A novel mechanism of cosmological baryogenesis through baryon capture by primordial black holes is suggested. In contrast to the conventional scenarios it does not demand non-conservation of baryonic number in particle physics and can proceed in thermal equilibrium. For implementation of this mechanism a heavy superweakly interacting particle with non-zero baryon number is necessary.

I. INTRODUCTION

The explanation of the observed excess of baryons over antibaryons in the universe was beautifully solved by Sakharov [1] in 1967. He formulated the following three necessary conditions for generation of the cosmological baryon asymmetry:

1. Violation of C and CP symmetries in particle physics.
2. Non-conservation of baryonic number, $B$.
3. Deviation from thermal equilibrium in the early universe.

With properly chosen parameters of the particle physics model at high energies these three principles allow to explain the cosmological excess of particles over antiparticles and to calculate the magnitude of the asymmetry. According to the review [2], the magnitude of the asymmetry, expressed in terms of the present day number densities, is equal to

$$\beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \cdot 10^{-10}$$

where $n_B$ and $n_{\bar{B}}$ are respectively the number densities of baryons and antibaryons (note that today $n_B \ll n_B$), $n_\gamma = 411(T_\gamma/2.73^\circ K)^3$ cm$^{-3}$, and $T_\gamma = 2.73^\circ K$ is the present day temperature of the cosmic microwave background (CMB) radiation.

There exists a plethora of different models of baryogenesis, which can successfully do the job, for reviews see refs. [3–9]. Here we consider rather special scenario invoking black holes for creation of cosmological baryon asymmetry. The idea that black hole evaporation can lead to different numbers of particles and antiparticles in outer world belongs to Hawking [10] and Zeldovich [11] and was quantitatively realized in refs. [12, 13].

Briefly the mechanism operates as follows. The evaporated particles initially have thermal equilibrium distribution and there should be equal numbers of particles and antiparticles. However, they propagate in the gravitational field of the parent BH with the effective potential barrier at a distance of several gravitational radii. The height of the barrier is different for particles of different masses, higher for larger mass. Hence the presence of the barrier breaks the equilibrium. Assume that among the evaporated particles there are some massive bosons which can decay into a pair of quark and antiquark of different flavor, e.g. into $u$ and $\bar{t}$ or vice versa into the charge conjugated channel, i.e. into $\bar{u}$ and $t$. Assume also that due to breaking of C and CP symmetries the probability of the decay into $u\bar{t}$ is larger than into $\bar{u}t$, then the flux of baryons into external space would be larger than the flux of antibaryons.

Here we consider in a sense opposite scenario of different absorption rate of baryon and antibaryons by a BH. This mechanism may generate cosmological baryon asymmetry in thermal equilibrium without breaking of B-conservation. In the following section we discuss the capture mechanism of $X/\bar{X}$ particles by PBH. In the third section the difference between $X$ and $\bar{X}$ scattering cross sections is estimated. In sec. IV we conclude.
II. CAPTURE MECHANISM BY PBH IN THE EARLY UNIVERSE

Assume that there exist heavy particles $X$ and antiparticles $\bar{X}$ with non-zero baryon number $B$. They are supposed to be unstable, but possibly long-lived, decaying into light particles through $B$-conserving decays. Let us consider the epoch of the cosmological evolution when the temperature was of the order of the $X$-particle mass, $T \approx m_X$, while all other particles have zero or much smaller masses. Also assume that there exists an interaction between $X$, $\bar{X}$ particles and light particles (e.g. quarks) which respects CPT symmetry but breaks CP and C symmetries.

Assume also that in the early universe there existed a population of primordial black holes with the energy density at the moment of their creation much smaller than the energy density of the background particles,

$$\theta_{BH} = \epsilon \theta_0,$$

with $\epsilon \ll 1$.

According to the suggested scenario, heavy particles $X$ and $\bar{X}$ have been captured by PBHs with some excess of $\bar{X}$ over $X$ due to a small difference of the interaction strength of $X$ and $\bar{X}$ with cosmological plasma.

The equations of motion for $X$ and $\bar{X}$ near the PBH can be written in analogy with those of ref. [14] and have the form:

$$\dot{v}_X = -\frac{G_N M}{r^2} + \alpha \frac{Q}{m_X^2} + \frac{L}{4\pi^2 m_X} \frac{\sigma_{0X} n_0 E_0}{m_X} v_X - \frac{n_X \sigma_{X\bar{X}} \delta P}{m_X} (v_X - v_{\bar{X}})$$

(3)

$$\dot{v}_\bar{X} = -\frac{G_N M}{r^2} - \alpha \frac{Q}{m_X^2} - \frac{L}{4\pi^2 m_X} \frac{\sigma_{0\bar{X}} n_0 E_0}{m_X} v_{\bar{X}} + \frac{n_{\bar{X}} \sigma_{X\bar{X}} \delta P}{m_X} (v_X - v_{\bar{X}}).$$

(4)

Here $M$ is the PBH mass, $G_N = 1/m_{pl}^2$ is gravitational constant, $m_{pl} = 1.22 \cdot 10^{19}$ GeV is the Planck mass, $v_X$ and $v_{\bar{X}}$ are the fluid velocities of $X$ and $\bar{X}$ (that is the average velocities of $X$ and $\bar{X}$ in the plasma which do not include typically larger chaotic thermal velocities), $Q$ is the electric charge of the PBH in elementary charge units, $\alpha = e^2/\pi = 1/137$, $\sigma_{ij}$ is the cross section of scattering of $i$ on $j$, sub-index $0$ means all the set of light relativistic particles in the primeval plasma, with masses much smaller than $m_X$; $L$ is the luminosity induced by the accretion to the PBH flow, $\delta P$ is the momentum transfer in $X\bar{X}$-scattering, $n_X$ and $n_{\bar{X}}$ are the number densities of $X$ and $\bar{X}$ around the PBH, $n_0$ is the number density of the light particles in thermal bath surrounding the PBH, and $E_0$ is the light particle energy, which is roughly equal to the momentum transfer in $X\bar{X}$ scattering on light particles. We neglect the angular momentum term in the equations above because it does not change appreciably our results.

We are interested in the difference of the capture velocities of $X$ and $\bar{X}$. The overall motion of the light particles towards PBHs are disregarded. The account of this motion would enhance the capture probability of heavy ones, $X$ and $\bar{X}$.

It is convenient to introduce the following quantities:

$$v_X + v_{\bar{X}} = 2v_+, \quad v_X - v_{\bar{X}} = v_-$$

$$\sigma_{0X} + \sigma_{0\bar{X}} = 2\sigma_+, \quad \sigma_{0X} - \sigma_{0\bar{X}} = \sigma_-.$$

(5)

In the first order in $v_-$ and $\sigma_-$ equations (3) and (4) turn into:

$$\dot{v}_+ = -\frac{G_N M}{r^2} + \frac{L}{4\pi^2 m_X} \frac{\sigma_+ n_0 E_0}{m_X} v_+,$$

(6)

$$\dot{v}_- = \frac{2\alpha Q}{r^2 m_X} + \frac{L}{4\pi^2 m_X} \frac{n_0 E_0}{m_X} (\sigma_+ v_- + \sigma_- v_+) - (n_X + n_{\bar{X}}) \frac{\sigma_{X\bar{X}} \delta P}{m_X} v_-.$$

(7)

The acquired by PBH electric charge $Q$ would be quickly neutralized by light charged particles so it is neglected in what follows.

We assume that the characteristic time is smaller than the Hubble time, so the coefficients in the above equations can be treated as constant and thus equation (6) is solved as

$$v_+ = \left( \frac{L \sigma_+}{4\pi m_X} - \frac{M}{m_{pl}^2} \right) \frac{m_X (1 - e^{-\gamma_+ t})}{r^2 \sigma_+ n_0 E_0}.$$

(8)

where $\gamma_+ = \sigma_+ n_0 E_0/m_X$. For large $t\gamma_+$ we can neglect $e^{-\gamma_+ t}$ in comparison with 1.
With known \( v_+ \), eq. (7) can be solved for large \( t \) as

\[
v_− = \frac{M}{m_{Pl}^2 r^2} \frac{\sigma_−}{\sigma_+} \frac{m_X}{n_0 E_0 \sigma_+} \left( 1 + \frac{n_X + n_\bar{X} \sigma_\bar{X} \delta E_0}{n_0} \right)^{-1} \approx \frac{M}{m_{Pl}^2 r^2} \frac{\sigma_−}{\sigma_+} \frac{m_X}{n_0 E_0 \sigma_+}. \tag{9}\]

The (anti)baryonic number could be accumulated inside PBH during the Hubble time when the cosmic temperature was close to \( m_X \). At that period there was: \( n_0 = 0.1 g_s T^3 \approx 10 m_X^3, n_X = k n_0 \) with \( k = 0.01 - 0.1, E_0 \approx m_X \) and \( \sigma_+ = f^2 g_s/m_X^2 \), where \( g_s \approx 100 \) is the number of particle species in the cosmic plasma, \( f \) is a small coupling constant of \( X \)-particles to other ones. The Hubble time at that period was:

\[
t_H = \frac{1}{2H} = \left( \frac{90}{32 \pi^4 g_s} \right)^{1/2} \frac{m_{Pl}}{T^2} \approx 0.03 \frac{m_{Pl}}{m_X}. \tag{10}\]

The total baryonic number of PBH collected from the volume inside the sphere of radius \( r \) during \( t = t_H \) would be:

\[
N_B = 4 \pi r^2 t_H n_X v_− B_X \approx \frac{k}{0.01} f^{-2} B_X M_g, \tag{11}\]

where \( M_g \) if the PBH mass in grams, \( B_X \) is a baryon number of \( X \) particle, and \( \sigma_+ / \sigma_+ \approx f^2 \), because the difference between cross-sections of particles and antiparticles due to breaking of C and CP symmetries arises in the lowest order loop corrections in the same way as the difference between partial decay width of particles and antiparticles appears due to rescattering in the final state as it is discussed in reviews on baryogenesis quoted above, especially in [3].

The baryonic asymmetry \( \beta = n_B / n_\gamma \), where \( n_B \) is the density of the baryonic number and \( n_\gamma \) is the present day number density of cosmic microwave background radiation, can be estimated as

\[
\beta = \frac{n_B}{n_0} N_B = \frac{9_{PBH} 3T}{M \rho_0} N_B \approx 5 \cdot 10^{-24} B_X \frac{\epsilon}{T^2} \frac{m_X}{GeV}, \tag{12}\]

assuming that this ratio remains constant in the course of cosmological evolution. This is approximately true if the entropy rise due to annihilation of massive particle species is not too strong. In the standard model the entropy dilution is equal to the ratio of particle species from \( T = m_X \) down to a fraction of MeV. It dilutes \( \beta \) roughly by factor 10. However, an abundant population of evaporating PBHs could lead to considerable dilution. According to the calculations of ref. [15] the dilution factor is

\[
S = 10^5 \epsilon M_g, \tag{13}\]

which we demand to be not much larger than unity.

If the coupling constant \( f^2 \) is of the order of the fine structure constant \( \alpha \sim 0.01 \), it is difficult to generate the observable asymmetry \( \beta \sim 10^{-9} \) through \( X/\bar{X} \)-capture by PBH, but super-weakly interacting \( f \ll \alpha \), and sufficiently massive \( X \)-particles could successfully do the job.

### III. DIFFERENCE BETWEEN MOBILITIES OF \( X \) AND \( \bar{X} \) PARTICLES IN THE BACKGROUND PLASMA

As we have already mentioned, C and CP symmetries are assumed to be broken, while CPT remains intact. As it is well known out of these three symmetries only CPT has rigorous theoretical justification. Namely its validity follows from the locality of particle interactions, Lorentz invariance, and hermicity of the Hamiltonian.

CPT invariance implies equality of the particle and antiparticle masses and their total decay widths, while the partial decay widths of particles and antiparticles into charge conjugate channels may be different, due to breaking of C and CP. However, it can happen only in higher orders of perturbation theory. Similar inequality may also exist for probabilities of particle and antiparticle scattering:

\[
\sum_{a,b} \Gamma(X + a \rightarrow X + b) \neq \sum_{\bar{a},\bar{b}} \Gamma(\bar{X} + \bar{a} \rightarrow \bar{X} + \bar{b}), \tag{14}\]

where summations are done over all light particle sets in initial, \( a \), and final states, \( b \).

However, we should take into account that according to CPT theorem the total probability of a process from an initial state, containing a certain set of particles is equal to the total probability of the process containing antiparticles with opposite spin projection state, e.g. with opposite helicities \( \lambda \) [10].
\[ \Gamma [p_1, \lambda_1, a_1, p_2, \lambda_2, a_2, ...] = \Gamma [p_1, -\lambda_1, \bar{a}_1, p_2, -\lambda_2, \bar{a}_2, ...] \] (15)

In particular, this condition leads to the mentioned above equality of the total decay width of particles and antiparticles while allows for a difference of among the partial decay rates.

To achieve desired difference of \(X\) and \(\bar{X}\) particles scattering we need to introduce a new interaction leading to disappearance of \(X\) and \(\bar{X}\) particles through decay or scattering process, such as

\[ a + X \rightarrow b + H, \] (16)

where the heavy particle \(H\) has zero baryonic number and the light state \(b\) should have the same baryonic number as \(a + X\) if we want to avoid non-conservation of baryons.

It is instructive to consider an example of how a difference between partial decay rates appears in the case of two-body decays of \(X\)-particle. A detailed study of the necessary number of the decay channels and the number of different \(X\)-like particle species is presented in ref. [3]. In the lowest order in perturbation theory the decay is described by the diagram presented in figure 1(a). Evidently in this order the probability of charge conjugated decays are equal due to hermicity of the Lagrangian. So the amplitudes of particle and antiparticle decays have opposite phases but equal absolute values. To avoid this limitation we need add the higher order correction depicted in figure 1(b). This higher order correction to the amplitude has an additional imaginary part due to on-mass-shell re-scattering in the final state through an exchange of another heavy particle \(Y\), usually different from \(X\).

\[ \Gamma( X \rightarrow a + b ) = c_0 m_X (1 + c_1), \] (17)

where \(c_0\) and \(c_1\) are numerical constants generically of the order of unity; \(c_0\) is the same for particles and antiparticles, while \(c_1\) is different if \(C\) and \(CP\) are broken. However, as we have already mentioned, the sum over all final states produced in the decay are the same for \(X\) and \(\bar{X}\). The difference in the partial decay widths is a cornerstone of the popular model of baryogenesis by heavy particle decays.

The equalities of the total probabilities means in particular that the total cross-section of \(X\)-scattering on a particle \(^"a"\) \(\sigma_{tot}(X + a \rightarrow All)\) is equal to the same of particles and antiparticles \(\sigma_{tot}(\bar{X} + \bar{a} \rightarrow All)\). If the final state \(^"All"\) contains one and only one \(X\)-particle, then the mobilities of \(X\) and \(\bar{X}\) in the cosmological plasma would be the same and the discussed here mechanism of baryogenesis would not operate. However, if the complete set of the final states include a state or states where \(X\) (or \(\bar{X}\)) is
missing, then the cross-sections of the processes $\sigma_{tot}(X + a \rightarrow X + All)$ and $\sigma_{tot}(\bar{X} + \bar{a} \rightarrow \bar{X} + All)$ may be different, leading to the needed conservation of baryonic number in particle interactions is unnecessary. So the proton must be almost absolutely stable. To be more precise it may decay by Zeldovich mechanism [21] through formation of a virtual black hole from three quarks inside proton. But the life-time with respect to such decay is almost infinite, $	au_p \sim 10^{45}$ years. Also one could hardly expect neutron-antineutron oscillations to be observable (for a recent review see e.g. [22]).

Another unusual feature of the model is a possibility to create baryon (or any other type of asymmetry between particles and antiparticles) in thermal equilibrium. Normally the suppression factor is of the order of the ratio of the Hubble expansion rate to the particle expansion rate, $H/T$. The former is inversely proportional to a huge value of the Planck mass, $H \sim T^2/m_{Pl}$, where $m_{Pl} = 1.22 \cdot 10^{19}$ GeV and $T$ is the cosmological plasma temperature. According to the estimates [10] and [11], for the mechanism considered here the situation is opposite: the larger is the Planck mass (or the slower is the cosmological expansion), the larger is the baryon asymmetry.

### IV. CONCLUSION

The proposed here scenario of baryogenesis has a novel feature that non-conservation of baryonic number in particle interactions is unnecessary. So the proton must be almost absolutely stable. To be more precise it may decay by Zeldovich mechanism [21] through formation of a virtual black hole from three quarks inside proton. But the life-time with respect to such decay is almost infinite, $\tau_p \sim 10^{45}$ years. Also one could hardly expect neutron-antineutron oscillations to be observable (for a recent review see e.g. [22]).

Acknowledgment

This work was supported by RNF Grant 19-42-02004.

The Feynman diagrams was drawn by JaxoDraw [23].

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