Possible origin of antimatter regions in the baryon dominated universe

Maxim Yu. Khlopov
Center for CosmoParticle Physics "Cosmion," 4 Miusskaya pl., 125047 Moscow, Russia,
Institute for Applied Mathematics, 4 Miusskaya pl., 125047 Moscow, Russia,
and Moscow Engineering Physics Institute, Kashirskoe shosse 31, 115409 Moscow, Russia

Sergei G. Rubin
Center for CosmoParticle Physics "Cosmion," 4 Miusskaya pl., 125047 Moscow, Russia
and Moscow Engineering Physics Institute, Kashirskoe shosse 31, 115409 Moscow, Russia

Alexander S. Sakharov
Labor für Höchenergiephysik, ETH-Hönggerberg, HPK–Gebäude, CH–8093 Zurich, Switzerland,
Center for CosmoParticle Physics "Cosmion," 4 Miusskaya pl., 125047 Moscow, Russia,
and Moscow Engineering Physics Institute, Kashirskoe shosse 31, 115409 Moscow, Russia

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We discuss the evolution of a $U(1)$ symmetric scalar field in the inflation epoch with a pseudo-Nambu-Goldstone tilt being revealed after the end of the exponential expansion of the Universe. The $U(1)$ symmetry is supposed to be associated with baryon charge. It is shown that quantum fluctuations lead in a natural way to a baryon dominated universe with antibaryon excess regions. The range of parameters is calculated at which the fraction of universe occupied by antimatter and the size of antimatter regions satisfy the observational constraints, survive to the modern time, and lead to effects that are accessible to an experimental search for antimatter.

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I. INTRODUCTION

The statement that our Universe is baryon asymmetrical as a whole is a quite firmly established observational fact of contemporary cosmology. Indeed, if large regions of matter and antimatter coexist, then annihilation would take place at the borders between them. If the typical size of such a domain was small enough, then the energy released by these annihilations would result in a diffuse γ-ray background, in distortions of the spectrum of the cosmic microwave radiation and light element abundance, neither of which is observed (see for review, e.g., [1]). A recent analysis of this problem [2] for a baryon symmetric universe demonstrates that the size of regions should exceed 1000 Mpc, being comparable with the modern cosmological horizon. It therefore seems that the Universe is fundamentally matter-antimatter asymmetric. However, the arguments used in [2] do not exclude the case when the Universe is composed almost entirely of matter with relatively small insertions of primordial antimatter. Thus we may expect the existence of macroscopically large antimatter regions in the baryon asymmetric universe, which are much smaller than the modern cosmological horizon. Since this situation differs drastically from the case of the baryon symmetric universe, we call the region filled with antimatter in the baryon dominated universe the local antimatter area (LAA). Of course the existence of LAA's is not a rigorous requirement of baryosynthesis, but some modification of baryogenesis scenarios will result in the formation of domains with a different sign of baryon charge (see, for example, [3]). The only condition which is necessary to satisfy is that the amount of antibaryons within LAA's must be small compared to the total baryon number of the Universe.

At first glance it is not difficult to have some amount of LAA's if we simply suppose that in the early Universe when the baryon excess is generated the C and CP violation have different signs in different space regions [4]. This may be achieved, for example, in models with two different sources of CP violation, an explicit and a spontaneous [5] one. However, any spontaneous CP-violation processes are a result of the early phase transition of first or second order which implies a very small size of primordial LAA's [3]. For example, if the LAA's are formed in the second-order phase transition, their size at the moment of formation is determined by $l_i \simeq 1/(\lambda T_c)$, where T_c is the so-called Ginsburg temperature (the critical temperature at which the phase transition takes place) and λ is the self-interaction coupling constant of field which breaks CP symmetry [5]. As a result of the expansion the modern sizes of domains would reach $l_0 \simeq l_i(T_c/T_0) = 1/(\lambda T_0) \simeq 10^{-21}\,\mathrm{pc}/\lambda$, where T_0 is the present temperature of the background radiation.

On the other hand, it has been revealed [6] that the average displacement of the LAA's boundary caused by annihilation with surrounding matter is about 0.5 pc at the end of radiation dominated (RD) epoch. Therefore, any primordial LAA having initial size up to 0.5 pc or more at the end of RD stage survives to the contemporary epoch and in the case of successive homogeneous expansion has the size $\simeq 1$ kpc or more. Any primordial LAA with a scale less then critical survival size $l_c \simeq 1$ kpc at the contemporary epoch must be eaten up by the annihilation process. Thus it is a serious problem which any model with thermal phase transition encounters to create primordial LAA with the size exceeding the critical survival size l_c to avoid complete annihilation.

There is an additional problem for baryosynthesis with surviving LAA's sizes. The point is that any phase transition is accompanied by formation of topological defects. If we blow up the region with different signs of charge symmetry, we automatically blow up the scale of respective topological defect structure. If the structure decays sufficiently late in the observable part of the Universe, the contribution of energy density of such topological defects could be sufficiently high to contradict other observations. It can be easily estimated that the structure with the scale corresponding to the survival size enters the horizon and starts to decay at $T \leqslant 0.1$ MeV, i.e., in the period of big bang nucleosynthesis. To remove these unwanted relics sufficiently early it is necessary to have a mechanism for symmetry restoration. This mechanism implies that the baryogenesis is going on within a rather narrow time interval [7,8].

In the present paper we have elaborated the issue for inhomogeneous baryosynthesis without the difficulties pointed out above. The proposed approach is based on the mechanism of spontaneous baryogenesis [9]. This mechanism implies the existence of a complex scalar field carrying the baryonic charge with explicitly broken U(1) symmetry. The baryon-antibaryon number excess is produced when the phase of this additional field moves along the valley of its potential [9,10].

It is supposed that the vacuum energy responsible for inflation is driven by any scalar inflaton field, and an additional complex field coexists with the inflaton. Due to the fact that the vacuum energy during the inflational period is too large, the tilt of the potential is vanished. This implies that the phase of the field behaves as ordinary massless Nambu-Goldstone (NG) boson and the radius of the NG potential is firmly established by the scale of spontaneous U(1) symmetry breaking. Owing to quantum fluctuations of the massless field at the de Sitter background [21,22] the phase is varied in different regions of the Universe. When the vacuum energy decreases the tilt of potential becomes topical, and the pseudo-NG (PNG) field starts to oscillate. As the field rolls down in one direction during the first oscillation, it preferentially creates baryons over antibaryons, while the opposite is true as it rolls down in the opposite direction. Thus to have a globally baryon dominated Universe one must have the phase sited in the point, corresponding to the positive baryon excess generation, just at the beginning of inflation (when the size of the modern Universe crosses the horizon). Then subsequent quantum fluctuations can move the phase to the appropriate position causing the antibaryon excess production. If it takes place not too late after the inflation begins, the size of LAA may exceed the critical surviving size l_c.

The main idea of this paper is based on the existence of quantum fluctuations along the effectively massless angular direction of the baryonic charged scalar field. Thus, more generally, the considered issue of generation of LAA's is applicable practically to all mechanisms of baryogenesis where the number density and sign of the baryon asymmetry depend on the angular component of the complex scalar field. The advantage of the mechanism of spontaneous baryogenesis [9] considered here is the quite simple unambiguous inflation dynamics of scalar field-generated baryon charge. This fact allows us to establish quantitatively a definite relationship between the effects of inflation and generation of baryon (antibaryon) excess in inhomogeneous baryogenesis. However, this relationship may be too rigid for the realistic model of antimatter domain formation compatible with the whole set of astrophysical constraints. The consistent picture may need more sophisticated scenarios. The principal possibility for such a scenario can be considered on the base of an Affleck-Dine (AD) [12] baryogenesis mechanism that still receives a lot of attention [12–17].

AD baryogenesis also involves the cosmological evolution of the effective scalar field, which carries the baryonic charge, being composed of supersymmetric partners of electrically neutral quark and lepton combinations. The important feature of supersymmetric extensions of the standard model is the existence of "flat directions" in field space, on which the scalar potential vanishes [11–13]. We will refer for the definiteness to the flat directions of minimal standard supersymmetric model (MSSM) [13,18]. Thus, if the some component of the scalar field lies along a flat direction, this component can be considered as a free massless complex scalar, the so-called AD field [12,13]. At the level of renormalizable terms, "flat directions" are generic, but supersymmetry breaking and nonrenormalizable operators lift the "flat directions" and sets the scale for their potential. During the inflational period the AD field develops a nonzero vacuum expectation value and subsequently when the Hubble rate becomes of the order of the curvature of AD potential, the condensate starts to oscillate around its present minimum. Baryon asymmetry can be induced in such a condensate only if there exists a phase shift between the real and imaginary parts of the AD field. Such a shift and consequently B and CP violation is provided by the A term in the potential which parametrizes the MSSM "flat direction" [12,13]. The resulting sign and number density of baryon asymmetry depends on the magnitude of the initial phase of the AD field and on the phase shift created by the A term at the relaxation period [12–14]. Therefore, the de Sitter fluctuations can generate LAA's in the baryon asymmetric universe in a way similar to the spontaneous baryogenesis if the angular direction of the AD field is characterized by the mass that is much smaller than the Hubble constant H during inflation. It takes place if there are no of order H corrections to the A term [17].

The early dynamics of the AD field are quite complicated [16] owing to the nontrivial background energy density driving the inflation in MSSM. Moreover, the AD potential can get corrections from the vacuum energy that removes its minimum from the original one [13,14,16,17]. In general there are two types of inflation in MSSM, D-term or F-term inflation (see, for a review [19]), depending on the type of vacuum contributing the energy density during the de Sitter stage. In the case of D-term inflation AD fields and the inflaton slow roll coherently [16] (in the absence of order H^2 corrections to the mass-squared term of the AD potential). It implies that the radius of the effectively massless angular AD direction is determined by the immediate value of the inflaton field. For the case of F–term inflation the AD scalar will get an order H^2 negative mass-squared term

[13,14,16,17] causing the minimum of the AD potential. The AD field is closed to the minimum during the F-inflation stage [16] and this minimum determines the radius of the circle valley of the effectively massless angular direction.

The conclusion from this explicit example based on the MSSM is the following. For any complicated inflation dynamics of a baryon charged field it is possible to simulate an appropriate massless direction that behaves similar to the circle valley of the NG potential. This fact makes the proposed issue for the generation of LAA's viable not only for the spontaneous baryogenesis mechanism, but for the all mechanisms dealing with effectively massless angular directions during inflation [20].

The paper is organized as the following. In Sec. II we discuss the quantum behavior of the nondominant U(1) symmetric scalar field at the inflation period. We estimate the amplitude and space scale of the fluctuations of the phase for this field without PNG tilt. The size distribution of these fluctuations determines the size distribution of LAA's. Section III contains calculations of baryon-antibaryon net excess production at the relaxation of the phase when the tilt of the Mexican hat potential becomes topical. We summarize our conclusions and discuss some problems of the considered scenarios in Sec. IV.

II. PHASE DISTRIBUTION FOR NG FIELD AT THE INFLATION PERIOD

We start our consideration with the discussion of the evolution of the U(1) symmetric scalar field which coexists with the inflaton at the inflation epoch. The quantum fluctuations of such a field during the inflation stage causes the perturbations for the phase marking the Nambu-Goldstone vacuum. In our model this phase determines the sign and value of baryon excess, so the size distribution of domains containing the appropriate phase values, caused by those fluctuations, coincide with the size distribution of LAA's.

Thus to estimate the number density of antimatter regions with sizes exceeding the critical survival size l_c in the baryogenesis model under consideration we have to deal with long-wave quantum fluctuations of the NG boson field at the inflation period. Various aspects of this question have been examined in numerous papers [23–31] in connection with the cosmology of the invisible axion. Also the de Sitter quantum fluctuations have been analyzed in the framework of AD baryogenesis [15,16].

The effective potential of the complex field is taken in the usual form

$$V(\chi)=-m_\chi^2\chi^*\chi+\lambda_\chi(\chi^*\chi)^2+V_0, \tag{1}$$

where the field χ can be represented in the form

$$\chi=\frac{f}{\sqrt{2}}\exp\left(\frac{i\alpha}{f}\right). \tag{2}$$

The U(1) symmetry breaking implies that the radial component of the field χ acquires a nonvanishing classical part, $f=m_\chi/\sqrt{\lambda_\chi}$ and field α in Eq. (2) becomes a massless NG scalar field with a vanishing effective potential, $V(\alpha)=0$. In this case, χ has the familiar Mexican hat potential, and the degenerated vacua correspond to the circle of radius f. Throughout this paper we deal with the dimensionless angular field $\theta=\alpha/f$.

We are concerned here with the possibility of storing an appropriate phase value in the domain with the size exceeding the critical survival size. Such a value of the phase plays the role of a starting point for counterclockwise movement, which is going to generate antibaryon excess when the tilt of potential breaking U(1), explicitly, will turn to be topical.

We assume that the Hubble constant varies slowly during inflation. Also we use well established behavior of quantum fluctuations on the de Sitter background [28]. It implies that vacuum fluctuations of every scalar field grow exponentially in the inflating Universe. When the wavelength of a particular fluctuation becomes greater than H^{-1} the average amplitude of this fluctuation freezes out at some nonzero value because of the large friction term in the equation of motion of the scalar field, whereas its wavelength grows exponentially. In the other words such a frozen fluctuation is equivalent to the appearance of a classical field that does not vanish after averaging over macroscopic space intervals. Because the vacuum must contain fluctuations of every wavelength, inflation leads to the creation of more and more new regions containing the classical field of different amplitudes with a scale greater than H^{-1}. The averaged amplitude of such NG field fluctuations generated during each time interval H^{-1} is given by [21]

$$\delta\alpha=\frac{H}{2\pi}. \tag{3}$$

During such a time interval the universe expands by a factor of e. Since the NG field is massless during the inflation period (the PNG tilt is vanish yet), one can see that the amplitude of each frozen fluctuation is not changed in time at all and the phases of each wave are random. Thus the quantum evolution of the NG field looks like the one-dimensional Brownian motion [28,31] along the circle valley corresponding to the bottom of the NG potential. This statement implies that the values of the phase θ in different regions become different, and the corresponding variance grows as [22]

$$\langle(\delta\theta)^2\rangle=\frac{H^3t}{4\pi^2f^2}, \tag{4}$$

which means that dispersion grows as $\sqrt{\langle(\delta\theta)^2\rangle}=(H/2\pi f)\sqrt{N}$, where N is the number of e-folds. In the other words the phase θ makes a quantum step with the scale $H/2\pi f$ at each e-fold, and the total number of steps during some time interval Δt is given by $N=H\Delta t$.

Let us consider the scale $k^{-1}=H_0^{-1}=3000h^{-1}$ Mpc which is the biggest cosmological scale of interest. We suppose that the Universe is baryon asymmetric in this scale which leaves the horizon at definite e-fold $N=N_{max}$. On the other side this scale is the one entering the horizon now,

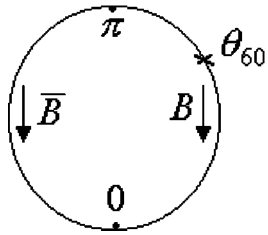

FIG. 1. Baryosynthesis in the spontaneous baryogenesis mechanism. The sign of baryon asymmetry depends on the starting point of phase oscillations.

namely $a_{max}H_{max}=a_0H_0$, where the subscript 0 indicates the contemporary epoch. This implies that

$$N_{max}=\ln\frac{a_{end}H_{end}}{a_0H_0}-\ln\frac{H_{end}}{H_{max}}, \tag{5}$$

the subscript *end* denotes the epoch at the end of inflation. The slow-roll paradigm tells us that the last term of Eq. (5) is usually $\leqslant 1$. The first term depends on the evolution of a scale factor a between the end of the slow-roll inflation and the present epoch. Assuming that inflation ends by a short matter-dominated period, which is followed by the RD stage lasting until the present matter dominated era begins, one has [32]

$$N_{max}=62-\ln\frac{10^{16}\ \text{GeV}}{\sqrt{H_{end}M_p}}-\frac{1}{3}\ln\frac{\sqrt{H_{end}M_p}}{\rho_{reh}^{1/4}}, \tag{6}$$

where $\rho_{reh}^{1/4}$ is the reheating temperature when the RD stage is established. With $H_{end}\simeq 10^{13}$ GeV and instant reheating this gives $N_{max}\approx 62$, the largest possible value. However, if one has to invoke supersymmetry to prevent the flatness of the inflation potential, for example, as in the case of AD baryogenesis, the $\rho_{reh}^{1/4}$ should not exceed 10^{10} GeV to avoid too much gravitino overproduction [33], and one has $N_{max}=58$, perhaps the biggest reasonable value. Throughout the paper we will use $N_{max}=60$. The smallest cosmological scale of LAA that is survived after annihilation is $k_c^{-1}=l_c\approx 8h^2$ kpc [6]. It is nine orders of magnitude smaller then H_0^{-1}, which corresponds to

$$N_c\approx N_{max}-13-3\ln h\approx 45. \tag{7}$$

Thus the l_c should have left the horizon at 45 folds before the end of inflation.

Let us assume that the phase value $\theta=0$ corresponds to South Pole of NG field circle valley, and $\theta=\pi$ corresponds to the opposite pole. The positive gradient of phase in this picture is routed as anticlockwise direction, and the dish of PNG potential would locate at the South Pole of circle (see Fig. 1). It will be shown below (see Sec. III) that the antibaryon production corresponds to the regions that would contain phase values caused counterclockwise rolling of PNG field α during the first half period of oscillation. If the field α rolls clockwise towards the dish of tilted potential just after the start of first oscillation then baryon production will take place.

Now we are in the position to estimate the fraction of the Universe containing LAA's. To ensure that the Universe would be baryon asymmetric as a whole it is necessary to suppose that the phase average value $\theta=\theta_{60}$ within the biggest cosmological scale of interest emerging at the $N_{max}=60$ e-folds before the end of inflation is located in the range $[0,\pi]$. The θ_{60} is the starting point for Brownian motion of the phase value along the circle valley during inflation. As it has been mentioned above, the phase makes the Brownian step $\delta\theta=H/2\pi f$ at each e-fold. Because the typical wavelength of the fluctuation $\delta\theta$ generated during such timescale is equal to H^{-1}, the whole domain H^{-1}, containing θ_{60}, after one e-fold effectively becomes divided into e^3 separate, causal disconnected domains of radius H^{-1}. Each domain contains an almost homogeneous phase value $\theta_{60-1}=\theta_{60}\pm\delta\theta$. In half of these domains the phase evolves towards π (the North Pole) and in the other domains it moves towards zero (the South Pole). To have LAA with appropriate sizes to avoid full annihilation one should require that the phase value crosses π or zero not later than after 15 steps. Only in this case the LAA's would have the sizes larger than l_c and are conserved up to the modern era. This means that one of the two following inequality must be satisfied

$$\pi-\frac{15H}{2\pi f}\leqslant\theta_{60}\leqslant\frac{15H}{2\pi f}. \tag{8}$$

Consider initially the case of exact equalities in expression (8) when the main part of antimatter is contained in the LAA's of size l_c. The number of domains containing the equal values of phases at the 45 e-folds before the end of inflation is given by the following expression

$$n_{45}\approx(e^3/2)^{15}\approx 10^{15}. \tag{9}$$

Then the probability that every domain of size l_c would not be separated into e^3 domains with a size of one order of magnitude less then l_c at the next e-fold is given by $P_s\approx(1/2)^{e^3}\approx 10^{-6}$. Thus the number of domains serving as the prototypes for LAA's of size l_c looks like

$$\overline{n}=n_{45}P_s\approx 10^9. \tag{10}$$

There are about 10^{11} galaxies in the Universe. Thus, according to such a simple consideration, we reveal that 1% of the volume boxes corresponding to each galaxy contains the region of size l_c filled with antimatter of the highest possible antibaryonic density if the θ_{60} coincides with the left side of inequality (8) or the lowest one in the case if the opposite equality is held.

We are able also to find the size distribution for LAA's. For this purpose it is necessary to study the inhomogeneities of the phase induced by Eq. (3). It has been well established that for any given scale $l=k^{-1}$, the large scale component of the phase value θ is distributed in accordance with Gauss's law [21,22,28,31]. The quantity which will be especially interesting for us is the dispersion (4) for quantum fluctuations of the phase with moments from $k=H^{-1}$ to $k_{min}=l_{max}^{-1}$

TABLE I. The sample of distribution of proto-LAA's by sizes and numbers of e-folds at $\theta_{60}=\pi/6$; $\bar{\theta}=-0$; $h=0.026$

N	N_{LAA}	$L_{LAA}h$
59	0	1103 Mpc
55	5.005×10^{-14}	37.7 Mpc
54	7.91×10^{-10}	13.9 Mpc
52	1.291×10^{-3}	1.9 Mpc
51	0.499	630 kpc
50	74.099	255 kpc
49	8.966×10^{3}	94 kpc
48	8.012×10^{5}	35 kpc
47	5.672×10^{7}	12 kpc
46	3.345×10^{9}	4.7 kpc
45	1.705×10^{11}	1.7 kpc

(where the l_{max} is the biggest cosmological scale that corresponds to 60 e-folds). This quantity can be expressed in the following manner:

$$\sigma_l^2=\frac{H^2}{4\pi^2}\int_{k_{min}}^{k} d\ln k=\frac{H^2}{4\pi^2}\ln\frac{l_{max}}{l}=\frac{H^2}{4\pi^2 f^2}(60-N_l), \tag{11}$$

where N_l is the number of e-folds which relates the biggest cosmological scale to the given scale l. This means that the distribution of the phase has the Gaussian form

$$P(\theta_l,l)=\frac{1}{\sqrt{2\pi}\sigma_l}\exp\left\{-\frac{(\theta_{60}-\theta_l)^2}{2\sigma_l^2}\right\}. \tag{12}$$

Suppose that at e-fold N_t before the end of inflation the volume $V(\bar{\theta},N_t)$ has been filled with phase value $\bar{\theta}$. Then at the e-fold $N_{t+\Delta t}=N_t-\Delta N$ the volume filled with phase $\bar{\theta}$ will follow the iterative expression

$$V(\bar{\theta},N_{t+\Delta t})=e^3V(\bar{\theta},N_t)+(V_U(N_t)-e^3V(\bar{\theta},N_t)P(\bar{\theta},N_{t+\Delta t}))h. \tag{13}$$

Here the $V_U(N_t)\approx e^{3N_t}H^{-3}$ is the volume of the Universe at N_t e-fold. Expression (13) makes it possible to calculate the size distributions of domains filled with an appropriate value of the phase numerically. In order to illustrate quantitatively the number distribution of domains, we present here the numerical results for definite values of θ_{60}, $\bar{\theta}$, and $h=H/2\pi f$. Table I contains the results concerning the number of domains with average phase $\bar{\theta}$ at e-fold number N.

The fraction of the Universe filled with phase $\bar{\theta}$ appears to be equal to 7.694×10^{-9}. Thus we see that the distribution of domains with size is very abrupt and should be peaked at the smallest value of size. Adjusting the free parameters θ_{60} and h we are able to achieve the situation where the volume box corresponding to each galaxy contains (1–10) regions with an appropriate phase $\bar{\theta}$. The sizes of such regions are larger or equal to the critical surviving size. In spite of the sufficiently large total number of LAA's only the small part of our Universe will be occupied by LAA's (see the last line in the presented table).

The nontrivial question on the actual forms of astrophysical objects LAA's can have in the modern Universe needs spacial analysis, which, in general, strongly depends on the assumed form of the nonbaryonic dark matter, dominating in the period of galaxy formation. However, based on the early analysis [6,34,35] the two extreme cases can be specified, when the evolution of LAA's is not strongly influenced by the dark matter content. In the first case, the antibaryon density within the LAA is by an order of magnitude higher than the average baryon density, so that the over density inside this region can exceed the dark matter density and rapid evolution of such a LAA with the size exceeding the surviving scale can provide the formation of a compact antimatter stellar system [globular cluster (see, for review, [36])], which can survive in the galaxy [34,35]. The other extreme case is LAA with extremely low internal antibaryon density $\Omega_{\bar{B}}<10^{-5}$. Then the diffused antiworld is realized, when no compact antimatter objects are formed and LAA's evolve into low density antiproton-positron plasma regions in voids outside the galaxies [6,34].

III. SPONTANEOUS BARYOGENESIS MECHANISM

The following element of our scenario of inhomogeneous baryogenesis should contain a conversion of the phase θ into baryon-antibaryon excess. We consider the ansatz of the spontaneous baryogenesis mechanism [9]. The basic feature of this mechanism is that the sign of the baryon charge created by the relaxation of the energy of the PNG field critically depends on the direction that the phase is rotated on the bottom of the Mexican heat potential. It provides us with the necessary mechanism to convert the domains containing the appropriate phase value, caused by fluctuations, to the LAA's at the period when the tilt of the NG potential becomes significant compared to the expansion rate.

The one reasonable issue concerning spontaneous baryogenesis [9] has been considered in the Ref. [10]. Let us briefly discuss it. It was assumed that in the early Universe a complex scalar field χ coexists with inflaton ϕ responsible for inflation. This field χ has a nonvanishing baryon number. The possible interaction of χ that violates the lepton number can be described by following Lagrangian density (see, e.g., [10])

$$L=-\partial_\mu\chi^*\partial^\mu\chi-V(\chi)+i\bar{Q}\gamma^\mu\partial_\mu Q+i\bar{L}\gamma^\mu\partial_\mu L-m_Q\bar{Q}Q-m_L\bar{L}L+(g\chi\bar{Q}L+\text{H.c.}). \tag{14}$$

The fields Q and L could represent a heavy quark and lepton, coupled to the ordinary quark and lepton matter fields. Since fields χ and Q possess a baryon number while the field L does not, the couplings in Eq. (14) violate the lepton number [10]. The U(1) symmetry that corresponds to the baryon number is expressed by following transformations:

$$\chi\rightarrow\exp(i\beta)\chi,\quad Q\rightarrow\exp(i\beta)Q,\quad L\rightarrow L. \tag{15}$$

The effective Lagrangian density for θ, Q, and L eventually has the following form after symmetry breaking [10]:

$$L=-\frac{f^2}{2}\partial_\mu\theta\partial^\mu\theta+i\bar{Q}\gamma^\mu\partial_\mu Q+i\bar{L}\gamma^\mu\partial_\mu L-m_Q\bar{Q}Q-m_L\bar{L}L$$
$$+\left(\frac{g}{\sqrt{2}}f\bar{Q}L+\text{H.c.}\right)+\partial_\mu\theta\bar{Q}\gamma^\mu Q. \quad (16)$$

At the energy scale $\Lambda\ll f$, the symmetry (15) is explicitly broken and the Mexican hat circle gets a little pseudo-NG tilt described by the potential

$$V(\alpha)=\Lambda^4(1-\cos\theta). \quad (17)$$

This potential, of high $2\Lambda^4$, has a unique minimum at $\theta=0$. Of course, in most cases, the potential (17) is the lowest–order approximation to a more complicated expressions emerging from particle physics models (see, e.g., [37] and references therein).

The important parameter for spontaneous baryogenesis is the curvature of Eq. (17) in the vicinity of its minimum, which is determined by the mass of the PNG field

$$m_\theta^2=\frac{\Lambda^4}{f^2}. \quad (18)$$

As was mentioned above the field χ is an additional field with a nondominant energy density contribution to the Hubble constant derived by the de Sitter stage. Suppose that the tilt was formed during inflation. Then the order of magnitude estimation for fluctuations induced by large-scale inhomogeneity of oscillations of the field χ gives $\delta T/T=(1/3)(\delta\rho/\rho)(\Lambda/T)^4$. Thus, for $T=H/2\pi$ and reasonable value $\Lambda\simeq 10^{-5}H$ (see the end of this section), the thermal electromagnetic background fluctuations are within the observational limits.

Also, we assume that the field θ behaves as a massless NG field during inflation implying that the condition

$$m_\theta\ll H \quad (19)$$

is valid, where the H is the Hubble constant during the inflation. After the end of inflation, condition (19) is violated and the oscillations of field θ around the minimum of potential (17) are started. The energy density $\rho_\theta\simeq\theta_i^2 m_\theta^2 f^2$ of the PNG field which has been created by quantum fluctuations of θ during the inflation converts to baryons and antibaryons [9,10]. The sign of the baryon charge depends on the initial value of the phase from which the oscillations are started.

Let us estimate the number of baryons and antibaryons produced by classical oscillations of field θ with an arbitrary initial phase θ_i. The appropriate expression for the density of produced baryons (antibaryons) $n_{B(\bar{B})}$ is represented in [10]

$$n_{B(\bar{B})}=\frac{g^2}{\pi^2}\int_{m_Q+m_L}^{\infty}\omega d\omega\left|\int_{-\infty}^{\infty}dt\chi(t)e^{\pm 2i\omega t}\right|^2, \quad (20)$$

which is valid if $\chi(t\to-\infty)=\chi(t\to+\infty)=0$. The general case can be obtained in the limits $\chi(t\to-\infty)\neq 0;\chi(t\to+\infty)=0$ without a loss of generality. After integration by parts expression (20) has the form

$$N_{B(\bar{B})}=\frac{g^2}{4\pi^2}\Omega_{\theta_i}\int_{m_Q+m_L}^{\infty}d\omega\left|\int_{-\infty}^{\infty}d\tau\dot{\chi}(\tau)e^{\pm 2i\omega\tau}\right|^2, \quad (21)$$

where the Ω_{θ_i} is the volume containing the phase value θ_i. Here the surface terms appear to be zero at $t=\infty$ due to asymptotic of field χ and at $t=-\infty$ due to Feynman radiation conditions.

For our estimations it is enough to accept that the phase changes as

$$\theta(t)\approx\theta_i(1-m_\theta t) \quad (22)$$

during the first oscillation. We also set $m_Q=m_L=0$, which is reasonable for estimations. Substituting Eqs. (22) and (2) into Eq. (21) we come to

$$N_{B(\bar{B})}\approx\frac{g^2f^2m_\theta}{8\pi^2}\Omega_{\theta_i}\theta_i^2\int_{\mp\theta_i/2}^{\infty}d\tilde{\omega}\frac{\sin^2\tilde{\omega}}{\tilde{\omega}^2}, \quad (23)$$

where the sign in the lower limit of the integral corresponds to baryon or antibaryon net excess generation, respectively. The reasonability of our approximation follows from a comparison of Eq. (23) at small $\theta_i\ll 1$

$$N_B-N_{\bar{B}}=\frac{g^2f^2m_\theta}{8\pi^2}\Omega_{\theta_i}\theta_i^3 \quad (24)$$

with the result of [10].

Using for the spatially homogeneous field $\chi=(f/\sqrt{2})e^{i\theta}$ the expression for baryon charge

$$Q=i(\chi^*d\chi/dt-d\chi^*/dt\chi)=-fd\theta/dt, \quad (25)$$

one can easily conclude that $Q>0$ if $\theta>0$ during the classical movement of phase θ to zero. Thus the counterclockwise rotation gives rise to antibaryon excess while the clockwise rotation leads to baryon excess.

During reheating, the inflaton energy converts into the radiation. It is assumed that reheating takes place when the Mexican hat potential is not yet sensitive to the PNG tilt. This implies that the total decay width of inflaton Γ_{tot} into light degrees of freedom exceeds the mass m_θ. In the other words the reheating is going on under condition (19). The relaxation of the θ field starts when $H\approx m_\theta$ and converts to the baryons or antibaryons. Baryonic charge is converted inside a comoving volume after reheating owing to very effective decay during the cosmological time. This means that the baryon-to-entropy ratio in $n_{B(\bar{B})}/s=$const in the course of expansion. The entropy density after thermalization is given by

$$s=\frac{2\pi^2}{45}g_*T^3, \quad (26)$$

where g_* is the total effective massless degrees of freedom. Here we are concerned with the temperature above the electroweak symmetry-breaking scale. At this temperature all the degrees of freedom of the standard model are in equilibrium and g_* is at least equal to 106.75. The temperature is connected with the expansion rate as follows:

$$T=\sqrt{\frac{m_p H}{1.66 g_*^{1/2}}}=\frac{\sqrt{m_p m_\theta}}{g_*^{1/4}}. \quad (27)$$

The last part of expression (27) takes into account that the relaxation starts under the condition $H \approx m_\theta$. Using the formulas (23), (26), (27) we are able to get the baryon-antibaryon asymmetry

$$\frac{n_{B(\bar{B})}}{s}=\frac{45 g^2}{16\pi^4 g_*^{1/4}}\left(\frac{f}{m_p}\right)^{3/2}\frac{f}{\Lambda}Y(\theta_i). \quad (28)$$

The function $Y(\theta)=\theta^2\int_{-\theta/2}^{\theta/2} d\omega(\sin^2\omega/\omega^2)$ takes into account the dependence of the amplitude of the baryon asymmetry and its sign on the initial phase value in the different space regions during inflation.

Expression (28) allows us to get the observable baryon asymmetry of the Universe as a whole $n_B/s \approx 3\times 10^{-10}$. In the model under consideration we have supposed initially that $f \geqslant H \simeq 10^{-6} m_p$. The natural value of the coupling constant is $g \leqslant 10^{-2}$. We are coming to observable baryon asymmetry at the quite reasonable condition $f/\Lambda \geqslant 10^5$ (see, e.g., [37]).

IV. DISCUSSION

In this paper we have proposed a model for inhomogeneous baryosynthesis on the basis of the spontaneous baryogenesis mechanism [9]. The model predicts the generation of LAA's with sizes exceeding the critical surviving size. The antibaryon number density relative to background baryon density in the resulting LAA's and its number depends on the value of the phase established at the beginning and on the parameters of the PNG field potential. It is possible to have one or several LAA's in the volume box corresponding to every galaxy depending on the parameter values. The observational consequences of existence of LAA's and the restrictions on their number and sizes have been analyzed in Refs. [6,34,35].

Of course, we may in general expect that some region with size exceeding l_c would contain antibaryon excess after the annihilation of small primordial domains and antidomains contained in this region is completed. However, the probability to have such a region is suppressed exponentially. Therefore, to have an observationally acceptable number of antimatter regions [34] with the size exceeding the critical survival size, a superluminous cosmological expansion in the formation of primordial antimatter protodomain seems necessary.

As we have mentioned, the additional problem for most models of inhomogeneous baryogenesis invoking phase transitions at the inflation epoch is the prediction of the large scale unwanted topological defects. Our scheme contains the premise for the existence of domain walls too. Such walls are not formed when only the minimum of the PNG potential exists, which corresponds in the considered model to the fluctuations around $\theta=0$, when the North pole ($\theta=\pi$) is not crossed. But in the case when such crossing takes place, the multiple degeneracy of vacua appears (e.g., vacua with $\theta=0$ and $\theta=2\pi$). The equation of motion that corresponds to potential (17) admits a kinklike, domain-wall solution, which interpolates between two adjacent vacua. Thus, when the PNG tilt is significant, a domain wall is formed along the closed surface (e.g., $\theta=\pi$) [38]. In the other words every LAA with high relative antibaryon density will be encompassed by the domain-wall bag. The wall stress energy $\Delta \approx 8 f \Lambda^2$ [38,39] leads to the oscillation of the wall bag after the whole bag enters the cosmological horizon. During the oscillations the energy stored in the walls is released in the form of quanta of NG field and gravitational waves. As we take $0<\theta_{60}<\pi$, the wall's bag will have the scale of the order of a modern horizon, if the dispersion $\sigma_{l_{max}}$ is as large as $\pi-\theta_{60}$. Owing to the very large oscillation period, such a big wall bag would presumably survive to the present time, which would be a cosmological disaster [29,30]. Thus the upper limit on the dispersion will be $\sigma_{60}<\pi$. On the other hand, this condition should be valued if we want to have parameters of the LAA population that do not contradict direct and indirect observational constraints [2]. It means that we will have wall bags with sizes less than the cosmological horizon and that walls had to decay until the present time. The mechanisms of their decay is the subject of a separate paper, in which we also plan to obtain additional constraints on the model, and which follow from the condition that walls do not dominate within the cosmological horizon before the bag decays. If the energy density of walls is sufficiently high to give local wall dominance in the border region before the bag enters the horizon, it is of interest to analyze the role of superluminous expansion in the border regions in the bag evolution (see, e.g., [40]). The interesting question is on the wall interaction with baryons in the course of wall contraction; decay will be also studied separately.

In general all baryogenesis models that are able to generate some amount of antimatter regions look like the radical limit of models with local baryon number density fluctuations, so-called isocurvature fluctuations [32,41]. It is known that the contribution of isocurvature fluctuations to the cosmic microwave background (CMB) anisotropy obeys

$$\frac{\delta T}{T}=-\frac{1}{3}\frac{\Omega_B}{\Omega_0}\delta_{B_i},$$

where δ_{B_i} is the amplitude of the initial baryon number fluctuations and Ω_0 (Ω_B) are the total (baryon) density (in units of critical density). As it follows from our numerical illustration [see Sec. II and expression (23)], we must have quite a large amplitude of initial baryon number fluctuations $\delta_{B_i} \sim h/\theta_{60} \simeq 10^{-2}$ at the biggest cosmological scales, and consequently we would have large amplitude of isocurvature fluctuations at large scales, which contradicts the cosmic background explorer (COBE) measurements [41].

To avoid the problem of large-scale isocurvature fluctuations, we can, for example, prevent the fluctuations of the phase at the largest cosmological scales. The point is that to have LAA with a size exceeding few kpc, we do not need to start phase fluctuations at the e-folds that correspond to the biggest cosmological scales. It is sufficient to start fluctuations of the phase from the moment, for instance, when the scale $8h^{-1}$ Mpc leaves the Hubble horizon during inflation, namely after the 6.2 e-folds from the beginning of inflation. We took this scale, because it is known that at a scale less then $8h^{-1}$ Mpc we could generate initial baryon number fluctuations at the level $\delta_{B_i}\simeq 10^{-2}$–$10^{-3}$ without any contradictions with observations.

One of the natural ways to prevent the phase fluctuations at the early inflation is to keep U(1) symmetry restored during first 7 e-folds. The mechanism that is able to restore symmetry during inflation has been consider in Refs. [24,27,28,42]. According to those works we can introduce the interaction between the inflaton field ϕ and field χ. The simple potential of such a kind may be chosen as $V(\phi,\chi)=\frac{1}{4}\lambda_\phi\phi^4+V(\chi)+\nu\phi^2\chi^*\chi$, where $\nu=m_\chi^2/cM_p^2$, and $c\simeq 1$. The effective mass of the field χ depends on ϕ directly $m_\chi^2(\phi)=m_\chi^2+\nu\phi^2$. One considers here for simplicity the case $\nu=m_\chi^2/cM_p^2$. This implies that the effective value of mass $m_\chi^2(\phi)$ during inflation is given by $\nu(\phi^2-cM_p^2)$ and is positive because of the very large value of the inflation field. It means that our U(1) symmetry is restored during the period when the amplitude of the inflaton field exceeds $\phi_c=\sqrt{c}M_P$, and the field χ settles into the minimum of its symmetric potential. During this period there was no NG boson valley and phase fluctuations. After the moment that the inflaton field turns to be less than ϕ_c, the symmetry breaking takes place and the NG potential has the radius $f_{eff}=\sqrt{\nu(cM_p^2-\phi^2)/\lambda_\chi}$ and fluctuations are started. To keep symmetry restored during first 7 e-folds we should have $\phi_c=4M_p$. After the moment of symmetry breaking, it is allowed to start the fluctuations of the phase with appropriate dispersion to create LAA's, without any contradictions with observed CMB anisotropy. Of course to evaluate the distribution of LAA's by sizes we have to take another parameter than we have used in our numerical example, but it does not change the main result of this paper.

Another story will take place if we would like to consider the AD baryogenesis as a basis for the generation of LAA's.

As was discussed in the Introduction, the dynamics of the AD field is more complicated than in the case of spontaneous baryogenesis. Moreover, it depends on the fact that, D- or F-term inflation takes place. Also some details depend on the dimension ($d=4,6\ldots$) of the nonrenormalizable term lifting the flat direction [16,13], but it is enough for the brief discussion to concern ourselves with the minimal AD baryogenesis [16], where $d=4$. Thus in the case of D- term inflation, when the coherent slow rolling of the AD field and inflaton are already established, the maximal radius $f_{eff}^{AD(D)}\simeq 10^{16}$ GeV of the effectively massless angular direction can be obtained from the requirement that radial de Sitter fluctuations of the AD field would not disturb significantly the spectral index of the primordial adiabatic density perturbations [16] measured by COBE. Thereby, it is possible to get dispersion of phase fluctuations at the level $h\simeq 10^{-2}$ that is required for successful generation of LAA's. A similar situation is observed in the case of F-term inflation [16,13] because the AD potential gets an order of H^2 negative mass-squared term during inflation, which causes the effective minimum at $f_{eff}^{AD(F)}\simeq C_F\sqrt{Hm_p}\simeq 10^{16}$ GeV (the C_F is a constant of order of one).

The isocurvature fluctuations in the model of inhomogeneous AD baryogenesis with dispersion of phase fluctuations appropriate for the generation of LAA's should be already observed by the Cosmic Background Explorer (COBE) [16]. Moreover this fluctuations can get some amplification owing to the possible transformation of fluctuations of AD condensate into the isocurvature fluctuations of neutralinos [15]. The exact solution of the problem of isocurvature fluctuations for the AD based antimatter generation is the subject of separate investigation. Here we can only present some speculations, how to avoid the large isocurvature fluctuations at large cosmological scales, which are based on the similar strategy that has been chosen in the case of spontaneous baryogenesis.

As it has been mentioned in the Introduction, to organize the angular, effectively massless direction in the AD potential we should accept the condition of the absence of order H correction to the A term both during and after inflation [16]. This condition gets automatically satisfied in the case of D-term inflation [17], while it is not true if the inflation is F-term dominated (see, for example, [13]). According to this observation we can hope to find the kind of trajectory of the inflaton in field space that corresponds to the F-term dominated inflation in the beginning and then goes into D-term dominated regime. It implies that during the F-term dominated inflation the angular direction gets a mass of order H and the imaginary component of the AD field is dumped and exponentially close to the minimum caused by this effective mass term. In such a situation there are no de Sitter fluctuations of the phase. The fluctuations start only at the moment when the inflation goes to the D-term dominated regime and the angular direction turns out to be effectively massless, because there is no correction of order H to the A term anymore. As we estimated before, to put the maximal scale of isocurvature fluctuations far below the modern cosmological horizon the transition from F- term to D- term inflation should take place 5–10 e-folds after the beginning of inflation. How to organize such a transition is the subject of a separate publication, but it seems that it could appear, for example, in the context of a realistic supergravity theory deriven from the weak coupled supestring [43], which is already beyond the MSSM. There is some possibility to generate the F- term from a Fayet-Iliopoulos D- term [44]. It could preserve the flatness of the F-term direction during the first 5–10 e-folds of inflation causing the F-term domination firstly and subsequent transformation of the vacuum energy into the D-term domination mode, when it is allowed to begin phase fluctuations of the AD field with dispersion appropriate for generation of LAA's, and without contradictions with COBE measurements.

We would like to note in conclusion that the regions with antimatter in the matter-dominated universe could arise naturally in a variety of models. The main issue that is needed, is a valley of potential. It is the valleys that are responsible for formation of causally separated regions with different values of field which in its turn give rise to antimatter domains. Many extensions of the standard model based on supersymmetry possess this property, which strongly extends the physical basis for cosmic antimatter searches.

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