COSMOLOGICAL MATTER-ANTIMATTER ASYMMETRY AND
ANTIMATTER IN THE UNIVERSE

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Models of baryogenesis which may lead to astronomically significant amount of antimatter in
the universe are reviewed. Observational features are briefly discussed.

1 Introduction

Prediction of antimatter by Dirac\(^1\) (1928) and quick subsequent discovery of the first antimatter
particle, positron, by Anderson\(^2\) (1933) are among greatest scientific achievements of XX cen-
tury. Discovery of antiproton 22 years later\(^3\) was the next step which had opened a whole new
world of antiparticles. Now for (almost) every elementary particle a corresponding antiparticle
has also been observed. The latter have opposite signs of all associated charges and, according
to CPT theorem\(^4\), the same masses and, if unstable, life-times. Such symmetry between par-
ticles and antiparticles naturally leads to suggestion that the universe as a whole may be also
symmetric with respect to transformation from particles to antiparticles and there should exist
astronomically large regions consisting of antimatter: anti-stars, clouds of diffuse antimatter,
whole anti-galaxies, or even large clusters of anti-galaxies. As Dirac\(^5\) said in his Nobel lecture:

"... we must regard it rather as an accident that the Earth (and presumably the whole solar
system), contains a preponderance of negative electrons and positive protons. It is quite possible
that for some of the stars it is the other way about, these stars being built up mainly of positrons
and negative protons. In fact, there may be half the stars of each kind."

In reality, at least in our neighborhood, the picture is different. One sees that the nearest
part of the universe is strongly matter dominated. Our Galaxy is definitely made of matter

\(^{1}\)I have found this quotation in the recent review on experimental search for cosmic antimatter
and only a minor fraction of antimatter is allowed by astronomical observation. In the case of distant galaxies, either colliding or situated in a common cloud of intergalactic gas, an absence of proton-antiproton annihilation features makes one to conclude that these objects are made of the same form of matter (or antimatter). So the simplest conclusion is that all the universe consists of matter only and there is no cosmologically significant antimatter, despite CPT-symmetry between particles and antiparticles. The mechanism that explained the observed picture and could lead to 100% baryonic universe (possibly without any antimatter) was proposed in 1967 by Sakharov.

Still there persists the question, if there may exist astronomically large domains or objects of antimatter? Where are they? How much antimatter are in the universe? These problems present an interesting and important challenge to astronomy of XXI century and to cosmology of the early universe.

Up to the present day no traces of cosmological antimatter have been seen. A small amount of antiprotons and positrons observed in cosmic rays may be explained by their secondary origin in collisions of energetic cosmic particles or in catastrophic stellar processes. Not a single, anti-nuclei, even as light as anti-deuterium, has ever been registered. According to the analysis of the data on gamma-ray background with energy around 100 MeV, made in the review, the nearest anti-galaxy should be away at least at 10 Mpc:

\[ l_B > 10 \text{ Mpc} \]  

A much stronger limit was obtained relatively recently by Cohen, De Rujula, and Glashow who concluded that the nearest part of the universe dominated by antimatter should be at least at Gigaparsec distance scale. The result was obtained for baryo-symmetric universe (equal amount of matter and antimatter) and for the so called adiabatic density perturbations. Lifting these constraints may allow to weaken this very restrictive limit (see discussion below).

Despite these bounds, an existence of astronomically large objects of antimatter (gas clouds, anti-stars, antigalaxies,...) is not excluded and even theoretically natural. They may be as close as halo of the Galaxy and rich of heavy anti-nuclei, e.g. \(^\bar{C}\), \(\bar{N}\), \(\bar{O}\), ... and maybe \(\bar{Fe}\). It is evidently very interesting to look for such anti-objects. Their discovery would lead to better understanding of the nature of C and CP violation in cosmology, would allow to get an insight into mechanisms of baryonic charge non-conservation, and may give another proof (or evidence) of inflation.

2 The problems to think about

The excess of baryons over antibaryons is usually presented as the dimensionless ratio:

\[ \beta = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 6 \cdot 10^{-10} \]  

where \(N_{B,\bar{B},\gamma}\) are the cosmological number densities of baryons, antibaryons, and photons in cosmic microwave background radiation (CMBR). The last number is precisely determined from direct observations, \(N_\gamma = 410/\text{cm}^3\), while the baryon number density is independently found from big bang nucleosynthesis (see e.g. [10]) and from relative positions and heights of acoustic peaks in angular spectrum of CMBR (see e.g. [11]).

At the present day \(N_B \ll N_{\bar{B}}\), but in the early universe when the temperature was above QCD phase transition, \(T > 100 \text{ MeV}\), number of baryons was very close to the number of the antibaryons, \(N_B = N_{\bar{B}}(1 - \beta)\). The quantity \(\beta\) is often called baryon asymmetry of the universe.

There are a few “five-star” questions to be addressed in connection with baryon asymmetry:

1. Is \(\beta = \text{const}\) or it may change in different space points, i.e. baryon asymmetry may be inhomogeneous?
2. Is $\beta > 0$ and the universe is dominated by matter everywhere or somewhere $\beta < 0$ and there are regions of antimatter?

3. Is total baryonic charge of the universe:

$$B_{\text{tot}} = \int \beta \, dV$$

positive, negative, or exactly zero? The last case is particularly appealing because it means that the universe is globally charge symmetric, while locally and at a very large scale it is strongly asymmetric.

4. If baryon asymmetry is not homogeneous, i.e. $\beta = \beta(x)$, then what is the characteristic scale of its variation, $l_B$?

5. What kind of anti-objects may exist?

Data possible exclude $B_{\text{tot}} = 0$ inside horizon, $l_{\text{hor}} \sim 3 \text{ Gpc}$, as was mentioned above, but all other questions remain unanswered.

3 Principles of baryogenesis

The idea of dynamical generation of baryon asymmetry of the universe based on possible non-conservation of baryon number was pioneered by Sakharov\textsuperscript{7}. Two years later another suggestion was put forward by Omnès\textsuperscript{12} that the observed cosmological baryon asymmetry is only local and that it was created by spatial separation of baryons and antibaryons on astronomically large scales. It can be realized if baryons are conserved. However it seems impossible to create such separation and the Omnès idea is abandoned now. Maybe it may revive in a modified form if one finds a mechanism for spatial separation of baryons and antibaryons along orthogonal direction to our 3-dimensional space, into higher dimensions, but at the moment it looks too far-fetched.

According to Sakharov three basic principles of baryogenesis are the following:

1. **Non-conservation of baryons.**

   It was the weakest point in 1967 when the common belief was that baryons are conserved: “we exist, hence protons must be stable”. Since that time our understanding became opposite: “we exist, hence protons must be unstable”, because most probably the universe suitable for life could not be created if baryonic charge is conserved. Present day theory has a favorable attitude to non-conservation of baryons: both electroweak theory and grand unification ones predict that baryonic charge is not conserved.

2. **Violation of charge symmetry, both C and CP.**

   Both C and CP breakings are well established in experiment and though the concrete mechanism of CP-breaking is unknown it can be easily implemented into theory by introducing complex mass matrices of particles or complex Yukawa coupling constants.

3. **Deviation from thermal equilibrium.**

   In thermal equilibrium occupation number in phase space is given by Bose or Fermi (depending on particle spin) distribution functions:

   $$f = \left(1 \pm e^{E/T}\right)^{-1} \quad (4)$$

   where $E$ is the particle energy and $T$ is the temperature. Chemical potentials must vanish in equilibrium if the corresponding charge is not conserved. Due to CPT-theorem the masses of particles and antiparticles are equal and thus for equal values of particle momenta
their energies must be equal too. Correspondingly $f = \bar{f}$ and in thermal equilibrium numbers of particles and antiparticles must be the same. If CPT is broken then charge asymmetry may appear even in thermal equilibrium.\(^3\)

However breaking of CPT is not necessary because the universe is non-stationary, it expands and for massive particles some deviations from equilibrium are always present. Also a noticeable breaking of thermal equilibrium could arise as a result of possible first order phase transitions in the primeval cosmic plasma in the process of expansion and cooling down.

Thus all necessary conditions for baryogenesis are naturally fulfilled and one may expect that some asymmetry between particles and antiparticles should be created in the universe. Moreover, none of three formulated above conditions are obligatory and in some (possibly rather exotic) models cosmological baryon asymmetry might be generated even in thermal equilibrium, or with conserved baryonic charge in particle physics, or in CP-invariant particle theory - examples of such scenarios are given below.

4 Mechanisms of CP-breaking in cosmology

There are three possible ways of breaking symmetry between particles and antiparticles in cosmology. One is a standard explicit mechanism when CP-breaking is achieved by complex constants in the Lagrangian. In this case baryon asymmetry in the universe would be directly related to CP-violating processes in elementary particle physics. Baryon asymmetry in this case would be the same homogeneous one over all the universe, $\beta = \text{const}$.

Another mechanism is spontaneous CP-breaking, proposed by T.D. Lee.\(^4\) It can be achieved by vacuum condensate of a complex scalar field, $\langle \phi \rangle$, which introduces complex constants into Lagrangian over the vacuum state with a certain non-zero value of $\langle \phi \rangle$. For example, the Yukawa interaction term $g\phi \bar{\psi}\psi$ gives rise to the complex mass term $m_\psi = g\langle \phi \rangle$. One needs, of course, several different terms with $\phi$ in the Lagrangian so that the phase of $\langle \phi \rangle$ could not be rotated away by redefinition of the fields.

Also in this case CP-violation observed in particle physics can be related to the cosmological charge asymmetry but now $\beta$ cannot be spatially constant. Spontaneous breaking of a discrete symmetry (as e.g. CP) would give rise to domain structure of the universe with a different signs of $\langle \phi \rangle$ in different domains. This might lead to cosmological disaster, as was shown by Kobzarev, Okun and Zeldovich.\(^5\) The problem is that domains with different signs of CP-breaking amplitude $\langle \phi \rangle$ must be separated by domain walls with a huge surface energy density and even a single domain wall per horizon would destroy the observed isotropy of the universe. If there are too much walls per horizon the universe would be over-closed. To solve the domain wall problems one should either invent a mechanism enlarging the size of the domains beyond the present day cosmological horizon or to destroy the walls at an early stage of cosmological evolution.

Evidently in the domains with different signs of $\langle \phi \rangle$ the sign of CP-violation would be different and correspondingly either an excess of matter over antimatter would be created or, another way around, antimatter over matter.\(^6\) With such mechanism of CP-breaking the universe would be globally charge symmetric, $B_{\text{tot}} = 0$. However in a simple version of the model the size of the domains should be much smaller than galactic size in evident contradiction with the data. A way out was suggested by K. Sato who assumed that there could be a moderate exponential expansion to inflate the domains to astronomically interesting scales. However, the problem of domain wall still has to be solved. Even if the walls are eliminated by one or other mechanism, matter and antimatter remain in close contact and according to the arguments of ref.\(^5\) the nearest antimatter region should be practically at the horizon distance, around Gpc.
There could be another mechanism of CP-violation which operated only in the early universe and is absent in the particle physics. This mechanism may be called *stochastic* breaking of charge symmetry. In a sense it is similar to spontaneous one but does not suffer from the domain wall problems and not necessary leads to globally charge symmetric universe. Such mechanism could be realized if a complex scalar field did not relax down to its equilibrium value at some stage of cosmological evolution. It maybe be a result of a phase transition or of infrared instability of light scalars in De Sitter (inflationary) stage. If such a field remains non-zero during baryogenensis its amplitude would give rise to CP-breaking in particle interactions, while later it would relax down to zero and would not contribute to CP-breaking. Since we know that CP is broken in particle physics, then both stochastic and explicit mechanisms might operate at baryogenesis.

5 Models of Baryogenesis

I will briefly describe below possible models of baryogenesis that exist in the literature. More detailed discussion can be found e.g. in the review papers.

5.1 GUT-baryogenesis or heavy particle decays

This is historically first model of baryogenesis, it was practically proposed in the pioneering paper and renewed interest to it was stimulated by the paper a decade later. According to Grand Unified Theories (GUT) there exist superheavy gauge of Higgs bosons whose decay do not conserve baryonic charge. For example such bosons can decay into the channels $X \to qq$ or $X \to \bar{q}l$, where $q$ is a quark and $l$ is a lepton. Due to possible CP-nonconservation the decay branchings $B(X \to qq)$ and $B(\bar{X} \to \bar{q}q)$ could be different and in out-of-equilibrium situation such decays would produce an excess of baryons over antibaryons (or vice versa - the sign of CP breaking at GUT scale is unknown).

The deviation from equilibrium is determined by the ratio of the universe expansion rate, $H$, when the temperature was close to X-bosom mass, $m_X$, to the decay width of X-bosons:

$$\epsilon = \frac{H(T = m_X)}{\Gamma_X} \approx \frac{m_X}{\alpha m_{Pl}} \approx \frac{m_X}{10^{17} \text{GeV}}$$

(5)

where $\alpha \sim 10^{-2}$ is the gauge coupling constant. Thus, if X-bosons are as heavy as $10^{16}$ GeV, as we believe now, the deviation from equilibrium could be quite large to produce significant baryon asymmetry even with entropy dilution by approximately two orders of magnitude in the course of cosmological cooling down from $10^{16}$ GeV to the present state.

In simple versions such mechanism naturally gives $\beta = const$ and no antimatter. A problem with its realization is that probably the universe was never at very high temperatures about $10^{16}$ GeV, since normally after inflation the universe was heated to much lower temperature.

5.2 Electro-weak baryogenesis

It was suggested by Kuz’min, Rubakov, and Shaposhnikov that baryon asymmetry might be generated at much lower temperatures, $\sim \text{TeV}$, by the usual electro-weak interactions. Indeed, all the necessary ingredients are present in the standard low energy physics. It is known that CP is broken, baryonic charge is non-conserved due to quantum chiral anomaly, and thermal equilibrium would be broken if the electro-weak phase transition is first order. It is evident from eq. (3) that deviation from equilibrium due to non-zero masses of $W$ and $Z$ bosons is negligibly small. Generation of baryon asymmetry in this model takes place not in massive particle decays but on the boundary between two phases with unbroken and broken $SU(2) \times U(1)$-symmetry of weak interactions respectively. In the high temperature phase, where the symmetry is unbroken, sphaleron transitions, which break baryon conservation, are believed to be very active, so
equilibrium with respect to B-nonconserving processes is quickly established. To be more exact, anomalous electroweak interactions conserve the difference between leptonic and baryonic charge, \((B - L)\), while \((B + L)\) is non-conserved. So \((B - L)\) remains constant in comoving volume and equal to its initial value, while non-conserved \((B + L)\) may evolve. In low temperature phase the baryonic charge is practically conserved but if the phase transition was first order and phases coexisted, in the boundary between them both baryon non-conservation and deviation from equilibrium could be strong enough to generate the observed asymmetry.

However, as we now know from the LEP data (see e.g.\(^{26}\)), the lower limit on the Higgs boson mass is higher than 100 GeV and this makes first order phase transition quite problematic. There exist many modifications of the minimal scenario of electroweak baryogenesis but the model became much less popular now. For review one can see refs.\(^{20,27}\); a discussion of the latest development and an impressive list of references can be found in the recent papers\(^{28}\).

Normally electroweak models do not lead to creation of antimatter domains in the universe but with a simple modification they could do that.

### 5.3 Baryo-thru-lepto-genesis

This mechanism presents a combination of the two discussed above (subsections 5.1 and 5.2) and was proposed by Fukugita and Yanagida\(^ {29}\). Initially lepton asymmetry, \(L_{\text{in}}\), was generated by decays of heavy Majorana neutrino, \(\nu_M\), and later this asymmetry was redistributed between baryonic and leptonic ones by electro-weak interactions at equilibrium stage due to non-conservation of \((B + L)\). Final baryon asymmetry would be roughly equal to \(L_{\text{in}}/2\) (the exact value of the coefficient depends upon the particle content of the theory\(^{30,18}\)). This scenario is very popular now, one can find detailed discussion of different versions and a list of references in the reviews\(^ {31}\).

Lepton asymmetry generated by the decays of \(\nu_M\) can be roughly estimated as:

\[
L = \epsilon_M \frac{N_{\nu_M}}{N_{\text{tot}}} \frac{\Delta \Gamma}{\Gamma}
\]

where \(\epsilon_M = m_{\nu_M}/(\alpha_M m_{Pl})\) is the parameter characterizing deviation from thermal equilibrium\(^ {5}\), \(N_a\) are number densities of the corresponding particles, \(\Gamma \sim \alpha_M m_{\nu_M}\) is the total decay width of \(\nu_M\), and \(\Delta \Gamma \sim \alpha_M^2 m_{\nu_M} \delta\) is the difference of lepton non-conserving decay rates of \(\nu_M\) into charge conjugated channels with \(\delta\) being the amplitude of CP-breaking. With \(m_{\nu_M} \sim 10^{10}\) GeV the lepton asymmetry seems to be too small but experts in the field are more optimistic and according to majority of the works on the subject, the discussed mechanism may successfully generate observed baryon asymmetry of the universe.

Recently a modification of “lepto-thru-baryo” scenario was proposed in ref.\(^ {32}\). It was suggested that \((B + L)\)-asymmetry was generated at GUT scale by heavy particle decays, while \((B - L)\) remained zero since it is conserved in simple models of grand unification. Lepton asymmetry was washed out in equilibrium reactions with Majorana neutrino at a later stage and remaining baryon asymmetry cannot be completely destroyed by sphaleron processes since they conserve \((B - L)\).

All these models are not particularly good for creation of cosmic antimatter but one can easily modify them to this end by introducing e.g. stochastic CP-violation (see sec. 4). Still it looks rather unnatural.

### 5.4 Black hole evaporation

Cosmological baryon asymmetry might be created by the evaporation of primordial black holes with low mass\(^ {33,34,35}\). A concrete mechanism was suggested in the paper\(^ {35}\) and the calculations of the effect were performed in ref.\(^ {36}\). This mechanism does not demand direct non-conservation
of baryonic charge in particle physics. On the other hand, according to estimates made by Zeldovich proton may decay through formation of virtual black hole with life-time about $m_\text{Pl}/m_p^5 \sim 10^{52}$ sec. If this estimate is correct then in the high dimensional models with TeV-scale gravity the proton life-time would be catastrophically short, $\sim 10^{-8}$ sec. A lower bound on quantum gravity scale based on the analysis of proton decay through formation of virtual black holes has been recently done in the paper.

In the process of evaporation black hole emits all kind of particles with the mass smaller than black hole temperature, $T_{BH} = m_{BH}^2/(8\pi M_{BH})$. A massive meson, still in gravitational field of black hole, could decay into a light baryon and a heavy antibaryon (e.g. $u$ and $\bar{t}$ quarks) or vice versa. The decay probabilities may be different because of C(CP) violation. Since back capture of heavy particles by the black hole is more probable then that of light ones, such process could create a net flux of baryonic charge into external space, while equal anti-baryonic charge would be hidden inside disappearing black hole. This mechanism could explain the observed value of the baryon asymmetry of the universe if at some early stage the total cosmological energy density was dominated by those black holes.

Without special efforts this model is also inefficient for creation of cosmologically significant amount of antimatter.

5.5 Spontaneous baryogenesis

The mechanism was proposed by Cohen and Kaplan and is based on the assumption that there exists a $U(1)$-symmetry, related to baryonic or some other non-orthogonal charge, which is spontaneously broken. A toy-model Lagrangian can be written as:

$$\mathcal{L} = -|\partial \phi|^2 + \lambda \left( |\phi|^2 - f^2 \right) + \sum_a \bar{\psi}_a (i\partial + m_a) \psi + \sum_{a,b} (g_{ab} \phi \bar{\psi}_b \psi_a + \text{h.c.})$$

where some fermionic fields $\psi_b$ possess non-zero baryonic charge, while some other do not. The theory is invariant with respect to simultaneous phase rotation:

$$\phi \leftarrow \phi \exp(i\theta) \text{ and } \psi_b \rightarrow \psi_b \exp(i\theta)$$

which ensures conservation of “baryonic” charge. In the broken symmetry phase where $|\phi| = f$ the conservation of baryonic current of fermions also breaks down (due to presence of the last term in the Lagrangian above) and the Lagrangian takes the form:

$$\mathcal{L} = -f^2 (\partial \theta)^2 + \partial_\mu \theta \bar{\psi}_b \gamma^\mu \psi_b + \ldots$$

where $\theta$ is the massless Goldstone field induced by the breaking of the global $U_b$-symmetry. If there are some additional terms in the Lagrangian producing an explicit symmetry breaking then $\theta$ would be massive and is called pseudo-Goldstone field. Baryogenesis would be much more efficient in the latter case.

In the homogeneous case when $\theta = \theta(t)$ the second term in expression looks like $\dot{\theta} n_b$ where $n_b$ is the baryonic charge density. So it is tempting to identify $\dot{\theta}$ with chemical potential of baryons. Though it is not exactly so, still this term shifts equality between number densities of quarks and anti-quarks even in thermal equilibrium, allowing baryogenesis without deviation from thermal equilibrium. In a sense this mechanism is equivalent to breaking of CPT because the process goes in time dependent background.

The sign of the created baryon asymmetry is determined by the sign of the $\dot{\theta}$ and could be both positive or negative producing baryons or antibaryons. To create the matter/antimatter domain of astronomically large size the $U(1)$-symmetry should be broken during inflation and in this case the sign of $\dot{\theta}$ would be determined by the chaotic quantum fluctuations at inflationary stage. The analysis of density perturbations created by the fluctuating field $\theta$ was done in ref.
In this scenario C(CP)-violation is not necessary for generation of baryon asymmetry. As a whole the universe could be charge symmetric. We know however that an explicit C(CP)-violation is also present. If it also participates in creation of baryon asymmetry, then the amount of matter and antimatter in the universe would be unequal with unknown ratio that should be determined from observations.

5.6 SUSY condensate baryogenesis

All known baryons are fermions but if there is supersymmetry then scalar superpartners of baryons should exist. Such scalar fields might form a condensate in the early universe and accumulate a large baryonic charge. A very efficient scenario of baryogenesis based on this observation was proposed by Affleck and Dine. In many supersymmetric models self-potential of scalar fields has so called flat directions along which it does not rise. As a toy model we can consider the potential of the form:

$$U(\chi) = \lambda \left[ |\chi|^4 - \left( \chi^4 + \chi^*^4 \right) / 2 \right] = \lambda |\chi|^4 \left( 1 - 4 \cos \theta \right) \quad (10)$$

where $\chi = |\chi| \exp(i\theta)$. This potential has four valleys $\theta = \pi n/2$ with $n = 0, 1, 2, 3$ and is not invariant with respect to rotation in two-dimensional (Re$\chi$, Im$\chi$)-plane. This leads to non-conservation of baryonic current of $\chi$. The latter is defined as

$$J^B_{\mu}(\chi) = (-i/2) \left( \chi^* \partial_{\mu} \chi - \partial_{\mu} \chi^* \chi \right) = \partial_{\mu} \theta |\chi|^2 \quad (11)$$

Initially the field $\chi$ could be far away from the origin along one of the valleys, either by unspecified initial conditions or due to rising quantum fluctuations at inflationary stage, which lead to $\langle \chi^2 \rangle = H^3 t/2\pi$. When inflation is over and due to some symmetry breaking, $\chi$ acquires mass, it starts to move down to the origin with baryonic charge accumulated in its angular motion, $B_\chi = \dot{\theta} |\chi|^4$. There is a convenient mechanical analogy in the case of homogeneous $\chi = \chi(t)$. Its equation of motion

$$\ddot{\chi} + 3H \dot{\chi} + U'(\chi) = 0 \quad (12)$$

describes classical mechanical motion of a point-like particle in the potential $U(\chi)$. The second term, induced by the cosmological expansion, presents liquid friction force. In this language the baryonic charge of $\chi$ is simply angular momentum of the particle in this potential. If the potential is spherically symmetric (in two dimensions: \([\text{Re}\chi, \text{Im}\chi]\)) then baryonic charge is conserved, otherwise not.

When $\chi$ approaches zero it decays into quarks and transfers baryonic charge of its angular motion to baryonic charge of quarks. The sign of the asymmetry depends upon the direction of the rotation. The latter may be determined by chaotic initial fluctuations in the directions orthogonal the the valley, in this case CP-violation is unnecessary, or by explicit CP-breaking terms in the potential, e.g.

$$U(\chi) = \lambda |\chi|^4 (1 - \cos 4\theta) + m^2 |\chi|^2 \left[ 1 - \cos (2\theta + 2\gamma) \right] \quad (13)$$

where a non-zero phase $\gamma$ induces explicit CP-violation.

If $\chi$ condensed along the valley with $\theta = 0$ it would start rotating clock-wise when it approaches zero and starts to feel mass valley (for $0 < \gamma < \pi/2$). If $\chi$ “lived” in $\pi/2$-valley it would start rotating anti-clock-wise. Thus, depending upon initial position of $\chi$, both baryons and antibaryons may be created with the same sign of CP-violating phase $\gamma$. In this model the universe most probably would be globally charge asymmetric because the magnitude of the angular momentum depends upon the relative angles between $\chi^4$ and $\chi^2$ valleys. The size
of baryonic and anti-baryonic domains are expected to be very large, maybe even larger than horizon, because the regions of initial values of $\chi$ in different valleys could be strongly separated during inflation.

On the other hand, if all the observed part of the universe originated from the same $\chi$ valley the size of regions with definite sign of baryon asymmetry could be much smaller. Such situation could be realized in the model with potential (13) with $\gamma = 0$, i.e. with conserved CP. If $\chi$ evolves down along the valley with $\theta = \pm \pi/2$, then for sufficiently small $|\chi|$ this direction becomes unstable and $\chi$ would go down to $\theta = 0$ or $\theta = \pi$ rotating either clockwise or anti-clockwise. So in this model there would be equally probable baryonic and anti-baryonic domains. Slightly changing direction of mass valley, taking a non-zero $\gamma$ would allow to create the universe with arbitrary fraction of baryons with respect to antibaryons.

6 Creation of domains or objects of antimatter

As we have seen above, antimatter could be quite naturally created in the universe in astronomically interesting amount. Probably the most efficient mechanisms for creation of cosmic antimatter are spontaneous baryogenesis (sec. 5.5) and Affleck-Dine one (sec. 5.6). If the scalar baryon of SUSY model is coupled to the inflaton field $\Phi$ by the following general renormalizable coupling

$$\mathcal{L} = (\lambda \chi^2 + h.c.)(\Phi - \Phi_1)^2$$

(14)

a very interesting and unusual features in generation of baryon asymmetry may appear. Because of this interaction favorable conditions for baryogenesis might be created only for a short time and correspondingly in relatively small fraction of space. As a result there would be separate bubbles with very large baryon asymmetry, even of order unity which would be floating in the usual cosmological baryo-asymmetric background with $\beta = 6 \times 10^{-10}$. This baryon-rich bubbles would be with practically equal probability baryonic or anti-baryonic and many of them would form primordial black holes and because of that would be indistinguishable. Some of them would survive collapse and form disperse clouds of matter and antimatter with unusually high baryonic number. Some of this objects may form unusual stars and anti-stars with a high initial fraction of heavy nuclei (or anti-nuclei). The mass distribution of (anti)baryon-rich regions, according to ref. 44, is

$$\frac{dN}{dM} \sim \exp \left( -C \ln^2 \frac{M}{M_1} \right)$$

(15)

where $M_1$ is unknown mass parameter which could be a fraction of solar mass up to many solar masses and $C$ is a constant.

It is an interesting possibility that such primordially formed black holes constitute dark matter in the universe. It would be a cold dark matter but, in contrast to the standard one, having a disperse mass distribution. With a small probability there could be even very heavy black holes with the masses up to $10^6 - 10^9 M_\odot$, where $M_\odot$ is the solar mass. Most of these black holes might have mass near solar mass and could live in galactic halos. Their non-captured atmospheres may be anti-baryonic and, if so, considerable amount of antimatter could be even in halo of the Galaxy. The model naturally predicts early formation of quasars and evolved chemistry in their atmospheres because in the (anti)baryon-rich regions primordial nucleosynthesis would not stop at $^7$Li. Regions with a smaller $\beta$ might survive collapse and form either clouds of antimatter or anti-stars. Encounter of a star and anti-star could be a very spectacular phenomenon. More details about this model can be found in refs. 44.
Still a few comments about formation and properties of such antimatter black holes may worth making. They were formed when the density contrast inside horizon was of order unity, \((\delta \rho/\rho)_{\text{hor}} \sim 1\). One can simply estimate this ratio as

\[
\frac{\delta \rho}{\rho} \approx \frac{m_p}{3T} \frac{N_B}{N_\gamma} = \frac{1}{3} \beta \frac{m_p}{T}
\]

where \(m_p\) is the proton mass and \(T\) is the cosmological temperature. The mass inside horizon is given by:

\[
M_{\text{hor}} = \frac{8\pi}{3} (2t)^3 \rho = 5 \times 10^4 M_\odot \left( \frac{t}{\text{sec}} \right)
\]

Black holes formed in antibaryon rich regions could possess atmosphere of antimatter. Before hydrogen recombination diffusion is slow and the atmosphere might survive. Recombination in high \(|\beta|\) regions occurs earlier, at temperatures in eV range, instead of normal 0.1 eV. Hence atmosphere would not be stripped by CMBR at the onset of structure formation. Annihilation on the boundary could heat the plasma and create secondary ionization. All these phenomena deserve more detailed investigation.

An efficient way to create cosmic antimatter in any model of baryogenesis is based on stochastic CP-breaking (sec. 4). If some complex scalar field was nonvanishing during baryogenesis then effective CP-breaking induced by this field would participate in creation of cosmological charge asymmetry and if the field changed sign as a function of space point the sign of asymmetry might also be different. For example, if the field \(\phi(t, x)\) was a slowly varying function of \(x\) and its potential was not strictly harmonic, i.e. contained e.g. quartic terms, \(\lambda \phi^4\), and since frequency of oscillations in non-harmonic potential depends upon the amplitude, then smooth \(\phi(x, t)\) would turn into an oscillating (and quasi-periodic) function of space point. Depending upon the ratio between amplitudes of explicit and stochastic CP-violation astronomically interesting antimatter domains might be formed.

Discussion of some other models of antimatter creation, can be found in the papers 18, 47. This subject is also actively discussed in this conference 48.

### 7 Bounds on existence of antimatter

Let us first discuss the most stringent lower bound on the distance to antimatter domains in baryo-symmetric cosmology found by Cohen, De Rujula, and Glashow 9. Matter and antimatter cannot be separated by the distance, \(l_B\), larger than 20 Mpc (at the present day scale) because in the boundary region with deficit of both matter and antimatter density contrast would be incompatible with measurements of angular fluctuation of CMBR accessible at such scales. If \(l_B < 20\) Mpc diffusion of protons and antiprotons would bring them into contact and they would annihilate. Naively one would expect that the excessive pressure created by annihilation would force matter and antimatter apart inhibiting the annihilation. However the picture is opposite. The energetic products of annihilation have a large mean free path so they transfer their energy (and pressure) to the plasma far away and the excessive pressure pushes matter and antimatter together and enhances annihilation. Thus the CDRG 9 limit \(l_B > (\sim \text{Gpc})\) was obtained. As it was already mentioned it is valid in the case of baryo-symmetric cosmology when the universe is equally rich of baryons and antibaryons. If however, the fraction of antibaryons is much smaller than that of baryons (or vice versa) the limit would be weaker, roughly by the same amount.

Another assumption made in the derivation of CDRG bound is adiabatic density perturbations, i.e. the same perturbations in all forms of matter. The limit may be invalid for isocurvature perturbations, when initially \(\delta \rho = 0\) but chemical content of plasma varies in different space points. Now let us consider three regions: one with baryonic excess, another with
equal anti-baryonic excess and some boundary between them with no baryons. By assumption the energy density of all three regions were initially the same. The plasma in baryonic and anti-baryonic regions would be less relativistic and thus, when the temperature drops, their energy density would be higher than the energy density of the baryon-free part. On the other hand, nonrelativistic matter cools faster and the temperature of radiation in baryon free region would be higher. Hence the pressure of photons would be higher and it may prevent baryons and antibaryons from close contact and annihilation. This mechanism may significantly relax CDRG bound, but accurate calculations are needed.

Matter-antimatter annihilation on the domain boundaries might distort energy spectrum of CMBR if the annihilation takes place before recombination[49]. The effect would be noticeable for large size domains. At the present time this phenomenon does not permit to obtain any interesting limit.

Of course an unambiguous proof of existence of cosmic antimatter would be an observation of anti-nuclei in cosmic rays, especially heavier than anti-deuterium because the latter might be produced in secondary processes[50] with small but not vanishingly small probability. Some indication for antimatter could be anomalies in the spectrum of antiprotons in cosmic rays but the data may have an ambiguous interpretation. Earlier works on search of cosmic antiprotons and their relation to cosmological antimatter can be found in refs. [51]. Program of search and existing limits are discussed in many talks at this Conference, too many to mention them all, but for reviews one can see refs. [6, 52].

8 Conclusion

Simplest models of baryogenesis predict charge asymmetric universe with $B_{tot} \neq 0$. Normally, without additional assumptions, they do not lead to cosmological antimatter domains or astronomically large objects. On the other hand, they generally meet some problems with explanation of the observed value of baryon asymmetry, $\beta$.

Spontaneous baryogenesis or Affleck-Dine scenario can successfully explain the observed asymmetry and naturally predict existence of astronomically interesting antimatter.

In a version of Affleck-Dine model with coupling between the scalar baryon and inflaton fields relatively small regions with very high $\beta$, both positive and negative, can be created. Such objects would mostly form primordial black holes. They may be abundantly present even in halo of our Galaxy. An interesting possibility is that they form all dark matter in the universe. Around such black holes heavy (anti)nuclei should be present and, though one cannot distinguish between black hole and anti-black-hole, anti-nuclei stripped from the neighborhood of the latter may be registered. Thus one may hope to discover anti-nuclei in cosmic rays and not only $^4\bar{He}$ but also (and quite probably more abundant) heavier anti-nuclei, $\bar{C}$, $\bar{N}$, $\bar{O}$ and maybe even $\bar{Fe}$.

Other models give less optimistic scenarios for possibility of registration of anti-nuclei. But there are no iron-strong predictions and one should rely on future observations and detailed theoretical calculations to make more definite conclusions. At the present day our knowledge is too scarce and one even cannot exclude that we live in antimatter dominated universe with minor domains of matter as e.g. our group of galaxies inside 10 Mpc.

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