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COSMOLOGICAL CHARGE ASYMMETRY AND RARE PROCESSES IN PARTICLE PHYSICS

A.D. Dolgov
Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara,
I-44100 Ferrara, Italy
Dipartimento di Fisica, Università degli Studi di Ferrara,
I-44100 Ferrara, Italy
Institute of Theoretical and Experimental Physics,
113259, Moscow, Russia

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Abstract

Two scenarios of low temperature baryogenesis in theories with TeV scale gravity are discussed. It is argued that strong gravity at TeV energies is very favorable for baryogenesis. In both scenarios the proton decay is either absent or suppressed far below existing bounds. On the other hand, neutron-antineutron oscillations are at the verge of discovery. Some other rare decays with non-conservation of lepton or baryon numbers are predicted.

It is experimentally established that neither baryonic nor individual leptonic numbers are conserved. Neutrino oscillations are known to mix electronic, muonic, and tauonic neutrinos, resulting in nonconservation of all these quantum numbers. On the other hand, astronomy proves that baryon number is not conserved. One can say that since we exist, baryons are not forever. Indeed a suitable for life universe canot be created if baryonic charge were conserved. The chain of arguments goes as follows. First, the asronomical data strongly suggest that inflation is an "experimental" fact. There are many reasons to believe that this is true:

1. We do not know any other way to make the observed universe.
2. It explains the origin of expansion.
3. It solves the problems of homogeneity, isotropy, flatness and predicts $\Omega = 1$.
4. Inflation creates density perturbations with the observed spectrum.

The next important statement is that inflation is impossible with conserved baryons. Inflation could be realized if the total cosmological energy density is (almost) constant. However, if baryons are conserved the energy density might stay constant at most during 4-5 Hubble times, while for successful inflation at least 60 Hubble times are necesary. For more details see e.g. review [1].

If baryon and lepton quantum numbers are not conserved one should expect this nonconservation to manifest itself in particle physics. The well known phenomena searched for are the following: unstable proton, $(n - \bar{n})$-oscillations, some rare decays, as e.g. $\mu \to e\gamma$, and similar decays of heavier quarks with B or L nonconservation. Yet nothing is observed. Though cosmology predicts non-conservation of baryons and consequently a manifestation of this nonconservation in particle physics, the magnitude of such effects is expected to be very small or, at best, unknown because the energy scale of cosmological baryogenesis is normally much higher than that available in terrestrial experiments and, what's more, there is usually no direct relation between physics of baryogenesis and proton decays or neutron-antineutron oscillations.

Here we will discuss some new scenarios of baryogenesis which explain the observed baryon asymmetry of the universe and lead to observable consequences in particle physics. My talk is based on the works made in collaboration with F. Urban [2] and C. Bambi and K, Freese [3, 4].

Let us first consider a rather conservative scenario based on SUSY with broken $\mathcal{R}$-parity . The operators which break $\mathcal{R}$-parity and experimental bounds on their coupling constants are enumerated e.g. in review [5]. Cosmological baryogenesis in this model could proceed through B-nonconserving decays of massive SUSY particles induced by B-nonconserving $\mathcal{R}$-parity violating operators. If masses of supersymmetric particles are not very large, e.g. $M_{SUSY} \sim$ TeV, deviations from thermal equilibrium in the standard cosmology are negligible:

$$\frac{H}{\Gamma} \sim \frac{M_{SUSY}}{\alpha m_{Pl}} \sim 10^{-14}, \tag{1}$$

where $\alpha \sim 10^{-2}$ is the coupling constant. The baryon asymmetry would be further suppressed at least by factor α because CP-violation manifests itself only in higher orders of perturbation theory.

To obtain a reasonable baryon asymmetry the scale of supersymmetry must be very high:

$$M_{SUSY} \geq 10^{10} \text{ GeV} \tag{2}$$

However, in this case effects in particle physics would be unnoticeable.

A possible solution which allows both for successful baryogenesis and for nonnegligible effects in particle physics is offered by TeV scale gravity.

There are two known mechanisms for TeV gravity:

1. Gravity lives in higher dimensional space, while matter lives in $D = 4$[6].
2. Time variation of m_{Pl} due to the coupling $\xi R \phi^2$ [7]. It is assumed that initially (in the early universe) $\phi \sim$ TeV, and later, but prior to nucleosynthesis, it rises up to the Planck value 10^{19} GeV.

Both these possibilities are practicaly equally good for cosmological baryogenesis but in the first case care should be taken on the potential problems with light gravitinos [8].

Essential $\mathcal{R}$-parity -violating operators have the form:

$$\mathcal{L}_{int} = -\frac{1}{2}\,\lambda^{ijk}\left(\tilde{u}_i^*\,\bar{d}_j\,d_i^c + \tilde{d}_k^*\,\bar{u}_i\,d_j^c + \tilde{d}_j^*\,\bar{u}_j\,d_k^c\right) + h.c., \tag{3}$$

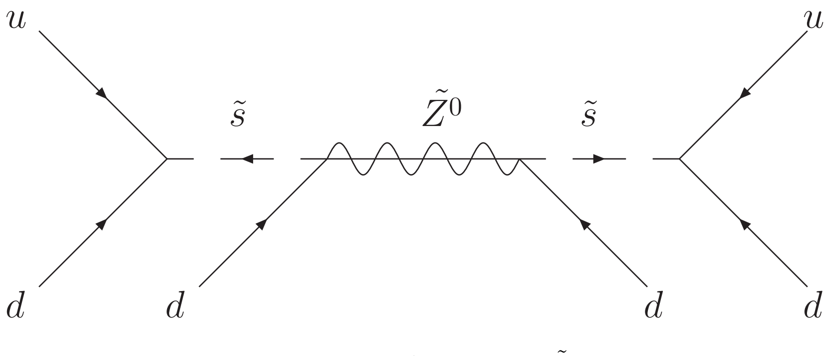
where i, j, k are the flavor indices and u and d are respectively operators of up and down quarks, tidle denotes a superpartner, and λ^{ijk} is a Yukawa type coupling constant. The color indices are suppressed. These operators do not conserve baryonic charge, B, by one unit and conserve leptonic charge, L. Correspondingly proton decay is forbidden but transformations of baryon into antibaryon and, in particular, neutron-antineutron oscillations are allowed. Such transformations inside a nuclei would lead to an energetic annihilation and nuclear decay. Correspondingly experimental bounds on nuclear stability allow to put quite strong constraint on some λ^{ijk}:

$$\lambda_{112} < 10^{-6}, \;\; \lambda_{113} < 10^{-3}, \tag{4}$$

while others could be even well above unity.

Non-zero λ_{112} would lead e.g. to $n\bar{\Xi}$ - transformation. To make $n\bar{n}$ oscillations out of it a $\Delta S = 2$ process is necessary. It is strongly suppressed in MSM but possibly not so much in a supersymmetric extension, in particular in minimal supersymmetric model, MSSM.

The diagramm which induces $\bar{n} - n$ transformation through $\Delta S = 2$ processes has the form:



Notice that strangeness non-conserving decays of zino, e.g. $\tilde{Z} \to \bar{u}\tilde{s}$, are allowed, while similar decays of Z-boson, not $Z \to \bar{u}s$, are not. Both successful baryogenesis and $n\bar{n}$ - transformation just above the experimental limit might take place. For more detail see ref. [2].

Much more exotic possibility was put forward in refs. [3, 4] in the frameworks of TeV gravity. The latter is known to suffer from a serious problem related to nonconservation of all global quantum numbers. The idea is basically that some (one or a few) particles, possessing non-zero baryonic, leptonic, or any other global charges, may form a very dense state inside their common gravitational radius. In other words, they would form a small virtual black hole. As is well known, black holes may have "hairs" associated only with conserved quantum numbers related to local (gauge) symmetries, as e.g. electric charge. On the other hand, if a black hole swallows particles with non-zero leptonic, L, or baryonic, B, charges, it immediately "forgets" about these charges and may decay into some state with zero or any other values of B or L. This was first observed by Zeldovich [9], who estimated the life-time of proton due to formation and decay of a virtual black hole:

$$\tau_p \sim m_{Pl}^4/m_p^5 \sim 10^{45} \text{ years} \tag{5}$$

This is by far larger than the existing experimental bound $\tau_p > 10^{33}$ years. But if $m_{Pl} \sim$ TeV, $\tau_p \sim 10^{-11}$ s. Similar problems exist for $\mu \to e\gamma$ and other rare decays.

These difficulties for low scale gravity was discussed in ref. [10] where it was argued that the fundamental Planck mass should be much larger than TeV, up to 10^{16} GeV. In our recent works [3, 4] we made an attempt to resolve the problem of strong gravitational B and L nonconservation proposing the so called classical black hole conjecture, which "dynamically" forbids an easy formation of black holes (BH). This conjecture is based on the fact that classical charged and rotating black hole can only be formed if it is sufficiently heavy:

$$\left(\frac{M_{BH}}{m_{Pl}}\right)^2 > \frac{Q^2}{2} + \sqrt{\frac{Q^4}{4} + J^2}, \tag{6}$$

where Q and J are respectively electric charge and angular momentum of BH. Formally it follows from this expression that if $M_{BH} < m_{Pl}$, the black hole can be only electrically neutral and non-rotating. The result (6) is valid for classical black holes and may be incorrect for quantum ones. However, physics of quantum black holes is unknown and one is free to make arbitrary and quite wild assumptions.

In addition to this conjecture of neutral and non-rotating BHs we impose some, maybe even more questionable, rules in calculations/estimates of the amplitude of reactions with broken global quantum numbers due to virtual BH. We assume essentially that virtual black holes could be formed only in s-channel with positive mass (energy) of the created black hole. Such an assumption and some of the rules which we use in what follows do not respect many usual conditions existing in quantum field theory, in particular crossing relations between amplitudes. For example, we allow a virtual BH to decay into, say, a proton and a electron, but we do not allow a proton to form a scalar BH plus a positron, with the same amplitude. The picture that we have in mind is a kind of time ordering: a BH could be formed in a collision of a neutral system of particles in the s-channel whereas a BH cannot be in the t-channel of a reaction. We assume that BHs can be formed out of positive energies of real particles only and not from virtual energies of particles in closed loops. For example, BH cannot be formed by vacuum fluctuations, despite the fact that, according to the standard picture, vacuum fluctuations might create a pair or more of virtual particles both with positive and negative energies. The mass of the BH should be of the order of the energy of incoming (or outgoing) particles. In an attempt to describe this in terms of the usual language we come to a version of the old non-covariant perturbation theory with all virtual particles having positive energies. It corresponds to the choice of only one mass-shell pole in the Feynman Green's functions. This rule allows only for BHs with masses which are of the order of the energies of the initial (or final) particles, as we postulated above. It may look very strange, to say the least, but virtual BHs are not well defined objects and we do not know what happens with space-time at the relevant scales. Taken literally these rules would lead to violation of some sacred principles of the standard theory (locality, Lorentz invariance, and more). Let us remind the reader, however, that the existing attempts in the literature to invoke virtual BHs are based on standard quantum field theory in a situation where it is almost surely inapplicable.

So it is not excluded that many properties of the standard field theory are broken, including even Lorentz invariance and locality. We cannot of course present any serious arguments in favor of our construction but it predicts quite impressive phenomena with clear signatures based on a very simple set of rules and if these effects are discovered, the approach, advocated here, may be taken more seriously. Our goal here is to formulate a reasonable(?) set of rules which may possibly describe processes with

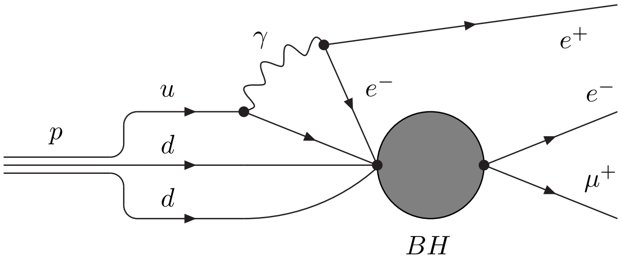


Fig. 1. Gravitationally induced proton decay through non-charged and nonrotating black hole.

virtual BHs and are, at least, not self-contradictory. Based on these rules we study phenomenological consequences in particle physics, which are quite rich and may be accessible to experiments after a minor increase of accuracy.

The diagramm that, according to our conjecture, describes gravitationally induced proton decay is presented in fig. 1 Since a 4-body collision is required in order to form a BH devoid of any quantum number, the process is strongly suppressed and experimental constraints can be compatible even with the gravity scale in TeV range.

Similar graphs give rise to $\mu \to e\gamma$ - decay and other rare processess with violation of lepton flavor and baryonic numbers. The results of our calculations, according to ref. [3] are collected in Table 1, where the lower bound on the fundamental gravity scale is presented for different numbers, n, of extra dimensions.

Process	Experiment	M_*, $n = 2\,(7)$
$p \to eee$	$\tau > 10^{33}$ yr	> 2 (8)
$\mu \to \gamma e$	$BR < 10^{-11}$	> 1 (10)
$\mu \to eee$	$BR < 10^{-12}$	> 1 (10)
$K \to \mu e$	$BR < 10^{-12}$	> 3 (4)
$K \to \pi\mu e$	$BR < 10^{-10}$	> 1 (1)
$n \leftrightarrow \bar{n}$	$\tau > 10^8$ s	> 1 (3) (MSSM)

Thus we see that TeV scale gravity does not lead to contradiction with experiment if the condition that virtual BH should have positive mass and be electrically neutral and non-rotating, is fulfilled.

TeV scale gravity allows also for succesful, even quite efficinet, baryogenesis at relatively low temperatures [4]. All three Sakharov conditions:
1) baryon non-conservation,
2) deviation from thermal equilibrium,
3) large CP-violation in MSM,
are much easier fulfilled than in the standard case.

Let us start from CP-violation. It is well known that CP-breaking in the minimal standard model (MSM) is extemely weak. The amplitude of CP-violation is known to be proportional to the mass differences of all quark families and their mixing angles, for detials see e.g. [11]:

$$\epsilon_{CP} \approx (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$
$$(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)\,(J/T^{12}) \tag{7}$$

where

$$J = \cos\theta_{12}\cos\theta_{23}\cos^2\theta_{13}\sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\sin\delta_{CP} \approx 3\cdot 10^{-5}. \tag{8}$$

Thus $\epsilon_{CP} \sim 10^{-19}$ at $T \sim 100$ GeV. At lower temperatures the B-nonconserving sphaleron processes are exponentially suppressed and one cannot expect baryon-to-photon ratio larger than 10^{-20}, while the observed value is $\sim 5\cdot 10^{-10}$.

Low scale gravity models lead to nonconservation of baryonic charge at much lower, than 100 GeV, temperatures because nonconservation of B takes place simply in decays of heavy quarks and non-perturbative sphalerons are unnnecessary. According to the estimates of ref. [4], non-conservation of baryons remains significant even at $T \leq 10$ GeV and the amplitude of CP-violation (7) becomes 12 orders of magnitude larger.

One may avoid any suppression of CP violation at high temperatures if time variation of quark masses is allowed [12, 4]. In this case both mixing angles and quark mass differences can be large in the early universe.

Deviation from thermal equilibrium would be unsuppressed as it follows from eq. (1) with $m_{Pl} \sim$ TeV.

So to conclude:

1. Low scale gravity allows for much more efficient baryogenesis than the standard model.
2. In conservative SUSY model with broken $\mathcal{R}$-parity successful baryogenesis may proceed with (practically) stable proton and with noticeable neutron-antineutron oscillations.
3. The classical black hole conjecture makes compatible TeV gravity and low probability of B and L nonconserving processes.
4. The probability of such rare processes can be quite close to the existing experimental bounds.

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