GRAVITATIONAL INSTABILITY OF VACUUM AND THE COSMOLOGICAL PROBLEM

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It is shown that, with the account of the gravitational interaction, the physical vacuum can spontaneously partially "dissociate" into particles and antiparticles without violation of any conservation laws. Possible cosmological significance of this effect is discussed. A "vacuum cosmological model" is formulated, in which vacuum is taken as the initial state of the Metagalaxy. A generalization of the classical cosmological Einstein equations is made which allows one to take into account phenomenologically the effect of gravitational instability of vacuum.

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(The seminar is lead by K. A. Piragas).

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1. The purpose of the present paper is to pay attention to the effect of the gravitational instability of vacuum and to consider its possible cosmological significance. The essence of this effect is that, with the account of the gravitational interaction, the vacuum in finite spatial volumes can spontaneously partially "dissociate" into particles and antiparticles (we call it "bimatter") without violation of the law of conservation of energy: the created bimatter falls into its own gravitational potential well and, in the case of sufficiently large proper mass M of bimatter (which is the mass without the account of the gravitational binding energy), this well can be sufficiently deep so that the gravitational binding energy $U(M)$ totally compensates for the energy Mc^2:

$$Mc^2 + U(M) = 0\,. \tag{1}$$

Such strong fields should be considered in frames of the general theory of relativity (GR); in this case, GR leads to the notion of a closed space [1, 2] (see below), but the essence of the effect can be qualitatively understood already on the level of the Newtonian description of gravity. In frames of the Newtonian theory,

$$U(M) = -\eta G M^2 a^{-1}\,, \quad \eta \sim 1\,, \tag{2}$$

where G is the gravitational constant, a is the spatial size (radius) of the system, and η is a dimensionless positive coefficient depending on the details of the mass distribution ($\eta = 3/5$ in the case of a uniform ball). Substituting (2) into (1), we arrive at the equation

$$Mc^2\left(1 - \frac{\eta G M}{c^2 a}\right) = 0\,, \tag{3}$$

which admits two solutions, namely, $M = 0$ and

$$M = \frac{c^2 a}{\eta G}\,. \tag{4}$$

The first solution corresponds to the vacuum state of quantum fields; the second one corresponds to the configuration under consideration (we shall call it "null system") arising as a result of partial dissociation of vacuum into particles and antiparticles. Both states have equal (zero) total values of strictly conserved quantities — energy, charge, baryon and lepton numbers (the difference is only in their spatial density distributions) — and, therefore, transitions between them are possible. In this case, dissociation of vacuum is a thermodynamically favorable process. Indeed, the vacuum, as a state without excitations, should be assigned zero entropy, whereas a null system is characterized by high entropy: because of decays of unstable particles and pair annihilations, it is quickly heated to temperatures corresponding to its density ($T \sim \rho^{1/4}$), even if it had zero temperature at the time of its creation.

In the transition $|\text{vacuum}\rangle \rightarrow |\text{null system}\rangle$, the average mass density ρ increases from $\rho_{\text{vac}} = 0$ to some maximum value ρ_0 which can be roughly estimated by assuming that the creation of the null system corresponds to a situation in which the components of every created hadron pair turn out to be

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[*] This preprint indisputably establishes priority of P.I. Fomin in problem of quantum birth of the Universe. The English version of the preprint printed by the Decision of the Scientific Counsel of the Institute for Theoretical Physics of the Ukrainian Academy of Sciences.

separated by distances

$$r \geq r_0 \sim 10^{-13}\,\mathrm{cm}\,, \tag{5}$$

starting from which one already can speak of the existence of real particles. Since hadron masses are of the order $m \sim 1$ GeV$/c^2$, this corresponds to the following condition on the average mass density:

$$\rho \leq \rho_0 \sim \frac{m}{r_0^3} \sim 10^{15}\,\mathrm{g}\cdot\mathrm{cm}^{-3}\,. \tag{6}$$

Expressing M in (4) through ρ,

$$M = \xi a^3 \rho\,, \quad \xi \sim 4\,, \tag{7}$$

we find

$$a = \frac{c}{\sqrt{\eta\xi G\rho}}\,, \qquad M = \frac{c^3}{\sqrt{\eta^3\xi G^3\rho}}\,. \tag{8}$$

From the physical reasoning, it is clear that most probable is creation of a null system with minimal possible values of a and M, hence, with maximal ρ. Accepting condition (6) for ρ, on the basis of (8), we obtain

$$a_{\min} \sim 3\cdot 10^6\,\mathrm{cm}\,, \qquad M_{\min} \sim 7\cdot 10^{34}\,\mathrm{g} \sim 35 M_\odot\,. \tag{9}$$

This estimate is, of course, conditional and can be modified with the modification of the estimate (6) of the upper bound for density. We note that the formally possible increase, relative to (5), of the "packing" of hadron pairs does not immediately lead to an increase of the mass density because one should take into account that, in this case, the mass deficit due to strong interactions also rapidly increases.

2. From the viewpoint of GR, the space occupied by a null system created from the vacuum is curved and closed. Its closeness is connected with the equality of the total energy to zero [1, 2]. In Fig. 1, we schematically show the curvature and topology of space before and after the creation of a null system. The space of the null system S_0 sort of "branches-off" from the vacuum space S_v. This process should be regarded as a peculiar tunneling transition from one quasi-stationary state of quantum fields to another one.

Fig.1

Here, we will not discuss the equations describing quantum transitions of this kind and the magnitude (undoubtedly, very small) of the corresponding probabilities. We shall pay attention to the important question of the future evolution of the created null system. Since, according to estimate (8), a null system is a macroscopic multi-particle state, for an approximate description of its evolution, one can apply the classical semi-phenomenological approach considering it as a result of averaging of the quantum equations. The evolution of the metric of the space of S_0 should be described in this case by the classical Einstein equations, somewhat generalized, however, to take into account the gravitational instability of the vacuum. We are talking now about the instability of the vacuum filling the curved space of the null system S_0. This instability is of two kinds. First, new closed spaces S_0' etc. can branch-off from S_0 as well as from S_v. These processes, however, do not affect the evolution of the space S_0 itself, and we will not take them into account. Second, the dissociation of the vacuum of S_0 can lead simply to an increase of the number of particles and antiparticles in the space S_0 and to the corresponding increase in the mass M of bimatter and entropy of the null system. This process is energetically allowed since, according to (4), an increase in M can be compensated by an increase in the system radius a (the role of which is played by the curvature radius in GR); moreover, it is thermodynamically favorable and, therefore, should necessarily occur. The question about its intensity cannot be solved theoretically at present and should be considered on a phenomenological level.

How should one generalize the Einstein equations to take into account phenomenologically the dissociation of vacuum? Vacuum can be characterized by energy-momentum tensor of the form [2, 3, 4] $T^{\mathrm{vac}}_{\mu\nu} = -\lambda g_{\mu\nu}$. We assume that the invariant vacuum energy density λ depends on the curvature of space (hence, on space and time coordinates), and, just for a trial, we take the simplest dependence

$$\lambda = k\kappa^{-1} R(x)\,, \tag{10}$$

where $\kappa = 8\pi G c^{-4}$, R is the scalar curvature, and k is a dimensionless constant having the meaning of the "coefficient of elasticity of vacuum." This assumption agrees with the idea due to A. D. Sakharov [5] that vacuum resists curving of space, demonstrating the property of "elasticity," and can in principle be verified in frames of quantum field theory in a Riemannian space. With the account of (10), the Einstein equations take the form

$$R_{\mu\nu} - \left(\frac{1}{2} - k\right) g_{\mu\nu} R = \kappa T_{\mu\nu}\,. \tag{11}$$

The divergence of the tensor of mass of bimatter $T_{\mu\nu}$ is now different from zero, $T^{\nu}_{\mu;\,\nu} \neq 0$, which reflects, in frames of the made assumptions, the contribution from the dissociation of vacuum. It is not difficult to show that equations (11), under certain conditions on the parameter k, indeed lead to an increase of the mass of bimatter M and to an increase of the volume of the space of S_0. These equations, at the same time, do not contradict the known gravitational effects since, outside the masses, they reduce to the usual equations $R_{\mu\nu} = 0$.

3. The effect of gravitational instability of vacuum gives a foundation for a new approach to the cosmological problem. Assuming that it is this effect that determines the creation and evolution of the Metagalaxy, we arrive at a "vacuum" cosmological model the main provisions of which can be formulated as follows:

1. The initial state of the Metagalaxy is vacuum;
2. The Metagalaxy is a "null system," i.e., it is characterized by zero total values of the strictly conserved quantities: energy, charge, baryon and lepton numbers; the consequence of this, according to GR, is the spatial closeness of the Metagalaxy;
3. The Metagalaxy is created from vacuum at some moment of time $t = 0$ as a result of the quantum transition $|\text{vacuum}\rangle \to |\text{null system}\rangle$ of the type described above, and has size and proper mass of order (9) at the moment of creation;
4. After that, its mass and entropy increase as a result of continuous dissociation of vacuum; this growth causes expansion of the space of the Metagalaxy;
5. The evolution of the Metagalaxy is approximately described by the Einstein equations of type (11).

Equations (11), in particular, imply that dissociation of vacuum proceeds with maximal intensity at places with maximal mass density — this opens up the possibility of explaining the mysterious activity of galactic nuclei [6]. In this case, one can indicate (this will be published elsewhere) a sufficiently effective mechanism of separation of the bimatter created in the nuclei into matter and antimatter and, therefore, to rebut the known arguments [2] against the charge death of the Universe.

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ГРАВИТАЦИОННАЯ НЕУСТОЙЧИВОСТЬ ВАКУУМА И
КОСМОЛОГИЧЕСКАЯ ПРОБЛЕМА

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Fig.2. *Title-page of the Preprint ITP-73-137P*

A more detailed development of the discussed issues will be published elsewhere.

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ГРАВИТАЦИОННАЯ НЕУСТОЙЧИВОСТЬ ВАКУУМА И КОСМОЛОГИЧЕСКАЯ ПРОБЛЕМА

П.И. Фомин

Показано, что при учете гравитационного взаимодействия, физический вакуум способен без нарушения каких-либо законов сохранения спонтанным образом частично "диссоциировать"на частицы и античастицы. Обсуждается возможное космологическое значение этого эффекта. Формулируется "вакуумная космологическая модель", в которой вакуум принимается за начальное состояние Метагалактики. Сделано обобщение классических космологических уравнений Эйнштейна, позволяющие феноменологически учесть эффект гравитационной неустойчивости вакуума.

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(Руководитель семинара К.А. Пирагас).

ГРАВІТАЦІЙНА НЕСТІЙКІСТЬ ВАКУУМУ І КОСМОЛОГІЧНА ПРОБЛЕМА

П.І. Фомін

Показано, що при врахуванні гравітаційної взаємодії, фізизичний вакуум спроможний без порушення будь-яких законів збереження спонтанним способом частково "дисоціювати"на частинки та античастинки. Обговорюється можливе космологічне значення цього ефекта. Формулюється "вакуумна космологічна модель", в якій вакуум приймається за початковий стан Метагалактики. Зроблено узагальнення класичних космологічних рівнянь Ейнштейна, які дозволяють феноменологічно врахувати ефект гравітаційної нестійкості вакуума.

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