Baryogenesis and Leptogenesis

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Last time

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- The question: Why $n(\overline{B}) \ll n(B)$ and $\eta \sim 10^{-10}$
- Answer: Baryogenesis and the Sakharov's conditions
- Model buildings

Today: The SM, CPV and start of model for BG

Basics of model building

$$\mathcal{L} = ?$$

Axioms of physics

1. Gauge symmetry
2. representations of the fermions and scalars (irreps)
3. SSB (relations between parameters)

Then $\mathcal{L}$ is the most general renormalizable one

Renormalzabilty and all that

What is a renormalizable field theory?

Please write it down!

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No operators with negative dimensions couplings

- $m\bar{\psi}\psi$
- $Y_h H\bar{\psi}\psi$
- $G(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)$

But what is the physics?

IR, UV and renormalizability

- The dimension tells us when an operator is important
- Consider standard dispersion relation

$$E^2 = p^2 + m^2$$

  - At the IR, low energy, $E \approx m$
  - At the UV, high energy, $E \approx p$
- What if

$$E^2 = m^2 + p^2 + \frac{p^4}{\Lambda^2} \, ?$$

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It is all about Λ

- For $p \ll \Lambda$ the last term in not important
- For $p \gg \Lambda$ the last term is important

MDR: Modified Dispersion Relation

$$E^2 = m^2 + p^2 + \frac{p^4}{\Lambda^2}$$

- Is the MDR Lorentz invariance?
- Is the MDR excluded experimentally?
- What can we say about Λ?

MDR: Modified Dispersion Relation

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- Is the MDR Lorentz invariance?
- Is the MDR excluded experimentally?
- What can we say about Λ?

- All we can say is that experimentally Λ is large compare to any scale we probed
- This is not the same as saying that we know $\Lambda \to \infty$. We set $\Lambda \to \infty$ since we deal with "low energy"

Back to QFT

- NR terms just refer to terms that are important at the UV
- When we construct a theory, at first we set all the NR terms to zero since we care about low energy
- At later stages, when we care about small corrections at “low” energies, we may add them
- Important: We are modest! We do not try to explain physics at energies we cannot probe
- The issue of mathematical consistency is just the above statement. It is inconsistent to use NR theories to explain physics at very high scale.

Global and Accidental symmetries

We only impose gauge (or local) symmetries

- Well, they are nicer (think about it...)
- There is an argument that quantum gravity always break them (so what?)
- We like to think that all global symmetries are accidental. They are there just because the field choices and the requirement of renormalizability
- Global symmetries can be there at the “classical” level but be broken at the quantum level (anomalies)
- We think all symmetries are either local or broken!

Lepton and baryon numbers

- The SM has a $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ global symmetry
- Only leptons carry L and only quarks carry B
- All processes observed so far conserve L and B
- Processes that violate it, like $P^+ \to e^+\gamma$, were not observed
- Baryon and lepton number are accidental symmetries of the SM
- B$+$L is broken by an anomaly
- B and L are broken by NR operators. Can you think of such operators?

Discrete space time symmetries

C, P, and T

- Any Local Lorentz invariant QFT conserves CPT
- No theoretical reason for C, P or T to be conserved separately
- In the SM the weak interaction breaks them all. This is also what we see in Nature.
- Any chiral theory break C and P
- The condition for CP violation is more complicated: a phase in $\mathcal{L}$

The SM

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A working example: the SM

- Symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- irreps: 3 copies of QUDLE fermions

$$Q_L(3,2)_{1/6} \quad U_R(3,1)_{2/3} \quad D_R(3,1)_{-1/3}$$
$$L_L(1,2)_{-1/2} \quad E_R(1,1)_{-1}$$

- SSB: one scalar with negative μ^2

$$\phi(1,2)_{+1/2} \qquad \langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$
$$\Rightarrow \quad SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

Then Nature is given by...

the most general $\mathcal{L}$

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

- Kinetic terms give rise to the gauge interactions
  - The Gauge interactions are universal (better emphasis that!)
  - 3 parameters, g, g' and g_s
  - In the SM only LH fields participate in the weak interaction
- The Higgs part gives the vev and the Higgs mass. 2 parameters
- Yukawa terms: $H\bar{\psi}_L\psi_R$. This is where flavor is. 13 parameters, one phase that lead to CPV

Quarks

$$Y_{ij}^{D}\left(\bar{Q}_L\right)_i \phi \left(D_R\right)_j + Y_{ij}^{U}\left(\bar{Q}_L\right)_i \tilde{\phi} \left(U_R\right)_j$$

- The Yukawa matrix, Y_{ij}^{F}, is a general complex matrix
- After the Higgs acquires a vev, the Yukawa terms give masses to the fermions. Also, after the breaking we can talk about U_L and D_L, not about Q_L
- If Y is not diagonal, flavor is not conserved
- If Y carries a phase, CP is violated. C and P are violated to start with

The CKM matrix

It is all about moving between bases...

- We can diagonalize the Yukawa matrices

$$Y_{\rm diag} = V_L Y V_R^\dagger, \qquad V_L, V_R \text{ are unitary}$$

- The mass basis is defined as the one with Y diagonal, and this is when

$$(d_L)_i \to (V_L)_{ij}(d_L)_j, \qquad (d_R)_i \to (V_R)_{ij}(d_R)_j$$

- The couplings to the photon is not modifies by this rotation

$$\mathcal{L}_\gamma \sim \bar{d}_i \delta_{ij} d_i \ \to \ \bar{d}_i V \delta_{ij} V^\dagger d \sim \bar{d}_i \delta_{ij} d_i$$

CKM, W couplings

- For the W the rotation to the mass basis is important

$$\mathcal{L}_W \sim \bar{u}^i_L \delta_{ij} d^i_L \;\to\; \bar{u}_i V_L^U \delta_{ij} V_L^{D\dagger} d \sim \bar{u}_i V_{CKM} d_i$$

where

$$V_{CKM} = V_L^U V_L^{D\dagger}$$

- The point is that we cannot have Y_U, Y_D and the couplings to the W diagonal at the same basis
- In the mass basis the W interaction change flavor, that is flavor is not conserved
- The CKM matrix is very close to a unit matrix. Off diagonal terms are very small

CPV

What is CP

- A symmetry between a particle and its anti-particle
- CP is violated if we have

$$\Gamma(A \to B) \neq \Gamma(\bar{A} \to \bar{B})$$

- It is not easy to detect CPV
  - Always need interference of two (or more) diagrams
  - CPT implies that total width are the same, so we need at least two modes with CPV
  - To see CPV we need 2 amplitudes with different of both weak and strong phase

CP violation

A simple "hand wave" argument of why CP violation is given by a phase

- It is all in the $+h.c.$ term

$$Y_{ij}\left(\bar{Q}_L\right)_i \phi\,(D_R)_j + Y^*_{ji}\left(\bar{D}_R\right)_j \phi^\dagger\,(Q_L)_i$$

- Under CP

$$Y_{ij}\left(\bar{D}_R\right)_j \phi^\dagger\,(Q_L)_i + Y^*_{ji}\left(\bar{Q}_L\right)_j \phi\,(D_R)_i$$

- CP is conserved if $Y_{ij} = Y^*_{ji}$
- Not a full proof, since there is still a basis choice...

All these phases

Weak phase (CP-odd phase). Change sign under CP

$$CP(Ae^{i\phi}) = Ae^{-i\phi}$$

- Phase in $\mathcal{L}$

$$\mathcal{L} \propto V_{ub}\,\bar{u}\,b\,W^+ + h.c. \qquad CP(\mathcal{L}) \propto V_{ub}^*\bar{u}\,b\,W^+ + h.c.$$

- In the SM the CP odd phases arise only in the weak part so they are called weak phases
- In the SM all these phases are related to the one physical phase, $\delta_{\rm KM}$

All these phases: Strong phases

Strong phase (CP-even phase). Do not change under CP

$$CP(Ae^{i\delta}) = Ae^{i\delta}$$

- Due to time evolution

$$\psi(t) = e^{-iHt}\psi(0)$$

- They are also due to intermediate real states.
- When we have strong interactions, these phases have to do with “rescattering” of hadrons
- Such strong phases are very hard to calculate

Why we need the two phases?

Intuitive argument

- If we have only one amplitude $|A|^2 = |\bar{A}|^2$
- Two but only with a different of weak phase

$$\left|A + be^{i\phi}\right|^2 = \left|A + be^{-i\phi}\right|^2$$

- When both are not zero it is not the same (do it for HW!)

$$\left|A + be^{i(\delta-\phi)}\right|^2 - \left|A + be^{i(\delta+\phi)}\right|^2 = 4Ab\sin\delta\,\sin\phi$$

Some summary

- Model building is based on axioms: Gauge symmetries, field content and SSB
- The Lagrangian is the most general renormalizable one
- Renormalizability is really the point that we don't try to explain physics at very short distance
- Now that we have the Lagrangian, what can we do with it?
  - Measure its parameters
  - Make predictions and test them

Back to Baryogenesis

Baryogenesis in the SM?

Based on what we talked

- The SM has C violation (like any chiral model)
- There is CP violation. It is, however, in the flavor sector and requires 3 generations
- Baryon number is an accidental symmetry
- Did not even talk about the out of equilibrium condition

We will show later that one can have BG in the SM, but it is not “simple”

Total asymmetry

Consider decays of particle X that generate baryons

$$\eta = N_I \, \epsilon \, \eta_a$$

- N_I is the initial density of X at $T \gg m_X$

$$N_I = \frac{\# \times \zeta(3)}{g_*}$$

- $\epsilon < 1$ is the CP violation asymmetry
- $\eta_a < 1$ is an efficiency factor due to “washout” effects

Heavy particle decays

What is needed for X decays to generate Baryon asymmetry?

- X can decay in a Baryon number violating way
- CP violation from interference between tree and loop diagrams
- Strong phase arises when the loop diagram internal fields on-shell
- The decay is when the heavy particle is out of equilibrium (roughly when $T < M$)
- GUT baryogenesis is an example of such a scenario