B AND L VIOLATION AND BARYOGENESIS

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It is established that neither B nor $L_{e,\mu,\tau}$ are conserved. Quite possibly

$$L_{tot} = L_e + L_\mu + L_\tau$$

is nonconserved as well.

However, the data came mostly from the sky and from low energy neutrinos, solar and reactor.

Proton decay, $n\bar{n}$ oscillations,
$\mu \to e\gamma$, etc must exist but not (yet) discovered.

Probably the only remaining conserved charge is electric, Q.

But if the photon has even a tiny mass the cosmological electric asymmetry must be non-zero, i.e. the universe must be electrically charged, even if Q is conserved.

WHY WE ARE SURE THAT B AND L ARE NOT CONSERVED?

It is easy to break B and L conservation theoretically.

Anything not forbidden is allowed and must exist.

Experimentally verified EW theory predicts non-conservation of B and L
but effects are extremely, exponentially, weak in particle physics.
NB: $(B - L)$ is conserved.
EW non-conservation of $(B+L)$ might be significant in cosmology at high temperatures, $T \geq$ TeV.

GUTs break B and L.

In the simplest $SU(5)$ version $(B-L)$ is conserved, but broken in $SO(10)$.

Large GUT scale, $\sim 10^{16}$, GeV makes B and L nonconservation in particle physics practically unobservable.

More important than theory:
baryon nonconservation is established experimentally.
Astronomy proves that!

Half a century ago:

“we exist, so baryons are conserved”.

Now:

“we exist, so baryons are not forever”.

Cosmological arguments proving baryon nonconservation.

I. Inflation is an "experimental" fact:

1. It explains the origin of expansion.

2. It solves the problems of homogeneity, isotropy, flatness and predicts $\Omega = 1$.

3. Makes density perturbations with the observed spectrum.

II. Inflation is impossible with conserved baryons. Otherwise energy density associated with B would evolve as

$$\rho_B \sim 1/a^4.$$

Hence ρ_{tot} could be approximately constant at most during 4-5 Hubble times, because $\rho_B \approx 10^{-9}\rho_{tot}$ at QCD p.t.
To create our universe we need at least 60 Hubble times, $a \sim e^{60}$.

Thus we know that neither B and, probably, nor L are conserved.
Three possibilities:
1. B-nonconservation manifests itself only in cosmology to create cosmological baryon asymmetry and is negligible in particle physics. Frustrating.
2. Efficient baryogenesis demanding that observable processes in particle physics are almost at hand. Exciting!
3. Somewhere between two extremes above. Stimulating.

OBSERVATIONS:

1. Baryon asymmetry is non-zero:

$$\beta_B = N_B/N_\gamma = 6 \cdot 10^{-10}$$

Large fluctuations of β at small scales and even $\beta < 0$ (antimatter) are allowed theoretically and observationally.

2. Lepton asymmetry, not yet observed, may be non-zero and even large:

$$\beta_L = N_L/N_\gamma \leq 0.1.$$

This limit is from BBN because of LMA solution. If neutrinos are coupled to majoron, $\beta_L \sim 1$ is allowed. Theoretically natural: $\beta_L \sim \beta_B$ but much larger β_L is possible if created below EW p.t.

3. Electric asymmetry is usually assumed to be identically zero due to:
1. Conservation of electric current.
2. Zero photon mass and long range Coulomb force.
Observational bounds are very strong, $\beta_E < 10^{-45}$ but maybe questionable.
If $m_\gamma \neq 0$, electric asymmetry must be nonvanishing.

The only measured, and quite accurately, asymmetry is the baryonic one.
At the time of Sakharov's work (1967):
$\beta_B = 10^{-9\pm1}$,
now: $\beta_B = (5.5 \pm 1) \cdot 10^{-9}$.

Popular scenarios of baryogenesis:

1. GUT, probably not operative because $T \sim 10^{16}$ GeV was not reached after inflation. Gravitino problem.

2. Electroweak in MSM, excluded due to 2nd order phase transition and extremely weak CP-violation. Extension of MSM is necessary.

3. Baryo-thru-lepto. May work.

All three most popular scenarios do not predict observable proton decay and neutron-antineutron oscillations.

Baryogenesis at low temperatures with observable effects in particle physics is wanted.

Sakharov's conditions for generation of cosmological charge asymmetry:

1. **Charge nonconservation.**
2. **C and CP violation.**
3. **No thermal equilibrium.**

None is obligatory. **E.g. baryogenesis through BH evaporation with $\partial_\mu J^\mu_B = 0$.**

BARYOGENESIS IN LOW SCALE GRAVITY.

Advantages:

1. Easy breaking of equilibrium.
2. Possibility of stronger CP-violation.
3. Naturally large B-nonconservation.
4. Observable effects in particle physics.

Two mechanisms for TeV gravity:

1. Gravity lives in high dimensions, while matter lives in $D = 4$. Unification at EW?

2. Time variation of m_{Pl} due to coupling $\xi R \phi^2$. Initially all in EW scale.

Exponential or similar potential for ϕ is necessary.

High dimensional TeV gravity: strong nonconservation of global quantum numbers. Proton decay (Zel'dovich, 1976), three quarks form a black hole:

$$\tau_p \sim m_p^5 / m_{Pl}^4$$

For $m_{Pl} = 10^{19}$ GeV $\tau_p \sim 10^{45}$ years
But if $\mathrm{m_{Pl}} \sim$ TeV, $\tau_p \sim 10^{-11}$ s.
Similar problems for $\mu \to e\gamma$ and other rare decays.

Search for efficient low temperature baryogenesis scenarios with observable consequences for experiment, but without contradiction to existing bounds: long-lived proton, not too fast neutron-antineutron oscillations, etc.

SUSY with broken R-parity
(conservative possibility)

A.D., F. Urban, Nucl. Phys. B752 (2006) 297-315.

Enumerate possible operators, present experimental bounds and see what can be done with those still allowed.

Baryogenesis through B-nonconserving decays of SUSY particles

If M_{SUSY} is small, $M_{SUSY} \sim$ TeV, deviations from thermal equilibrium are negligible:

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

For large $M_{SUSY} \geq 10^{10}$ GeV, particle physics effects are very weak.

Possible solution: TeV gravity.
Higher dimensions may lead to too strong non-conservation of B and L in particle physics, if no mechanism for suppression is invented.
Time variation of G_N may be OK.

Some $\mathcal{R}$-parity -violating operators:

$$\mathcal{L}_{\mathrm{int}} = -\frac{1}{2}\lambda^{\mathrm{ijk}}\left(\tilde{\mathrm{u}}_{\mathrm{i}}^{*}\,\bar{\mathrm{d}}_{\mathrm{j}}\,\mathrm{d}_{\mathrm{i}}^{\mathrm{c}} + \tilde{\mathrm{d}}_{\mathrm{k}}^{*}\,\bar{\mathrm{u}}_{\mathrm{i}}\,\mathrm{d}_{\mathrm{j}}^{\mathrm{c}} + \mathrm{d}_{\mathrm{j}}^{*}\,\tilde{\bar{\mathrm{u}}}_{\mathrm{j}}\,\mathrm{d}_{\mathrm{k}}^{\mathrm{c}}\right) + h.c.$$

Non-conserved B and conserved L, allows for efficient baryogenesis and neutron oscillations, without proton decay.

Experimental constraints (from nuclear stability):
$\lambda_{112} < 10^{-6}$, $\lambda_{113} < 10^{-3}$,
while others could be well above unity.
λ_{112} leads e.g. to n$\bar{\Xi}$ - transformation. To make $n\bar{n}$ oscillations out of it a ΔS $= 2$ process is necessary. It is strongly suppressed in MSM (absence of strangeness changing neutral currents) but not so much in MSSM.

Hierarchy of constants may be related to that of quark masses(?).

In these frameworks is natural to expect

$$\tau(n-\bar{n}) \sim 10^9 \; sec$$

More exotic possibility: classical black hole conjecture, baryogenesis and rare processes.

C. Bambi, A.D., K. Freese,
Nucl. Phys. B763 (2007) 91;
JCAP 0704 (2007) 005.

How unwanted processes with $\Delta B \neq 0$ and $\Delta L \neq 0$ can be suppressed?

1. Higher scale gravity, $m_{Pl} \gg$ TeV.

2. Forbid easy formation of charged and spinning BH in low scale gravity.

In classical GR charged and rotating BH may be formed only if

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

If $M_{BH} < m_{Pl}$, BH must be neutral and non-rotating. Mixture of classical and quantum pictures.

ALARM:

Non-covariant perturbation theory with positive energy of virtual black hole states.

No crossing symmetry.

No Lorentz invariance?

No CPT?

More about baryogenesis in TeV gravity:

1. **Easy baryon non-conservation.**
2. **Large deviation from equilibrium.**
3. **Large CP-violation in MSM.**

CP-breaking in MSM:

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

where

$$J = sin\theta_{12} sin\theta_{23} sin\theta_{13} sin\delta \approx 3 \cdot 10^{-5}.$$

Thus $\epsilon_{CP} \sim 10^{-19}$ for $T \sim 100$ GeV.

With TeV gravity, baryon nonconservation might be significant at $T < 10$ GeV and CP-violation might be 10^{12} stronger.

If one allows for variation of quark masses, such that they were large at TeV scale, CP-violation would be unsuppressed.

Baryogenesis looks very efficient at relatively low T.

CONCLUSION.

1. Low scale gravity allows for an efficient baryogenesis.

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 non-conserving processes.
4. The probability of such rare processes as p-decay, $n\bar{n}$ oscillations, $\mu \to e\gamma$, $\mu \to 3e$ decays can be quite close to existing experimental limits.