Leptogenesis

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Given the broadness of the subject,

this will be an overview of some selected topics.

Apologizes if some interesting topics (and references) will not be covered.
Baryogenesis in a nutshell

Violation of Baryon Number (B);
Violation of C and CP;
Departure from Thermal Equilibrium

\[ \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.02 - 6.18) \times 10^{-10} \]

Planck Collaboration, arXiv:1807.06209

Dynamical mechanism for the generation of the matter-antimatter asymmetry (BAU) in the primordial Universe

Necessary requirements

The Standard Model cannot successfully account for the BAU. We need to look for Physics beyond the Standard Model.

**Baryogenesis**

Direct Baryogenesis: mechanism which created dynamically a baryon-antibaryon asymmetry.

Leptogenesis: First dynamical generation of a lepton asymmetry. Conversion of the lepton asymmetry into a baryon asymmetry, e.g. by B-L Sphalerons.

\[ \eta \leftrightarrow Y_{\Delta B} = A Y_{\Delta(B-L)} \]

System of Boltzmann’s equations

Source

State(s) generating the asymmetry e.g. out-of-equilibrium decaying heavy neutrino

\[ \frac{dY_N}{dT} = \ldots \]

Details of the system depend on the specific model

\[ \frac{dY_{\Delta(B-L)}}{dT} = \ldots \]
Leptogenesis requires violation of the lepton number (LNV).

Leptogenesis

Experimental tests

- Neutrinoless Double-beta decay
- Searches of extra neutrinos

Connection with other observables

Searches in Low energy experiments

Leptogenesis from Oscillations (ARS)
Asaka, Eijima, Ishida, 1112.5565
Asaka, Shaposhinokov, 0505013
Akhmedov, Rubakov, Smirnov 9803255

Leptogenesis from LPV decay of the Higgs
T. Hambye and D. Teresi arXiv:1606.00017
Eijima, Shaposhnikov 1703.06085
Eijima, Shaposhnikov, Timiryasov 1808.10833

Resonant Leptogenesis
A. Abada, H. Aissaoui, M. Losada 0406304

Possible connection with low energy phases. Lepton number violating processes

Thermal Leptogenesis
W. Buchmuller, P. Di Bari, M. Plumacher arXiv:0401240
R. Barbieri, P. Creminelli, A. Strumia, N. Tetradis
Case of study: interaction responsible of asymmetry generation associated to right-handed (sterile) neutrinos involved in the mass generation of active neutrinos.

Out-of-equilibrium (L-violating) decays of right-handed neutrinos produced in the Early Universe. CP-asymmetry generated by interference between tree level and loop diagrams.

\[ M_N > 100 \text{ GeV} \]

Examples of other possibilities (not exhaustive list):

- L. Covi, E. Roulet, F. Vissani 9605319
- S. Antush, S. F. King 0405093
- L. Boubekeur, T. Hambye, G. Senjanovic 0404038
- T. Hallgren, T. Konstandin, T. Ohlson 0710.2408
- T. Hambye 1212.2888
- T. Rink, W. Rodejohann, K. Schmitz 2006.03021

Asymmetry generated by CP-violating oscillation between extra neutrinos and active neutrinos

\[ M_N < 100 \text{ GeV} \]

L-violating decays of the Higgs
ARS Leptogenesis

(Ahmedov Rubakov Smirnov)

Right-handed neutrinos thermally produced in Early Universe with CP-violating oscillations.

Converted into baryon asymmetry by Sphalerons

Asymmetry converted into asymmetry between active flavors

Asymmetry in the active sector acts as background potential and enhances the asymmetry in the RH sector

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ARS Leptogenesis requires extra neutrinos to be at most as heavy as few tens of GeV.

Possibility of tests from low energy experiments.

A. Atre, T. Han, S. Pascoli, B. Zhang 0901.3589
Chrzaszcz et al: 1908.02302
The minimal realization of the ARS mechanism requires a pair of almost mass degenerate heavy (as opposed to active neutrinos) neutrinos.

M. Drewes, B. Garbrecht, D. Gueter, J. Klaric 1609.09609

P. Hernandez, M. Kekic, J. Lopez-Pavon, J. Racker, J. Salvador 1606.06719

L. Canetti, M. Drewes, T. Frossard, M. Shaposhnikov 1208.4607
In linear+inverse See-saw heavy neutrinos are pseudo-dirac

Inverse See-Saw

A. Abada, G.A., V. Domcke, M. Lucente 1709.00415
Including LNV decays of the Higgs

Leptogenesis from: Oscillations + LNV Decays

T. Hambye and D. Teresi arXiv:1606.00017

(See also Eijima, Shaposhnikov 1703.06085 Eijima, Shaposhnikov, Timiryasov 1808.10833)
Degeneracy removed for leptogenesis from 3 (or more) neutrinos. (Drewes and Garbrecht, arXiv:1206.5537
P. Hernandez, M. Kekic, J. Lopez-Pavon, J. Racker, N. Ruis 1508.03676)

A. Abada, G.A., V. Domcke, M. Drewes, J. Klaric, M. Lucente
arXiv: 1810.12463
Leptogenesis in low scale See-saw models is very promising for the variety of experimental tests.

Let’s now consider some intermediate scale scenarios ($10^3$–$6$ GeV).
TeV scale Leptogenesis in L-R model

See-saw based on $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

(See also A. Abada, P. Hosteins, F. Josse-Michaux, S. Lavignac 0808.2058)
$$R_L = \frac{\text{Same Sign}}{\text{Opposite Sign}} \text{Dileptons}$$

$pp \rightarrow W_R^\pm \rightarrow Nl^\pm$

Type-I See-saw.

Test mass degeneracy through charge asymmetries in $W_R$ decays.

P.S.B. Dev, R. Mohapatra, Y. Zhang, 1904.04787
Leptogenesis and neutrino option


Interesting possibility: Right-handed neutrino can provide successful leptogenesis and at the same time explain the generation of the EW scale and leptogenesis.

\[
\begin{align*}
1.2 \times 10^6 < M \ (\text{GeV}) &< 8.8 \times 10^6 & \text{Normal Ordering,} \\
2.4 \times 10^6 < M \ (\text{GeV}) &< 7.4 \times 10^6 & \text{Inverted Ordering.}
\end{align*}
\]
Finally an example of high energy See-saw.

\[ M_1 = 10^{10} \text{ GeV} \]

Leptogenesis is a viable option to explain the generation of the baryon asymmetry of the Universe.

It can be related to the origin of neutrino masses and many low energy observables.

Successful leptogenesis can occur for a broad range of New Physics Scales. Very challenging scenario to probe as a whole.

There are nevertheless interesting individual scenarios which can be tested at present and next future experimental facilities.