity arises as an effective theory of composite fields. H. Terazawa (Institute of Nuclear Research, Japan) discussed the temperature dependence of the gravitational interaction and the possible instability of gravitons at superhigh temperatures in the framework of such theories. As a manifestation of a corresponding phase transition, he drew attention to the possible existence of an era preceding the Big Bang and the possible existence of objects of a new type, namely, pregeometric holes, i.e., regions in space-time in which the metric vanishes. And although this paper presented to the seminar was of a preliminary nature, and the theory itself has not been developed in detail, the idea evoked justified interest.

In the construction of a mathematical formalism of the quantum theory of gravity, supergravity, and other such theories the theoreticians encounter numerous difficulties associated with the gauge invariance of these theories. These difficulties, which at the first glance are technical, often develop into the fundamental impossibility of using the standard, previously developed methods of quantization. A general approach to the solution of such problems was presented by I. A. Batalin and G. A. Vilkovyskiĭ, and also by B. L. Voronov and I. V. Tyutin.

D. M. Volkov and V. I. Tkach presented a new development of the approach to gravity theory in which the number of space-time dimensions initially exceeds four but (for example, through instability) there is a compactification ("closing") of the extra dimensions and transformation of them into internal degrees of freedom.

2. QUANTUM EFFECTS IN COSMOLOGY AND ORIGIN OF THE UNIVERSE

Almost a third of all the contributions was devoted to this problem.

Although at the present time there is no consistent theory explaining the origin of the Universe (and it is not even clear whether such a theory could be constructed), numerous requirements have already been established for such a theory if it is to explain observed facts in the evolution of the Universe. It is required of the future theory that it explain:

1) why our Universe is to a high degree homogeneous and isotropic on large scales (i.e., after averaging over scales of order 100 Mpc);
2) why the initial conditions were such that the Universe could survive to the present time and the matter density in it is near the critical density;
3) the origin of the perturbations that led to the formation of galaxies.

To explain why the first question is indeed nontrivial, it is sufficient to recall that in the framework of standard (classical) theory the expansion of the Universe takes place so rapidly that the regions from which we receive the microwave background radiation could not have exchanged signals, but nevertheless the characteristics of this radiation from causally disconnected regions are strictly correlated (the variations in the temperature of the background radiation arriving from fairly distant, causally disconnected regions of the primordial plasma does not exceed $\Delta T/T \lesssim 10^{-4}$). Moreover, one can show that this difficulty cannot be overcome in the framework of the standard model of the Universe without violating the dominant energy condition (the condition that the energy density and pressure of the matter be positive). Quantum theory opens up a possibility for violation of the dominant energy condition, since the energy density and pressure associated with the vacuum polarization effect in a gravitational field can be negative. Therefore, during the stage when vacuum polarization effects played a dominant role the Universe could have expanded more slowly and there could have been time for equilibrium between different regions to be established.

One concrete variant of a theory of such a kind was presented by A. A. Starobinskiĭ. In the model proposed by him, the Universe in the initial stage is a homogeneous world of Planck size without matter described by the de Sitter solution, i.e., the maximally symmetric solution of the Einstein equations with a Λ term. A Λ term, or, which is the same thing, an energy-momentum tensor of matter with equation of state $p = -\varepsilon$ (p is the pressure and ε the energy density), is formally identical with the vacuum polarization energy-momentum tensor in such a cosmology. Later, this world begins to expand because of instability, and after the production (due to the variability of the gravitational field) in it of matter, it provides the beginning of an ordinary (classical) expanding Friedmann Universe, and the matter density at the current time is automatically close to the critical density.

In their paper "Complete cosmological theories," L. P. Grishchuk and Ya. B. Zel'dovich considered the interesting possibility of the formation of our Universe from initial quantum fluctuations. According to the hypothesis proposed in their paper, such a fluctuation could result in the formation of a three-dimensional closed geometry, in the further evolution of which vacuum polarization effects could play an important part and lead to the instability and expansion of such a closed world. The further evolution of this world proceeds as in the model proposed by Starobinskiĭ. Grishchuk and Zel'dovich emphasized the importance of investigating the gravitational wave background radiation. Although the present-day experimental possibilities are not yet adequate for detection of this background, the development of gravitational experimental techniques offers hope that in future the necessary measurements will be possible. The information on the intensity and spectral profile of the background gravitons obtained in such experiments will make it possible to determine characteristics of the gravitational field in the very early Universe and will thus provide a sensitive test of the correctness of the ideas behind the hypothesis.

The existence of a de Sitter stage in the expansion of the Universe could also help to solve the problem of galaxy formation, since there is an appreciable growth of initially small perturbations during such a stage. D. A. Kompaneets, V. A. Lukash, and I. D. Novikov and also V. F. Mukhanov and G. V. Chibisov developed a quantum theory of small hydrodynamic perturbations in a Friedmann Universe and showed that in the presence of a sufficiently long de Sitter phase these quantum perturbations are already sufficient for the development of inhomogeneities and the formation of galaxies.

Another possibility for the occurrence of a de Sitter stage in the evolution of the Universe and solution of the problems discussed above was pointed out by A. D. Linde. He noted that in guage theories with spontaneous symmetry breaking at superhigh temperatures ($T \gtrsim T_{\rm GUT} = m_{\rm GUT}c^2/k$, where $m_{\rm GUT}c^2 \approx 10^{14}$ GeV is the characteristic Grand Unification mass) the equation of state can have the form $p = -\varepsilon$. The corresponding de Sitter phase then lasts until the end of the phase transition, and therefore the delay time, which is determined by the parameters of the Grand Unification theories, is appreciably longer than the Planck time. In the framework of the cosmological expansion scenario considered in Linde's paper, one can solve not only the cosmological problems listed above but also answer a number of questions associated with the possible cosmological consequences of Grand Unification theories (such as the problem of fossil monopoles and domain walls).

If our Universe is closed, a time will come when it begins to contract, and there is a possibility that in the final stages it will again pass through a de Sitter stage (this possibility was discussed by V. A. Berezin).

The present seminar was evidently the first international forum at which it was demonstrated that many problems in the theory of the evolution of the Universe can be solved by assuming the existence of a de Sitter stage in cosmology, and the consequences of this hypothesis were developed.

Among other directions, we must also mention the question of the influence of an external gravitational field on spontaneous symmetry breaking (discussed in the papers of A. V. Veryaskin, V. G. Lapchinskiĭ, V. A. Nekrasov, and V. A. Rubakov and A. A. Grib, S. G. Mamaev, and V. M. Mostepanenko.

3. QUANTUM EFFECTS IN BLACK HOLES

In this field, the main attention in the papers presented at the seminar was concentrated on the following questions:

1) vacuum polarization effects in the strong gravitational field of a black hole;
2) the influence of quantum effects on the space-time structure of a black hole;
3) quantum emission of black holes and the generalized second law of thermodynamics.

Great interest in the quantum physics of black holes arose after the paper published by Hawking in 1974, in which he showed that the vacuum is unstable in the gravitational field of a black hole. The decay of the vacuum leads to the appearance of radiation of thermal nature and characteristic temperature $T = \hbar c^3/(8\pi GMk)$, where M is the mass of the black hole. This effect is particularly important for low-mass black holes. Such black holes could have been formed only during the initial stages in the evolution of the Universe, and they have become known as primordial black holes. A complete review of modern ideas about primordial black holes and an analysis of the bounds on the number and mass spectrum of them obtained by comparing the theoretically predicted consequences of their evaporation with observational data were given by the English astrophysicist B. Carr.

After Hawking's paper in 1974, there was appreciable growth of interest in a further direction, which has become known as black hole thermodynamics. At the beginning of the seventies, mainly due to the work of J. Bekenstein, it was found that in many aspects black holes behave like thermodynamic systems, the role of entropy in this analogy being played by a quantity proportional to the surface area of the black hole. The theoretical discovery by Hawking of thermal radiation from black holes was a decisive step and confirmed the existence of a deep connection between black hole physics, thermodynamics, and information theory. Black hole thermodynamics predicts that in phenomena in which not only ordinary matter but also black holes participate the so-called generalized second law of thermodynamics must hold; it states that the sum of the entropy of the ordinary matter and the entropy associated with the black holes cannot decrease with time. Several attempts were made to prove this proposition, but they were all based on additional assumptions about the properties of matter. In his talk, the Canadian physicist W. Unruh drew attention to the fact that in all the preceding proofs no allowance was made for the additional forces associated with the quantum vacuum polarization around a black hole. Unruh gave a new proof (proposed by himself and the theoretician R. Wald from Chicago) of the generalized second law and demonstrated that allowance for the vacuum polarization by the gravitational field not only enables one to discard the additional assumptions about the structure of matter but also leads to the possibility of essentially new effects (for example, the ejection from black holes of perfectly conducting bodies and the possibility of controlling the intensity of the Hawking radiation).

Ya. B. Zel'dovich pointed out that if certain processes (for example, vacuum polarization effects) did not prevent the formation of black holes with mass less than the Planck mass (10^{-5} g) such black holes could possibly have a relatively long lifetime.

The influence of quantum effects on the space-time structure of a black hole was discussed by G. A. Vilkovyskiĭ and V. P. Frolov. They showed that on the collapse of a mass less than the Planck mass vacuum polarization prevents the development of a singularity and the formation of a black hole. This means, in particular, that black holes with mass less than the Planck mass do not exist in nature. The data they presented also indicate that when large masses collapse the vacuum polarization effects are important and may eliminate the singularity within a black hole. These results are important, in particular, for elucidating the question of the possible final state of an evaporating black hole, since they preclude the occurrence as such a final state of a black hole with mass less than the Planck mass and (apparently) a naked singularity. They developed an approach making it possible to take into account the back reaction of the vacuum polarization and the Hawking radiation on the space-time geometry of a black hole.

A contribution to V. P. Frolov was devoted to calculation of vacuum polarization effects near stationary (rotating and charged) black holes and investigation of the influence of rotation of a black hole on the vacuum polarization.

4. SUPERGRAVITY

The following two questions were mainly discussed at the seminar: 1) the creation of a convenient geometrical formalism and the description of the structure of the auxiliary fields in supergravity (contributions by A. S. Shvarts, V. I. Ogievetskiĭ, and P. West (Great Britain) and 2) the structure of divergences and possible renormalizability in different supergravity models [R. É. Kallosh and M. Duff (Great Britain)].

It can be seen from the problems listed above that were considered at the seminar and from the results presented how rapidly the investigations have developed in recent years in quantum gravity in a field of physics that not all that long ago was rather empty. In recent years, these investigations have resulted in some exceptionally interesting and fundamentally important results, indicating that the weakest of all the interactions, the gravitational, may possess the most unexpected properties.

It was generally agreed by the participants that the seminar was "very topical, very helpful, and very interesting." In his letter, Professor Hawking described the seminar in Moscow as "one of the best conferences in which he had participated in recent years."

Translated by Julian B. Barbour