Lorentz Violation on The Primordial Baryogenesis.

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XII Mexican Workshop on Particles and Fields
Mazatlán, México,
November 13,2009

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REFERENCE

- Lorentz Violation on The Primordial Baryogenesis. J.A. and Pablo Gonzalez, e-Print: arXiv:0909.3883 [hep-ph]

BARYON ASYMMETRY

- Why is our Universe made of matter and not antimatter?
- Parameter $B = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$, $n_b/n_{\bar{b}}$:number of baryons/anti-baryon per unit volume, n_γ:photons number density at temperature T.
- Related previous work:
  CPT Violation and Baryogenesis, O. Bertolami, Don Colladay, V. Alan Kosteleckt̆y, and R. Potting, Phys. Lett. B395(1997)178.

LIV

- Quantum gravity Phenomenology: Strings, LQG,SME.
- $E^2 = v_{max}^2 p^2 + m^2 c^4$

BARYOGENESIS.

- Boson X that produces baryons and anti-baryons when decaying.
- Baryon number violation
- C and CP Violation, with CPT symmetry.

- Departure from Thermal Equilibrium.
Boltzmann Equation:

$$\frac{\partial n(t)}{\partial t} + 3H(t)n(t) = \frac{g\, v_{max}}{(2\pi\hbar)^3} \int \hat{C}[f] \frac{d^3p}{E}$$

- Simpler model:

$$|\, M(X \rightarrow b + b)\,|^2 = |\, M(\bar{b} + \bar{b} \rightarrow X)\,|^2 = \frac{1}{2}(1 + \epsilon)\,|\, M_0\,|^2$$

$$|\, M(X \rightarrow \bar{b} + \bar{b})\,|^2 = |\, M(b + b \rightarrow X)\,|^2 = \frac{1}{2}(1 - \epsilon)\,|\, M_0\,|^2$$

Where $|\, M_0\,|^2$ is constant.

THRESHOLD ENERGY AND COLLISION FACTOR.

- For a process $a + b \longrightarrow 1 + 2 + ...$, the threshold condition is given by:

$$E_a + E_b \geq \sum_i E_i \quad p_a - p_b = \sum_i p_i$$

Since a and b go from one to the other(head on collision) and the particles i go in the same direction.

Reactions Allowed Zones

$X \longrightarrow b_1 + b_2$, b_i can be a baryon or anti-baryon.

- If $v_b > v_X$:

$$p_X \leq \sqrt{\frac{m_X^2 - 4m_b^2}{(v_b^2 - v_X^2)}} c^2 \quad p_b \leq \sqrt{\frac{m_X^2 - 4m_b^2}{4(v_b^2 - v_X^2)}} c^2$$

If we use $m_X \gg m_b$ and $\partial\alpha = \alpha_X - \alpha_b$, it is reduced to:

$$p_X \leq \frac{m_X c}{\sqrt{2\partial\alpha}} \quad p_b \leq \frac{m_X c}{2\sqrt{2\partial\alpha}}$$

- If $v_b \leq v_X$, we do not have a bound, since p_X^2, $p_b^2 \geq 0$.

$\boldsymbol{b_1 + b_2 \longrightarrow X}$

- $p_{b_1} \geq \dfrac{-v_b|p_X| + E_X}{2v_b}$

Collision Factor and Departure from Equilibrium Condition

- The Collision Factor is:

$$\frac{g\, v_{max}}{(2\pi\hbar)^3} \int \hat{C}[f] \frac{d^3 p}{E} = - \int (2\pi\hbar)^4 \delta^4 (p_X - p_{b_1} - p_{b_2})\, \Upsilon_{X, b_1, b_2}\, d\Pi_1 d\Pi_2 d\Pi_X$$

$$\Upsilon_{X, b_1, b_2} = f_X \left(\mid M(X \to b_1 + b_2) \mid^2 + \mid M(X \to \bar{b_1} + \bar{b_2}) \mid^2 \right)$$

$$- f_{b_1} f_{b_2} \,|\, M(b_1 + b_2 \rightarrow X)\,|^2 - f_{\bar{b}_1} f_{\bar{b}_2} \,| \\ M(\bar{b_1} + \bar{b_2} \rightarrow X)\,|^2$$

Where f_X, f_{b_i} and $f_{\bar{b}_i}$ are Boson, baryons and anti-baryons distribution functions respectively, and $d\Pi_i = \frac{g_b v_b}{(2\pi\hbar)^3}\frac{d^3 p_{b_i}}{2E_{b_i}}$ and $d\Pi_X = \frac{g_X v_X}{(2\pi\hbar)^3}\frac{d^3 p_X}{2E_X}$.

- In the high temperature approximation:

$$f_X = e^{-\frac{E_X - \mu_X}{k_B T}}$$

$$f_{b_i} = e^{-\frac{E_{b_i} - \mu}{k_B T}} \quad f_{\bar{b}_i} = e^{-\frac{E_{\bar{b}_i} + \mu}{k_B T}}$$

μ_X, μ are the boson and baryon chemical potential.

- Bosons, baryons and anti-baryons are still in chemical equilibrium with the thermal bath. So we have that $\mu_{b_i} = -\mu_{\bar{b_i}} = \mu$.

-
$$\frac{\partial n(t)}{\partial t} + 3H(t)n(t) = \frac{g_b^2 g_X v_X}{4 v_b (2\pi\hbar)^5} |M_0|^2 \left(I^{Neq}_{b_1,b_2,X} - I^{eq}_{b_1,b_2,X} \right)$$

$$I^a_{b_1,b_2,X} = \frac{f^a_X \delta^4(p_X - p_{b_1} - p_{b_2})}{2E_{b_1}E_{b_2}E_X} v_b^3 d^3 p_{b_1} d^3 p_{b_1} d^3 p_X$$

$I^{eq}_{b_1,b_2,X}$ and $I^{Neq}_{b_1,b_2,X}$ contains the distribution with and without equilibrium respectively and $p_i = [E_i; v_{max,i}\vec{p}_i]$

- We obtain, with:

$$\begin{aligned} a &= -(2v_b v_X |\vec{p}_{b_1}||\vec{p}_X|)^2 \\ b &= 4v_b v_X |\vec{p}_{b_1}||\vec{p}_X|\cos(\theta_X)(2E_X E_{b_1} - m_X^2 c^4) \\ c &= (2v_b v_X |\vec{p}_{b_1}||\vec{p}_X|\sin(\theta_X))^2 - m_X^4 c^8 - \\ & \quad 4E_X^2 E_{b_1}^2 + 4E_X E_{b_1} m_X^2 c^4 \end{aligned}$$

$$I^a_{b_1,b_2,X} = \frac{\pi}{v_b^3 v_X}$$

$$\int \frac{f_X^a \Theta(E_X - E_{b_1})\Theta(b^2 - 4a\,c)}{E_X p_X} d\,E_{b_1} d^3 p_X$$

Where we have used that $E_{b_1} = v_b p_{b_1}$. Analyzing the second Heaviside's, we can see that its argument is positive if:

$$\frac{E_X - v_X p_X}{2} \leq E_{b_1} \leq \frac{E_X + v_X p_X}{2}$$

X Decay $(a = N\,e\,q)$

- $v_b \leq v_X$

  $$I^{Neq}_{b_1,b_2,X}(v_b \leq v_X) = \frac{\pi}{v_b^3} \int \frac{f_X}{E_X} d^3 p_X \text{With: } 0 \leq p_X \leq \infty$$

  No difference to the case without Lorentz Violation

- But, if $v_b > v_X$ we have:

$$
\begin{aligned}
I^{Neq}_{b_1,b_2,X}(v_b > v_X) \;=\; & \frac{\pi}{v_b^3} \times \\
& \left[\int \frac{f_X}{E_X} d^3 p_X + \frac{4\pi y\, v_b}{v_X^3} \int_B f_X d\, E_X \right. \\
& \left. - \frac{4\pi}{v_X^3} \int_{B+C} E_X f_X d\, E_X \right]
\end{aligned}
$$

with $A \rightarrow (p_X \leq y)$, $B \rightarrow (y \leq p_X \leq 2y)$ and $C \rightarrow (p_X \geq 2y)$, where $y = \frac{m_X c}{2\sqrt{2\partial\alpha}}$

The integration zone in the first integral extend to all momenta.

Inverse X Decay $(a = e\,q)$

- $v_b \leq v_X$

$$I^{eq}_{b_1,b_2,X}(v_b \leq v_X) = \frac{\pi}{v_b^3} \int \frac{f_X^{eq}}{E_X} d^3 p_X$$

- $v_b > v_X, \quad I^{eq}_{b_1,b_2,X}(v_b > v_X)$

$$= \frac{\pi}{v_b^3} \left[\int \frac{f_X^{eq}}{E_X} d^3 p_X - \frac{4\pi}{v_X^3} \int_C f_X^{eq} E_X d\,E_X \right]$$

Differential Equation Solution and Analysis

- If $v_b \leq v_X$:

$$\ddot{n}(t) + 3\left[\dot{H}(t)n(t) + H(t)\dot{n}(t)\right] = M(t)[n_X^{eq}(t) -$$

$$n_X(t)] + \mu_X \frac{\partial \beta}{\partial t} \frac{e^{\beta\mu_X}}{e^{\beta\mu_X} - 1} [\dot{n}(t) + 3H(t)n(t)]$$

- If $v_b > v_X$:

$$\ddot{n}(t) \;+\; 3\Big[\dot{H}(t)n(t) \;+\; H(t)\dot{n}(t)\Big] \;=\; M(t)\Big[n_X^{eq}(t) - n_X(t) + \frac{4\pi g_X}{v_X^3(2\pi\hbar)^3}\frac{\partial J}{\partial \beta}\Big]$$

$$+ \quad \mu_X \frac{\partial \beta}{\partial t} \frac{e^{\beta \mu_X}}{e^{\beta \mu_X} - 1} [\dot{n}(t) \quad + \\ 3H(t) n(t)]$$

With $M(t) = \frac{g_b^2 v_X}{16 \pi v_b^4 \hbar^2} \mid M_0 \mid^2 \frac{\partial \beta}{\partial t}$

$$J = \frac{1}{\beta^2} e^{-\beta y v_b} \left[e^{-\beta y v_b} (2 \beta y v_b + 1) - \right. \\ \left. e^{\beta \mu_X} \left(\beta y v_b e^{-\beta y v_b} + 1 \right) \right]$$

LIV IN BARYOGENESIS

* LIV in Baryogenesis

$$F(\ddot{n}_X, \dot{n}_X, n_X, \mu_X) \propto -H(t)T^2 \propto -T^4$$

where F is the usual differential equation that represents Baryogenesis without Lorentz violation (or $v_b \leq v_X$). As the Baryogenesis temperature is very high (Grand Unification Level), the Lorentz violation effect, when the Baryogenesis starts, is very important; whenever $v_b > v_X$. The effects of this factor on the solution will be seen in a subsequent work. So far, the important result is that it is possible to find a trace of a possible Lorentz violation in the Baryogenesis.

TEMPERATURE OF BARYOGENESIS

- Temperature at the beginning of the Baryogenesis:

  Remembering the bound found with the Threshold Energy for the boson decay, if $v_b > v_X$:

$$p_X \leq \frac{m_X c}{\sqrt{2\partial\alpha}}$$

we can find a limit to the temperature when these reactions start. We are looking for the temperature to fullfill that:

$$\langle p_X \rangle = \frac{m_X c}{\sqrt{2\partial\alpha}}$$

For this, we need the relation between average momentum and temperature. Using a Fermi statistic and $E_X = v_X p_X$, we obtain:

$$\langle p_X \rangle = \frac{k_B T \pi^4}{30 c \zeta(3)}$$

So, the temperature at the beginning of the Baryogenesis is:

$$k_B T_B = \frac{30\zeta(3) m_X c^2}{\pi^4 \sqrt{2\partial\alpha}}$$

$$\frac{k_B T_B}{m_X c^2} \approx 0.3702 \times 10^{11}$$

Where we used $\partial\alpha = 5 \times 10^{-23}$. As the energies are in the Grand Unification level, it is required that $k_B T_B \gtrsim 10^{16}$ [GeV]. Then:

$$m_X c^2 \gtrsim 2.7012 \times 10^5 [GeV]$$

So, in spite of having an extremely high mass ($m_X \gg m_b$), these values are far below of the Grand Unification level (Desert). So, it is possible that the X Boson would be observed in the LHC where the maximum energies are $\sqrt{s} = 14$ [TeV] in proton-proton collisions.

CONCLUSIONS AND OPEN PROBLEMS.

- If the baryon and boson maximum velocities are related by $v_b > v_X$, an important LIV contribution to Baryogenesis appears.

- We estimated a condition for the moment when the Baryogenesis begun, given by the LIV. This condition tells us that $k_B T_B = 0.262 \times 10^{11} m_X c^2$. Then the majority of bosons start to decay.

- $$m_X c^2 \gtrsim 2.7012 \times 10^5 [GeV]$$

  So, it is possible that the X Boson would be observed in the LHC where the maximum energies are $\sqrt{s} = 14$ [TeV] in proton-proton collisions.

- OPEN PROBLEM: To estimate the effects of dilution mechanisms(sphalerons).

THANK YOU!