Baryogenesis during thermalization
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Seminar: Thermalization in the early Universe

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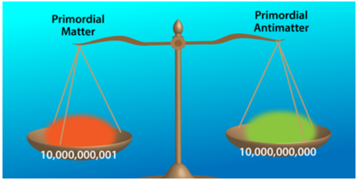

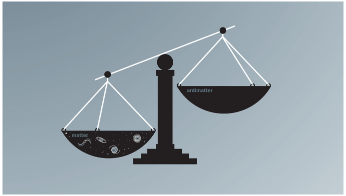

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[https://physics.aps.org/articles/v8/s17], [https://www.symmetrymagazine.org/article/october-2005/explain-it-in-60-seconds]

Outline

1. Baryogenesis
   - What is baryogenesis?
   - Necessary conditions
   - Source of B violation
   - Electroweak baryogenesis
2. Late Reheating, Hadronic Jets and Baryogenesis
   - Local overheating
   - Numerical estimates
   - Effects on baryogenesis
3. Conclusion

What is baryogenesis?

- Universe consists of matter, no antimatter
- present baryon abundance characterized by baryon-to-photon ratio

$$\eta_B = \frac{n_{B,0}}{n_{\gamma,0}} \simeq 6.05 \cdot 10^{-10}$$

or

$$\Delta_B = \frac{n_B - n_{\bar{B}}}{s} \simeq 0.86 \cdot 10^{-10}$$

* $\Delta_B = \mathrm{const.}$ in the hot stages of the evolution if there are no processes which
    - violate baryon number
    - produce large entropy

[Ch. 11 D. S. Gorbunov, V. A. Rubakov,"Introduction to the Theory of the Early Universe : Hot big bang theory"]

What is baryogenesis?

- natural assumption for initial state: baryon symmetry
- no easy explanation for the baryon asymmetry
  - ∗ produced during:
    - ▶ hot stage
    - ▶ earlier post-inflationary reheating epoch

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

[Mikhail Shaposhnikov 2009 J. Phys.: Conf. Ser.171 012005]

covered in [Ch. 11 D. S. Gorbunov, V. A. Rubakov,"Introduction to the Theory of the Early Universe : Hot big bang theory"]

covered in this talk

Necessary Conditions for Baryogenesis

- Sakharov conditions:
  1. Baryon number non-conservation
     - clear, otherwise no asymmetry
  2. C- and CP-violation
     - if C-/CP-invariance exact $\Rightarrow$ processes with q, l occur in the same way as $\bar{q}, \bar{l}$ $\Rightarrow$ no asymmetry
  3. Thermal inequilibrium
     - in th. equilibrium one would have $\Gamma(\Delta B < 0) = \Gamma(\Delta B > 0)$ (by definition: processes and their inverse processes have the same rates) $\Rightarrow$ no asymmetry

Source of B violation

- related to anomaly in baryonic current in SM (only left fermions interact with $F_{\mu\nu}$):

$$\partial^\mu j_\mu^B = 3\partial^\mu j_\mu^L = 3\frac{g^2}{32\pi^2} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- $$\Delta B = B(t_f) - B(t_i) = \int_{t_i}^{t_f} \mathrm{d}t \int \mathrm{d}^3x \partial^\mu j_\mu^B \quad \text{(similar for L)}$$

    * gives only (integer) non-zero values for strong fields $\sim g^{-1}$
    * B & L violation only when the system overcomes an energy barrier $E_{\mathrm{sph}} \sim M_W/g^2$

from now on: [Mikhail Shaposhnikov 2009 J. Phys.: Conf. Ser.171 012005], [Ch. 11 D. S. Gorbunov, V. A. Rubakov,"Introduction to the Theory of the Early Universe : Hot big bang theory"]

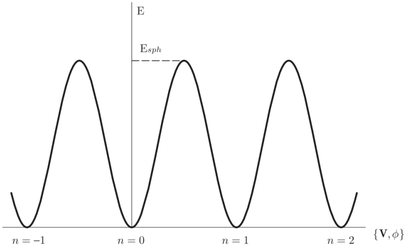
Source of B violation

- rate of B violation

$$\Gamma_{\mathrm{sph}} \sim \begin{cases} \exp\left(-\frac{4\pi}{\alpha_W}\right) \sim 10^{-160}, & T = 0 \\ \exp\left(-\frac{E_{\mathrm{sph}}}{T}\right), & T < T_c \\ \alpha_W^5 T^4, & T > T_c \end{cases}$$

- reactions are in th. eq. for

$$100\ \mathrm{GeV} \sim T_c < T < \alpha_W^5 M_{\mathrm{Pl}} \sim 10^{12}\ \mathrm{GeV}$$



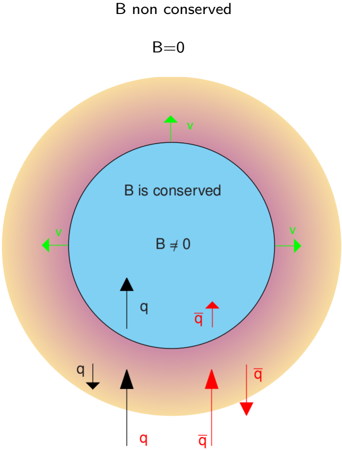
$\{V, \phi\}$ is the space of configurations; V: gauge fields, ϕ Higgs field

Electroweak Baryogenesis

- asymmetry may be generated around $T \sim 100$ GeV (end of th. eq. period)
- B violation only possible if EW phase transition is strongly 1st order
  - $*$ Γ_{sph} has to be smaller than H right after the phase transition
- 1st order phase transition:
  - $*$ creation of bubbles with the new phase $\rightarrow$ bubbles expand and percolate (strong inequilibrium phenomenon)
  - $*$ $\langle\phi\rangle = 0$ outside, $\langle\phi\rangle \neq 0$ inside
- outside the bubble B violation rate is large, inside small
- masses different inside and outside (inside interaction with ϕ)

Electroweak baryogenesis

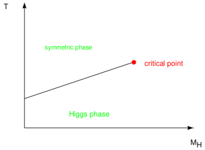
- non-eq. wall motion + fermion scattering on walls + CP-violation effects → separation of B (fermions go inside, anti-fermions stay outside)
- excess of anti-fermions outside destroyed by eq. sphaleron reactions, inside excess of fermions stays intact
- bubbles expand and broken phase finally fills the Universe, which is then baryon asymmetric



[Mikhail Shaposhnikov 2009 J. Phys.: Conf. Ser.171 012005]

Electroweak baryogenesis

- see if B asymmetry arises from electroweak anomaly: take a model and do explicit calculations
  - * first candidate: SM $\rightarrow$ is there a strong enough 1st order transition to suppress B violation after the transition?
    - phase diagram looks the same also in many extensions of the SM, just with different parameters on the horizontal axis
    - SM $\rightarrow$ all parameters besides M_H fixed experimentally $\rightarrow$ compute end point: $M_H \simeq 72$ GeV $< M_{H,\text{exp}} \approx 125$ GeV $\Rightarrow$ no phase transition in SM
  - * theories with extra scalar particles with masses ~ 100 GeV change strength of phase transition
    - theory with two Higgs doublets
    - extra singlet
    - Minimal Supersymmetric Standard Model (MSSM)



[M. Shaposhnikov 2009 J. Phys.:Conf. Ser.171 012005]

Electroweak baryogenesis

- strong 1st order transition in MSSM if lightest Higgs mass below 127 GeV and the right scalar top mass is below 120 GeV $\rightarrow$ in the range which could be tested at LHC
- one thing missing: correct amplitude of B violation
  - * encouraging: in many model calculations one obtains 10^{-10} for the right coice of parameters
  - * extra model constraints: sufficient amount of CP-violation
    - ▶ SM: only source CKM-phase (suppressed at high T)
    - ▶ extensions of SM contain extra sources of CP-violation $\rightarrow$ makes baryogenesis easier
    - ▶ new sources of CP-violation maybe measurable in next generation experiments for neutron electric dipole moment (EDM) measurement (zero if CP conserved); if EW baryogenesis is the origin of baryon asymmetry, EDM schould be measurable in beauty meson decays

Late Reheating, Hadronic Jets and Baryogenesis

- Goal: show how the late inflaton decay heats up the plasma non-uniformly
  - ∗ (local) temperature along trajectory of decay products is higher than the average temperature
  - ∗ in some parameter range T small enough to switch off sphaleron transitions, while they are possible in overheated regions $\rightarrow$ EW baryogenesis
    - ▶ advantage: no first order phase transition and therefore no bound on the Higgs mass

[T.Asaka et al., arXiv:hep-ph/0310100]

Local overheating

- M_ϕ inflaton mass, $\Gamma_\phi = f_\phi M_\phi$, $t_\phi = 1/\Gamma_\phi$
- reheating temperature: $T_R = \sqrt{f_\phi M_\phi M_0}$ with $M_0 = M_{\rm Pl}/1.66 g_*^{\frac{1}{2}}$
- interesting parameter range: $T_R < T_W \sim 100$ GeV (T_W: freezing of the sphaleron processes), $M_\phi > 10^{10}$ GeV, decay const. $f_\phi \sim 10^{-24}$ or smaller
- assume: $\phi \to q\bar{q}$ only
- n_ϕ decreases with time:

$$n_\phi a = n_0 e^{-\Gamma_\phi t} \qquad \text{(scale factor } a\text{)}$$

- first decays in vacuum $\to t \sim t_\phi$ inflatons surrounded by plasma ($T \sim T_R$)

Local overheating

- decay products (ultrarelativistic q) are injected into the medium and heat it locally
  - * What is the typical size and geometry of the overheated regions?
  - * What is the temperature in these regions?
- Quark energy loss in the medium:
  - * LPM effect
  - * non-abelian character of quark and gluon interactions

Local overheating

- largest amount of energy is lost by soft gluon emission (multiple scattering of hard partons with the plasma particles)
- energy spectrum I for $\omega_{\mathrm{BH}} \ll \omega \leq E_0$:

$$\omega \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z} = \frac{2}{\pi} \frac{\alpha_s}{\lambda_g} \sqrt{\frac{\omega_{\mathrm{BH}}}{\omega} \ln\left(\frac{\omega}{\omega_{\mathrm{BH}}}\right)}$$

  * ω gluon energy, E_0 parton energy, λ_g gluon mean free path, $\omega_{\mathrm{BH}} = \lambda_g \mu^2$ Bethe-Heitler frequency with screening mass μ
- stopping distance of initial parton:

$$L_{\mathrm{tot}} = \frac{\pi}{2} \frac{\lambda_g}{\alpha_s} \sqrt{\frac{E_0}{\omega_{\mathrm{BH}} \ln(E_0/\omega_{\mathrm{BH}})}} \quad \text{for} \quad E_0 \gg \omega_{\mathrm{BH}}$$

Local overheating

- average gluon energy: $\langle\omega\rangle = \sqrt{\omega_{\rm BH} E_0}/2$
- number of emitted gluons: $N_g = 2\sqrt{E_0/\omega_{\rm BH}}$
- if $\omega \gg \omega_{\rm BH}$ gluons loose the energy in the same way as the partons
  - * this cascade terminates as the gluon energies are of the order or smaller than $\omega_{\rm BH}$
- energy of n-th gluon in the cascade:

$$\langle\omega\rangle_n = \frac{1}{4^{1-1/2^n}}\omega_{\rm BH}\left(\frac{E_0}{\omega_{\rm BH}}\right)^{1/2^n}$$

  - * for $\langle\omega\rangle_0 = E_0$ to $\langle\omega\rangle_{\rm N_{BH}} \leq \omega_{\rm BH}$ typically 3-4 steps for $E_0 \sim 10^{10} - 10^{11}$ GeV

Local overheating

- radiation at frequency ω emitted in a small cone with angle θ

$$\theta_\omega^2 \simeq \frac{L_\omega \bar{\omega}_{\rm BH}}{\lambda_g^2 \omega^2} \quad \text{with} \quad L_\omega = \frac{2\pi}{9}\frac{\lambda_g}{\alpha_s}\sqrt{\frac{\omega}{\bar{\omega}_{\rm BH}}}, \; \bar{\omega}_{\rm BH} = \omega_{\rm BH} \ln(\omega/\omega_{\rm BH})$$

- transverse distance $r_\omega = L_\omega \theta_\omega$ traveled by a gluon:

$$r_\omega \simeq \left(\frac{2\pi}{9\alpha_s}\right)^{3/2} \frac{\lambda_g^{1/2}}{\omega_{\rm BH}^{1/4}\omega^{1/4}} \times \left[\ln\left(\frac{\omega}{\omega_{\rm BH}}\right)\right]^{-1/4}$$

(ln should be neglected at $\omega \sim \omega_{\rm BH}$)

- largest r_ω produced by gluons with lowest energy $\omega \simeq \omega_{\rm BH}$

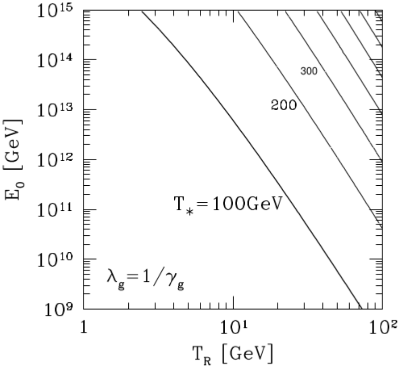
Local overheating

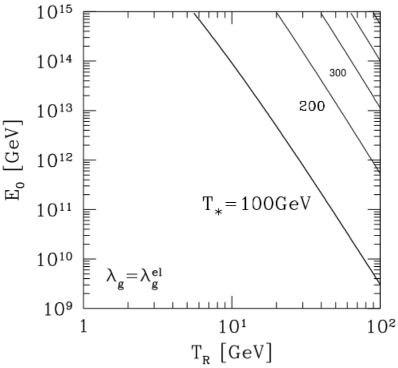
- overheated region: cylindrical form
  - $*$ length: $L_{\rm tot}$
  - $*$ radius: $r_* \simeq r_{\omega_{\rm BH}}$
  - $*$ volume: $V = \pi r_*^2 L_{\rm tot}$
- T estimate: (assume energy conservation and rapid thermalization)
  - $*$ effective temperature T_* from $\frac{\pi^2 g_*}{30} T_*^4 = \frac{E_0}{V}$:

$$T_* \simeq 5.3 \cdot 10^{-2} \left(\frac{100}{g_*}\right)^{1/4} \mu^{3/4} \left[\frac{E_0}{\lambda_g} \ln\left(\frac{E_0}{\omega_{\rm BH}}\right)\right]$$

Numerical estimates

- take values of μ from [K. Kajantie et al.,Phys. Rev. Lett. 79, 3130 (1997)], gluon mean free path λ_g^{el} from [Wang, Gyulassy, Plumer, Phys. Rev. D 51, 3436 (1995)] or gluon damping rate γ_g from [Braaten, Pisarski, Phys. Rev. D 42, 2156 (1990)] $\longrightarrow$ differ by one order of magnitude (uncertainty estimate)





- for $T_R = M_Z$, $E_0 = 10^{11}$ GeV $\Rightarrow T_* \simeq 212$ GeV ($\lambda_g = 1/\gamma_g$) or $T_* \simeq 151$ GeV ($\lambda_g = \lambda_g^{\rm el}$)

$\Rightarrow$ local temperature can exceed the freezing temperature of sphaleron processes (for high background temperature $T_R \gtrsim 10$ GeV and high parent parton energies $E_0 \gtrsim 10^{10}$ GeV)

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What are the effects on baryogenesis?

Effects on baryogenesis

- assumption: parameters of the inflaton are such that $T_* > T_{\rm sph} \sim 100$ GeV $> T_W$, with $T_{\rm sph}$ the temperature above which there is no suppression of the rate of sphaleron transitions $\Gamma_{\rm sph} \simeq \kappa\alpha_W^5 T_*^4$ ($\kappa \sim 10$)
- reheating temperature T_R can be small enough that B is conserved in regions which are not overheated
- estimate of baryon asymmetry:
  - ∗ number of sphaleron processes in overheated regions (asymmetrically due to CP-violation)

$$\frac{n_B}{s} \simeq \frac{n_{\rm parton}}{s} \times \kappa\alpha_W^5 T_*^4 V\Delta t \times \delta_{\rm CP}$$

  - ∗ $n_{\rm parton}$: highly energetic partons from ϕ decay, Δt: lasting time of rapid sphaleron processes, $\delta_{\rm CP}$: eff. magnitude of CP-violation

- 2 particle decay: $n_{\text{parton}} = 2n_\phi$ and $\frac{n_\phi}{s} \simeq \frac{3}{4}\frac{T_R}{M_\phi}$

$$\frac{n_B}{s} \simeq 10^{-8}\, T_R\, \Delta t\, \delta_{\text{CP}}$$

  * overheated regions must be in symmetric phase of EW theory (B violation is not suppressed there)
- overheated regions cool down and sphaleron processes stop at T_{sph}
  * estimates give: $\Delta t \simeq \frac{r_*^2}{4D}\left(\frac{T_*}{T_{\text{sph}}}\right)^4$, with $D \sim 1/\gamma_g \sim 0.1\lambda_g^{\text{el}}$
  * for a parameter region Δt is large enough to thermalize W-bosons (important for sphaleron processes)
- final result:

$$\frac{n_B}{s} \gtrsim (1-10)\cdot 10^{-7}\delta_{\text{CP}}$$

Conclusion

- Why does the Universe consist of matter?
  - ∗ Maybe EW baryogenesis can give the answer. Will be tested in the next generation experiments.
  - ∗ If EW baryogenesis is not the right model: there are others that could be tested experimentally: resonant leptogenesis (Nr. 17), baryogenesis via neutrino oscillations (Nr. 34).
- EW baryogenesis is possible in inflaton models with low reheating temperature
- plasma overheating takes place along the trajectories of the decay products of any heavy particle (if they interact with the plasma)
- in this hadronic jet approach there is no need for a 1st order phase transition (avoid bound on M_H)