

Baryogenesis

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Abstract: A review on the present state of the baryogenesis is given with an emphasis on electroweak baryogenesis. Technical details of the numerous models considered in the literature are not elaborated but unresolved problems of the issue are considered. Different logically possible alternatives of the electroweak scenarios are presented. A possible impact of baryogenesis on the universe structure formation is discussed.

Baryogenesis is a process of generation of an excess of baryons over antibaryons which presumably took place at an early stage of the Universe evolution. Two questions immediately arise in this connections: first, why do we need that and, second, if baryogenesis is obligatory or one can make the observed Universe without it and the existence of baryogenesis at an early stage (or stages) is only one of several possible alternatives in cosmology. In my opinion baryogenesis is not only possible and natural in the frameworks of modern physics but is also necessary for the creation of the observed Universe at least at the same level as inflation.

The idea of baryogenesis emerged from the observations that the Universe at some distance scale l_B around us is practically 100% charge asymmetric with baryon number density very much exceeding that

of antibaryons, $N_B \gg N_{\bar{B}}$. The magnitude of the asymmetry is characterized by the ratio of the baryonic number density to the number density of photons in cosmic microwave background radiation:

$$\beta = N_B/N_\gamma = 10^{-9} - 10^{-10} \quad (1)$$

This small number means in particular that the size of the charge asymmetry (which is practically 100% now) was tiny at high temperatures, $T > \Lambda_{QCD} \approx 100$ MeV. At these temperatures antibaryons were practically equally abundant in the primeval plasma and correspondingly $(N_B - N_{\bar{B}})/(N_B + N_{\bar{B}}) \approx \beta \ll 1$. Still this number, though very small, is not easy to obtain and the main goal of theoretical models is to get this number as large as possible.

There are three important problems related to the scale of the asymmetry l_B :

- 1. What is the magnitude of l_B ? Is it

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infinite or, what is practically the same, larger than the present-day horizon, $l_B > l_U \approx 10^{10}$ years? May it be rather small, say, like a few $\times 10$ Mpc? In the first case the whole Universe or at least the visible part is baryon dominated while in the second case there may be a considerable amount of antibaryons which can be in principle observed by their interaction with matter on the boundaries. Still since the distance is fairly large the gamma-flux from the annihilation would be sufficiently low.

– 2. May the Universe be charge asymmetric only in our neighbourhood, never mind how large it is (even larger than the horizon), and be charge symmetric as a whole? The last possibility is aesthetically appealing since particle-antiparticle symmetry is restored on large.

– 3. Is the amplitude of the asymmetry β a constant or may it be a function of space points $\beta = \beta(x, y, z)$? The last case corresponds to the so called isocurvature density fluctuations which may be very interesting for the structure formation in low Ω Universe.

The idea that the dominance of baryons over antibaryons can be explained dynamically was first proposed by Sakharov [1] in 1967. Before it was a common belief that a nonzero baryonic charge of the Universe is a result of mysterious initial conditions. At the present day there are several hundred papers on the subject discussing different possible scenarios of the generation of the baryon asymmetry of the Universe. The history of the problem as well as long lists of references can be found in the review papers [2–5]. Three very well known by now conditions of the baryogenesis which were

formulated by Sakharov are the following:

- 1. Baryonic charge nonconservation.
- 2. Asymmetry in particle-antiparticle interactions (breaking of C- and CP-invariance).
- 3. Deviation from thermal equilibrium.

It can be shown that neither of these conditions are obligatory (see ref. [4]) but counterexample are rather exotic. A nice feature of these three conditions is that they are perfectly natural in the frameworks of the present-day particle physics. Baryonic charge nonconservation, which was the most problematic 25 years ago, now is predicted by grand unification models and what's more by the standard electroweak theory. Unfortunately these are only theoretical arguments and the proton remains stable despite very strong efforts to discover its decays. The only "experimental" evidence in favor of baryonic charge nonconservation is given now by cosmology. On the contrary C- and CP-violation are observed experimentally in particle physics and we may be sure that particles and antiparticles are indeed different. Still theoretically this phenomenon is not well understood: there are many models for CP-violation and we do not yet know which one is true. As for deviation from thermal equilibrium it is provided by the universe expansion and always exists for massive particles with the relative magnitude of the order $(m^2/T^2)(H/\Gamma)$ where T is the temperature of the primeval plasma, H is the Hubble parameter characterizing the expansion rate, and Γ is the reaction rate. This expression is valid for $m \leq T$ and is typically rather small. For $m > T$ the

contribution of the particles with the mass m is usually exponentially suppressed so in both cases deviations from equilibrium are small. This smallness is not crucial for scenarios of baryogenesis at grand unification scale but may be very important for lower temperatures. Fortunately there is another way to break the equilibrium by the first order phase transition. In that case one may expect a low energy baryogenesis, $T \ll T_{GUT} \approx 10^{16}$ GeV. Anyhow some deviations from thermal equilibrium always exist in the cosmological plasma and this provides the third necessary condition for baryogenesis.

We see that baryogenesis might happen in the course of the Universe evolution and now I would like to argue that it indeed took place. The crucial point is that inflation is impossible without baryogenesis. One may argue that the existence of inflation could also be questioned. Strictly speaking this is true since we do not have rigorous proof that the Universe, as we see it, cannot be created without inflation. Moreover this proof can never be presented. However inflation is the only scenario which solves in a simple way many cosmological problems which cannot be addressed in any other known cosmological scenario. Among them are the problems of

- 1) flatness; the Universe should be flat with the accuracy 10^{-15} during primordial nucleosynthesis,
- 2) horizon, homogeneity, and isotropy,
- 3) generation of the primordial density fluctuations,
- 4) initial push which gave rise to the Universe expansion; the inflationary equa-

tion of state $p = -\rho$ corresponds to anti-gravitating medium creating expansion.

Of course inflationary models have their own problems like very small strength of the inflaton interactions and the absence of a natural inflationary scenario in the frameworks of the simplest gauge theories of particle interactions which is an argument against inflation. On the other hand the prediction of inflationary models of approximately flat spectrum of density perturbations is in a reasonable agreement with the COBE data (see the talk by J.Silk at this Conference). Slightly tilted spectrum of density fluctuations may better describe the Universe structure formation and fortunately there exist inflationary models which can give this prediction (see e.g. [6]). Another quantitative prediction of inflation that the density parameter Ω is most probably equal to one may be in agreement with observations but the latter are very inaccurate and one cannot make a decisive conclusion here. Plenty of people would be happy if Ω is considerably smaller than one. In that case we may not need nonbaryonic dark matter and in view of the recent announcements by the experimental groups EROS and MACHOS of possible microlensing events (see the talks by A. Milsztajn and B. Sadoulet at this Conference) one may think that all the dark matter in the Universe is baryonic. The claim that there is some baryonic dark matter in the Universe is supported by the primordial nucleosynthesis theory which gives $\Omega_B \approx 0.05(H/50\text{km/sec/Mpc})^{-2}$ [7] while the contribution of the visible baryonic matter is $\Omega_B \approx 0.01$. However purely baryonic universe encounters serious difficulties in large scale structure formation

especially because of very small fluctuations of the microwave background temperature. From this point of view nonbaryonic dark matter and large (close to 1) Ω are very desirable. Taken together with the nice inflationary solution of the basic cosmological problems this gives a very strong argument in favor of inflationary scenario.

For successful solution of the flatness and horizon problems duration of inflationary stage should be sufficiently large, $H_I t_I \geq 65 - 70$. If baryonic charge were conserved it would be diluted during inflation by a huge factor $e^{210} - e^{195}$. Unnatural by itself it does not exclude initial conditions with a very big baryonic charge density. But nonzero baryonic charge density implies simultaneously nonzero energy density associated with it. Inflation could be achieved only if energy density in the Universe is a constant or slowly varying function of the scale factor a . This is not true for the energy density associated with baryonic charge, ρ_B . It varies as $1/a^3$ for nonrelativistic particles and as $1/a^4$ for relativistic ones. From the value of β (1) we may conclude that at high temperature stage $\rho_B \approx 10^{-10} \rho_{tot}$. It means that the total energy density could be approximately constant for the period not larger than 6 Hubble times which is too little for a successful inflation. Thus inflation demands nonconservation of baryons.

Historically first papers on baryogenesis which were based on a well defined particle physics model were done in the frameworks of the grand unification theories (for the review and the literature see [2,3]). Grand unification models present a beautiful extension of the minimal standard

$SU(3) \times SU(2) \times U(1)$ -model (MSM). A strong indication of the validity of the grand unification is the crossing of all three gauge coupling constants of supersymmetric extension of MSM at the same point near $E_{GUT} = 10^{16}$ GeV. It is rather difficult to believe that there are no new particles and interactions in the region between electroweak or low energy supersymmetry scale and grand unification scale but if the essential quantity is the logarithm of energy the distance between these two scales is not too big and one may hope that MSM or supersymmetric version of it is the ultimate truth in low energy physics (up to E_{GUT}). One more argument in favor of low energy supersymmetry is provided by cosmology, namely, if one demands in accordance with the theory of large scale structure formation that the bulk of matter in the universe is in the form of cold dark matter and assumes that the cross-section of the annihilation of the latter is given by $\sigma = \alpha^2/m^2$ then the mass m should be in the region 100 GeV - 1 TeV. It is just the scale of low energy supersymmetry (for more details see e.g. ref. [8])

A strong objection against GUT baryogenesis is a low heating temperature after inflation. It is typically 4-5 orders of magnitude below E_{GUT} . It means that the GUT era possibly did not exist in the early Universe. A very interesting alternative to the GUT baryogenesis is the electroweak one (for the review see refs. [4,5]). Electroweak theory provides all the necessary ingredients for baryogenesis including baryon nonconservation (see below) so one may hope to get some baryon asymmetry of the Universe even in the frameworks of the MSM. A very interesting question is

if it is possible to get the right magnitude of the asymmetry in MSM or baryogenesis demands an extension of the minimal model.

One may say in support of the second possibility that cosmology already demands physics beyond the standard model. It should be invoked for realization of inflation, for the generation of the primordial density perturbations, for nonbaryonic dark matter, etc. A drastic change in the standard physics may be necessary for the solution of the cosmological term problem. (There is a hope however that it may be solved by infrared instability of quantum gravity in De Sitter background, see e.g. refs. [9,10].) So we have already a strong evidence that there is physics beyond the standard model and thus baryogenesis should not be confined to the MSM. Still the possibility of realistic baryogenesis in the minimal model is extremely appealing and moreover it gives the unique possibility to express the magnitude of the baryon asymmetry β through parameters of the standard model measured in direct experiments.

Baryonic charge nonconservation in the electroweak theory was discovered by 't Hooft [11]. It is a very striking phenomenon. Classically baryonic current, as inferred from the electroweak Lagrangian, is conserved

$$\partial_\mu j_{baryonic}^\mu = 0, \quad (2)$$

but the conservation is destroyed by the quantum corrections. The latter are given by the very well known chiral anomaly associated with triangle fermionic loop in ex-

ternal gauge field. The calculation which can be found in many textbooks gives

$$\partial_\mu j_{BL}^\mu = N_f \left(\frac{g_2^2}{32\pi^2} W\tilde{W} - \frac{g_1^2}{32\pi^2} Y\tilde{Y} \right) \quad (3)$$

Here N_f is the number of fermionic flavors, $g_{1,2}$ are the gauge coupling constants of $U(1)$ and $SU(2)$ groups, W and Y are the gauge field strength tensors for $SU(2)$ and $U(1)$ respectively, and tilde means dual tensor, $\tilde{W}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} W_{\alpha\beta}/2$. The products of the gauge field strength $W\tilde{W}$ and $Y\tilde{Y}$ can be written as divergences of vector quantities,

$$W\tilde{W} = \partial_\mu K_2^\mu \quad (4)$$

$$Y\tilde{Y} = \partial_\mu K_1^\mu \quad (5)$$

where

$$K_1^\mu = \epsilon^{\mu\nu\alpha\beta} Y_{\nu\alpha} Y_\beta \quad (6)$$

$$K_2^\mu = \epsilon^{\mu\nu\alpha\beta} (W_{\nu\alpha} W_\beta - \frac{1}{3} g_2 W_\nu W_\alpha W_\beta) \quad (7)$$

Here Y_ν and W_ν are gauge field potentials of abelian $U(1)$ and nonabelian $SU(2)$ groups respectively. Usually total derivatives are unobservable since they may be integrated by parts and disappear. This is true for the contribution into K^μ from the gauge field strength tensors $Y_{\mu\nu}$ and $W_{\mu\nu}$ which should sufficiently fast vanish at infinity. However it is not obligatory for the potentials for which the integral over infinitely separated hypersurface may be nonzero. Hence for nonabelian groups the current nonconservation induced by quantum effects becomes observable.

Because of conditions (3,4,7) the variation of

the baryonic charge can be written as

$$\Delta B = N_f \Delta N_{CS} \quad (8)$$

where N_{CS} is the so-called Chern-Simons number characterizing topology in the gauge field space. It can be written as a space integral of the time component of the vector K^μ :

$$N_{CS} = \frac{g_2^2}{32\pi^2} \int d^3x K_2^t \quad (9)$$

Though N_{CS} is not a gauge invariant quantity its variation

$$\Delta N_{CS} = N_{CS}(t) - N_{CS}(0)$$

is.

In vacuum the field strength tensor $W_{\mu\nu}$ should vanish while the potentials are not necessarily zero but can be the so called purely gauge potentials:

$$W_\mu = -\frac{i}{g_2} U(x) \partial_\mu U^{-1}(x) \quad (10)$$

There may be two classes of gauge transformations keeping $W_{\mu\nu} = 0$: one that does not change N_{CS} and the second that changes N_{CS} . The first one can be realized by a continuous transformation of the potentials while the second cannot. If one tries to change N_{CS} by a continuous variation of the potentials one has to pass the region where $W_{\mu\nu}$ is nonzero. It means that vacuum states with different topological charges N_{CS} are separated by the potential barriers. The probability of the barrier penetration can be calculated in quasiclassical approximation. The trajectory in the field space in imaginary time which connects two vacuum states differing by a unit

topological charge is called the instanton. As in the usual quantum mechanics action evaluated on this trajectory gives the probability of the barrier penetration [12]:

$$\Gamma \sim \exp\left(\frac{4\pi}{\alpha_W}\right) \approx 10^{-170} \quad (11)$$

where $\alpha_W = g_2^2/4\pi$. This number is so small that it is not necessary to present a preexponential factor.

Expression (11) gives the probability of the baryonic charge violation at zero energy. We know from quantum mechanics that the probability of the barrier penetration rises with rising energy. Moreover in the system with nonzero temperature a particle may classically go over the barrier with the probability determined by the Boltzmann exponent, $\exp(-E/T)$. This analogy let one think that a similar phenomenon may exist in quantum field theory so that the processes with baryonic charge violation are not suppressed at high temperature. One should not of course rely very much on this analogy since there may be a serious difference between quantum mechanics which is a system with a finite number of degrees of freedom and quantum field theory which has an infinite (continuous) number of degrees of freedom. Still in a detailed investigation of this phenomenon convincing arguments have been found that baryonic charge nonconservation at high temperature may be strong and that baryogenesis by electroweak processes may be possible. A good introduction to the theory of the electroweak ($B + L$)-violation at high temperature can be found in lectures [13].

The first paper where this idea was se-

viously considered belongs to Kuzmin, Rubakov, and Shaposhnikov [14] (for the earlier papers see ref. [4]). They argued that the probability of baryonic charge nonconservation at nonzero T is determined by the expression

$$\Gamma \sim \exp\left(-\frac{U_{max}}{T}\right) \quad (12)$$

where U_{max} is the potential energy at the saddle point separating vacua with different topological charges. The field configuration corresponding to this saddle point is called sphaleron. It was originally found in ref. [15] and later rediscovered in paper [16]. In the last paper the relation of this solution to the topology changing transitions and baryonic charge nonconservation was clearly understood. Quantum mechanical analogue of the sphaleron is a single point in the phase space, i.e. the position of particle sitting at the top of the barrier. The energy of the sphaleron is

$$U_{max} \equiv U(\phi_{sphaleron}(x)) = \frac{2M_W}{\alpha_W} f\left(\frac{\lambda}{g^2}\right) \quad (13)$$

where λ is the self-interaction coupling constant of the Higgs field, f is a function which can be calculated numerically, $f = O(1)$, and M_W is the mass of the W-boson. At zero temperature $2M_W/\alpha_W \approx 10$ TeV. However at high temperatures close to the electroweak phase transition the Higgs condensate is gradually destroyed and the height of the barrier decreases together with the mass of W-boson $M_W^2(T) = M_{0W}^2(1 - T^2/T_c^2)$ [17,18] where $T_c = O(1TeV - 100GeV)$ is the critical temperature of the transition. Thus one may expect that the processes with baryonic charge nonconservation are indeed un-

suppressed at high temperatures.

The situation is not so simple however and there are a few problems which should be resolved before a definite conclusion can be made. They mostly stem from the difference between finite dimensional system like quantum mechanics and infinitely dimensional field theory. The first question is what is the probability of the processes with the change of topology in the gauge field space. Such processes proceed in presumably multiparticle collisions through formation of the classical field configuration with the coherent scale which is much larger than inverse temperature. If these processes are not fast enough the sphalerons may be not in thermal equilibrium and possibly far below the equilibrium so that the expression (12) would not be applicable. At the present day we do not know a reliable analytical way to address this problem. Numerical simulation of the analogous problem made in 1+1 dimensions [19] showed that the creation of soliton-antisoliton pairs are indeed fast enough to maintain the equilibrium value and this is one the strongest arguments in favor of efficient baryon nonconservation in electroweak processes. However such processes in one dimensional space may proceed much easier than those in three space dimensions simply because in $D = 1$ the change of topology means just a jump from one constant value of the Higgs field to another while in $D = 3$ much more fine tuning in every space point is necessary. Unfortunately numerical simulation in 3+1 case is much more difficult and correspondingly much less reliable. So strictly speaking the probability of the sphaleron transitions is not known and a better un-

derstanding of it is very much desirable though it seems plausible that they are not too much suppressed so that thermal equilibrium with respect to the topology changing transitions was achieved in the early universe.

Another question related to the probability of the processes with $\Delta B \neq 0$ is what is the entropy of the sphalerons or in other words what is the preexponential factor in expression (12). This factor characterizes the width of the potential near the saddle point in the directions orthogonal to the trajectory over potential barrier and was calculated in ref. [20]. With this factor taken into account the probability of electroweak processes with baryonic charge nonconservation in the phase with broken electroweak symmetry can be evaluated as

$$\frac{\Gamma_{\Delta B}}{H} = 10^{24} \left(\frac{M_W(T)}{T} \right)^2 e^{-120M_W(T)/T} \quad (14)$$

where H is the Hubble parameter characterizing the rate of the Universe expansion.

At temperatures above electroweak phase transition the rate of baryonic charge nonconservation is given by [20,21]

$$\Gamma_{\Delta B} \approx \alpha_W^4 T \quad (15)$$

Recall that expressions (14) and (15) are valid only if sphalerons are in thermal equilibrium. If this is true then $\Gamma_{\Delta B}/H \gg 1$ at high temperatures and then abruptly falls down with falling temperatures. Thus processes with baryonic charge nonconservation are in equilibrium at high T and at some point are instantly switched off. Thus any preexisting baryon asymmetry would

be washed out and a new one cannot be generated. This conclusion can be avoided however if deviations from thermal equilibrium existed at the time when baryonic charge nonconservation was still effective. This can be realized in particular if electroweak phase transition is of the first order. However it is still an open question what is the type of the phase transition depending in particular on the value of the Higgs boson mass.

One more comment may be in order here. We spoke before only about baryonic charge nonconservation. In fact electroweak interactions break equally baryonic and leptonic charges so that $(B-L)$ is conserved. With this correction in mind all the previous statements remain true with the substitution of $(B+L)$ instead of B .

Thus the following logical possibilities exist for the electroweak baryogenesis (we simply enumerate them here and discuss in some more detail giving recent references below):

- I. Change of the field topology is suppressed in three-dimensional space. Sphalerons are never abundant and electroweak nonconservation of $(B+L)$ is ineffective. In that case we should return either to GUT baryogenesis or to some other more recent proposals described in review paper [4].

- II. Sphaleron transitions are not suppressed above and near the electroweak phase transition and so $(B+L)$ is strongly nonconserved at these temperatures. If this is true the following two possibilities are open:

- II.1. The electroweak phase transition

is of the second order and so the baryon nonconserving processes, which were with a very good accuracy in thermal equilibrium above the phase transition, would be instantly completely switched off below it. In this case any preexisting $(B + L)$ would be washed out and we again meet two possibilities:

- 1a. The observed asymmetry might arise from an earlier generated $(B - L)$ either by $(B - L)$ nonconserved processes which exist e.g. in higher rank grand unification groups or by lepton charge non-conservation in decays of heavy Majorana fermion.

- 1b. Baryogenesis should take place at low energies below electroweak scale which for sure demands new low energy weak physics.

- II.2. Electroweak phase transition is first order so thermal equilibrium was strongly broken when both phases coexisted. If this is the case $(B + L)$ -asymmetry could be generated in electroweak processes at temperatures near 1TeV. An important subdivision in this situation is:

- 2a. The standard model is able to give a correct magnitude of the baryon asymmetry of the Universe so that baryogenesis does not demand any physics beyond the minimal standard $SU(3) \times SU(2) \times U(1)$ -model (MSM).

- 2b. An extension of the minimal standard model is necessary. This is not well defined and may include an introduction of additional Higgs fields (like in supersymmetric versions), considerable CP-violation in the lepton sector, CP-violation in strong interaction, etc.

The essential quantity which determines the character of the phase transition in the

minimal standard model is the magnitude of the Higgs boson mass. For a large value of the latter the phase transition is second order and for a small one it is first order. To illustrate this statement let us consider the following temperature dependent effective potential for the Higgs field ϕ (temperature dependent terms appear due to interactions of the field ϕ with the thermal environment of the cosmic plasma):

$$U(\phi, T) = m^2(T)\phi^2/2 + (\lambda\phi^4)\ln(\phi^2/\sigma^2)/4 + \gamma(T)\phi^3 + \dots \quad (16)$$

Notations here are selfexplanatory. The temperature dependence of the effective mass is roughly speaking the following $m^2(T) = -m_0^2 + AT^2$ where the constant A is usually positive. (It is positive in MSM.) Logarithmic dependence on ϕ came from one-loop quantum perturbative corrections to the potential. At high temperatures the potential has the only minimum at $T = 0$, vacuum expectation value of the ϕ is zero, and the electroweak symmetry is unbroken. At smaller temperatures a deeper minimum is developed at nonzero ϕ and mass of the field near this minimum is $m_H^2 \approx 2m_0^2$ (we neglected here logarithmic terms in U). One sees that the larger is m_0^2 (and correspondingly the physical mass m_H^2) the easier is the phase transition. There is no consensus in the literature about the value of m_H separating first and second order phase transitions. While earlier perturbative calculations in the MSM [22] give a rather small value $m_H \approx 45$ GeV, it was argued that higher loop effects are essential [23–25]. Moreover since thermal perturbation theory for non-abelian gauge fields suffers from severe infrared divergences, nonperturbative effects

might be important acting in favor of the first order phase transition with higher m_H [26]. It is supported by the recent lattice calculations [27,28]. For a more detailed discussion and list of references see papers [5,29]. Hence we cannot make any rigorous conclusion now about the nature of the electroweak phase transition though it seems probable that MSM with the existing lower experimental bound on the Higgs mass $m_H > 62$ GeV given by LEP favors second order phase transition while in extended models with several Higgs fields the transition might be first order.

Even if the electroweak phase transition in MSM is first order the generated asymmetry is expected to be very small. It is connected with a strong suppression of CP-violating effects at high temperatures. CP-breaking in the MSM is created by the imaginary part of the quark mass matrix (Cabibbo-Kobayashi-Maskawa matrix). If there are only two quark generations the imaginary part is not observable because the phase may be absorbed in a redefinition of the quark wave function. The statement remains true with more quarks families with degenerate masses because the unit matrix is invariant with respect to unitary transformations. One can see that the minimum number of quark families for which the imaginary part is observable is three with different masses of quarks with the same value of electric charge. (If we believe that there is no extension of the standard model then the necessity of CP-violation for the generation of the charge asymmetry of the Universe justifies the existence of at least three fermionic families.) Moreover the amplitude of CP-violation is proportional to the mixing angles between

different families because if the quark mass matrix and the kinetic term in the Lagrangian are simultaneously diagonal then the phase rotation would not change them. By these reasons the amplitude of CP-violation in MSM is suppressed by the factor (which is called the Jarlskog determinant):

$$A_- \sim \sin \theta_{12} \sin \theta_{23} \sin \theta_{31} \sin \delta_{CP} \frac{(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}{E^{12}} \quad (17)$$

Here θ_{ij} are mixing angles between different generations and δ_{CP} is the CP-odd phase in the mass matrix. The product of sin's of these quantities is about $10^{-4} - 10^{-5}$. E is the characteristic energy of a process with CP-breaking. In the case considered when the temperature of the medium is above 100 GeV, E is of the same order of magnitude. Correspondingly one should expect that baryon asymmetry in MSM should be of the order of 10^{-20} .

This conclusion was questioned recently by Farrar and Shaposhnikov [29,30]. They argued that flavor dependent temperature corrections to the quark masses in the vicinity of the domain wall where the expectation value of the Higgs field is changing nonadiabatically, may drastically enhance efficiency of the electroweak baryogenesis. This effect is especially pronounced at the low energy tail of the quark distribution in the phase space. As a result the value of the baryon asymmetry may be close to the observed one even in the minimal standard model. This very interesting proposal is discussed by Shaposhnikov at this Conference so I would not stop on the

details of the model.

Despite all the attractiveness of the possibility of effective baryogenesis in the MSM it should be excluded if the experimental lower bound on the Higgs boson mass proves to be above the value necessary for successful first order phase transition. This seems rather probable now and the models with several Higgs fields are possibly the next best choice. They may give a larger CP-violation and what's more in these models both experimental and theoretical bounds on the Higgs boson mass are much less restrictive.

The generic feature of all scenarios of electroweak baryogenesis is a coexistence of two phases in one of which baryonic charge is strongly nonconserved, the corresponding reactions are well in equilibrium, and no asymmetry can be generated, while in the second phase baryonic charge is practically conserved and the asymmetry also cannot be generated though by an opposite reason. So the only place where baryon asymmetry may be produced are the boundaries between the phases. The outcome of such a process strongly depends upon the interaction between the high temperature cosmic plasma and the domain walls and in particular upon the velocity of the wall propagation in plasma. These problems are addressed in several papers (for the recent ones see e.g. refs. [31,32]) but still more work in this field is desirable.

Despite all these uncertainties the electroweak baryogenesis is presently the most fashionable scenario of creation of the building blocks of our Universe. There is

a large selection of models the literature, each having a chance to be the right one. A possible exception is the model with a large CP-violation in the lepton sector [33] which demands a heavy tau-neutrino with the mass of the order of 10 MeV. However the recent nucleosynthesis bounds [34–36] which close the window for ν_τ -mass in the region 0.5-35 MeV strongly disfavor it.

In the case if the phase transition is second order, baryon asymmetry could not be generated by electroweak processes but, if sphalerons are effective, the latter may be very good for erasure of any preexisting $(B + L)$ -asymmetry. A nonzero initial $(B - L)_i$ -asymmetry is conserved by electroweak interactions and the subsequent sphaleron processes would result in equal baryon and lepton asymmetry $B_f = L_f = (B - L)_i/2$. Assuming that this is indeed the case one can derive a bound on the strength of $(B - L)$ -nonconserving interactions at lower temperatures when (and if) $(B + L)$ -erasure is effective. (One should keep in mind however that all these bounds are valid only if there is no baryogenesis at electroweak or lower temperature range.) If the rate of $(B + L)$ -nonconserving sphaleron transitions is given by eqs.(14, 15), the sphaleron processes are in equilibrium in the temperature range

$$10^2 - 10^3 < T < 10^{12} (GeV) \quad (18)$$

For successful baryogenesis the processes with $(B - L)$ -nonconservation should not be in equilibrium in this range. This idea was first used in ref.[37], where the model of baryogenesis through the decay of heavy Majorana fermion has been proposed, to put a bound on the Majorana mass of

light neutrinos, $m_M(\nu) < 50$ KeV. Neutrinos with a larger Majorana mass together with sphalerons would destroy both baryon and lepton asymmetry. There exists a large literature on the subject (the references can be found in the review paper [4]) where the bounds on different types of $(B - L)$ -nonconserving interactions are obtained. I would like to mention here only a recent paper [38] where it was argued that lepton asymmetry stored in right-handed electrons, which are singlets with respect to nonabelian part of the electroweak group and due to that do not interact with sphalerons, might be preserved for the temperature down to approximately 10 TeV. Below that the Higgs bosons would effectively transform right-handed electrons into left-handed ones and subsequently sphalerons would convert the lepton asymmetry in the sector of right-handed electrons into baryon asymmetry. The creation of the initial lepton asymmetry could be favored by a rather strong violation of leptonic charge conservation. All other $(B - L)$ -breaking interactions should be out of equilibrium above 10 TeV while the usual demand is that they are out of equilibrium at much higher temperatures where either sphalerons come into equilibrium or where the initial $(B - L)$ is produced. This invalidates some of the conclusions obtained in the earlier papers (not quoted here) of stronger bounds on $(B - L)$ -nonconservation. Still the assumption that baryogenesis proceeds through transformation of an initial $(B - L)$ -asymmetry into B-asymmetry permits to deduce in some cases more interesting bounds on e.g. L-nonconservation than that following from direct experiments. There are too

many possible forms of the interaction and theoretical models giving rise to them so that their more detailed description is outside the scope of the present talk and one should be addressed to original literature on the subject.

Now I would like to turn to some more exotic cases. The first one is a possibility of a large lepton asymmetry together with a normal small baryon asymmetry. Though the data gives a rather accurate value of β (within an order of magnitude), the value of the lepton asymmetry is practically unknown. The best limits follow from the primordial nucleosynthesis which permits muonic and taonic lepton asymmetry close to unity while electronic lepton asymmetry cannot exceed 1% (see [4] for the list of references). The bound on the chemical potential associated with electronic charge is stronger because it would directly shift proton-neutron equilibrium in weak reactions like $n + \nu_e \leftrightarrow p + e^-$, while ν_μ and ν_τ influence n/p -ratio only through the total energy density. Thus even in the most restricted case the value of lepton asymmetry may be as large as 10^{-2} .

A large lepton asymmetry could only be realized if the sphaleron processes were not effective or if the asymmetry was generated below electroweak scale. Even if this is true, the majority of models naturally give $L \approx B$ but there are some examples permitting $L \gg B$ (see e.g. [39,4]). In this case we would have at our disposal an extra free parameter for the theory of primordial nucleosynthesis, namely the chemical potential of leptons. What's more the characteristic scale of spatial variation of the leptonic charge density l_L might be much

smaller than l_B and if the former is in the range $l_{gal} < l_L < l_U$ one may observe that by spatial variation of the abundances of light nuclei and in particular of 4He .

The relatively strong isocurvature fluctuations in leptonic sector with a possibly nonflat spectrum may be also interesting for the theory of the large scale structure formation with a single dominant component of hot dark matter. Usually one considers isocurvature perturbations in baryonic sector which are stronger bounded by the isotropy of the cosmic microwave background.

Returning to the isocurvature fluctuations in baryonic sector one may find plenty baryogenesis scenarios (see [4]) providing very interesting perturbations with the spectrum varying from the flat one to that having a prominent peak at a particular wave length. The last case corresponds to a periodic in space distribution of baryonic matter. It may be naturally realized if three rather innocent assumptions are satisfied:

- 1. There exists a complex scalar field ϕ with the mass which is small in comparison with the Hubble parameter during inflation. The latter may be as large as 10^{14} GeV so one does not need a really light scalar field.
- 2. The potential of the field ϕ contains nonharmonic terms like $\lambda|\phi|^4$.
- 3. A condensate of ϕ was formed during inflationary stage which was a slowly varying function of space points.

If these conditions are fulfilled then it can be proven (for the details see refs. [40,41])

that the distribution of baryons in the Universe would be in the form:

$$N_B \approx N_{B0} + N_1 \cos \frac{\vec{r}\vec{n}}{l_B} \quad (19)$$

where \vec{n} is an arbitrary unit vector. The scale l_B of the fluctuations is given by the exponentially stretched Compton wave length of ϕ and could easily be as large as 100 Mpc as was indicated by the observations [42]. An interesting picture emerges if $N_0 = 0$ and the Universe consists of alternating baryonic and antibaryonic layers.

Another unusual picture of the Universe, the so called island universe model may be realized with the specific though not too complicated model of baryogenesis [40]. In this model our Universe is a huge baryonic island with the size large or about 10^{10} years (or $z = 5 - 10$), while floating in the sea of dark matter which is more or less uniformly distributed. There are two interesting features of this model which may be relevant to the structure formation. First, the background radiation comes to us from the baryon empty regions so that the fluctuations in its temperature is not directly related to the density perturbations inside the island. Second, our noncentral position inside the island would give rise to intrinsic dipole, $d \sim 10^{-3}$, in the angular distribution of the microwave radiation which is not related to our motion. The quadrupole asymmetry in this case would be rather small, $q \sim d^2 \sim 10^{-6}$. It may make easier structure formation in the cold dark matter model. (This point was emphasized to me by J. Silk.) Without intrinsic dipole and with the flat spectrum of perturbations more complicated models of the structure formation are necessary,

like e.g. a mixture of hot and cold dark matter [43] or a model with cold dark matter and nonzero vacuum energy (cosmological constant). Both these models demand some fine tuning which is not well understood today. The first one needs the energy density of hot and cold dark matter to be the same within the factor of 2 while the other demands ρ_{vac} which is normally time independent constant to be close today to the critical energy density which is time dependent, $\rho_c \sim m_{Pl}^2/t^2$. The latter may be explained if the smallness of the cosmological constant is ensured by the so called adjustment mechanism (for the review see [44]). Though these two possibilities are more conservative than the island model still they are not the most economic ones. Proliferation of the universe components from the purely baryonic universe to the mixed baryonic and hot dark matter or later on to baryonic and cold dark matter and now to the mixture of all three of them (baryonic+cold+hot) with close energy densities is rather mysterious. On the other hand there are stable neutrinos which are very likely to be massive and it is also very plausible that there is supersymmetry in particle physics so that there should be a stable heavy particle. These two are perfect candidates for the hot and cold dark matter (what's more we may have now dark solar size objects in galaxies) so that it would be only natural that these particles participates as building blocks of the Universe. The unresolved question is their interaction strength which provides very different number densities and similar mass densities for the particles of hot and cold dark matter.

One may try to make a cosmological model

assuming that the only massive stable particles in the Universe are protons and electrons [45] and all the dark matter is made of the normal baryonic staff. To do that one has to develop a scenario in which baryogenesis proceed much more efficiently in relatively small space regions giving $\beta = 1 - 0.01$ while it goes normally outside. The regions with that huge baryon number density mostly form black holes with the mass distribution

$$\frac{dN}{dM} \sim \exp\left(-\gamma \ln^2 \frac{M}{m_0}\right) \quad (20)$$

Parameters γ and M_0 cannot reliably found in the model but one reasonably expect that $\gamma = O(1)$ and M_0 is close to the solar mass. These black holes might be the objects observed in the microlensing search reported here. If there are no other massive stable particles one has to build a theory of the structure formation with these black holes which behave as normal cold dark matter. At the tail of the distribution in mass there should be very heavy black holes with masses like $10^6 - 10^9$ solar masses which may serve as seeds for the structure formation. Still tilted spectrum of the initial perturbations may be desirable if only cold dark matter is permitted.

Conclusions of the talk reflect to a large extend my personal opinion and may not be shared by everybody or not even by the majority.

I. The best choice for the baryogenesis scenario is the electroweak one and in its framework the one based on the minimal standard model is the most appealing. The problems with the electroweak baryogenesis are the unknown probabilities of

three dimensional reactions with classical field configurations, which may question the scenario as a whole, and the type of the electroweak phase transition. The knowledge of the value of the Higgs boson mass could be of great help here.

II. If not MSM the low energy SUSY is the next best choice. SSC could be very interesting for that but alas...

III. If electroweak interactions destroy but not generate baryon asymmetry (like e.g. in the case of the second order phase transition), a very interesting possibility is baryogenesis through leptogenesis. One needs to this end a heavy Majorana fermion with mass around 10^{12} Gev (plus-minus a few orders of magnitude) and correspondingly a new physics beyond the standard model.

IV. A very low temperature (below the electroweak scale) baryogenesis is not excluded but there is no natural particle physics model for that.

V. Majority of models give lepton and baryon asymmetry of approximately the same magnitude but one may find scenarios giving $L \gg B$ with interesting consequences for the primordial nucleosynthesis.

VI. A better understanding of baryogenesis may be of interest for the theory of the large scale structure formation in particular because in the process of baryogenesis isocurvature density fluctuations with a complicated spectrum might be created.

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