Hidden Sector Baryogenesis

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Basic Issue

• low-energy interactions seem to preserve baryon number
  – but world has more baryons than anti-baryons
  – how can we generate this asymmetry?
    • baryogenesis
  – Sakharov conditions
    • B violation (obvious)
    • C and CP violation (otherwise, create baryon/anti-baryons at same rate)
    • out-of-equilibrium (can’t generate asymmetry in thermal equilibrium)
A few major models

- some major ideas
  - GUT baryogenesis
  - Affleck-Dine
  - leptogenesis

- electroweak baryogenesis
  - treat $U(1)_B$ as a global symmetry
  - left-handed quarks have weak interactions, but not right-handed
    - mixed anomaly $U(1)_B - SU(2)_L^2$
    - anomaly provides B violation via sphalerons (1 negative eigenval.)
      - sphaleron processes transition between different electroweak vacua, which changes baryon number

$$\partial_\mu J_B^\mu \propto \text{Tr}[F_W \wedge F_W] = \partial_\mu n_{CS}^\mu(A_W)$$
So, what happens?

• need EWPT to be 1st order
• need C and CP violation
  – CKM not enough
  – need complex Higgs phase
• as universe cools, $T$ drops below $T_c$
  – bubbles nucleate
• at bubble walls
  – out of equilibrium
  – CP and B violation
  – end up with net baryon flow into broken region
• technical details depend on details of electroweak parameters
Constraints on EWBG

- need sphalerons to shut down after transition
  - otherwise “washout”
  - need $\langle \phi \rangle \gg T_C$

- electroweak data
  - need EWPT - 1st order
  - need sphalerons to shut down
    - constraint on $m_H$
  - need large enough CP violation
    - leads to EDM constraints

- status of EWBG
  - EWBG in SM
    - need $m_H < 70$ GeV to get first order phase trans.
    - ruled out
  - in MSSM
    - need $m_H < 120$ GeV
      - $120$ GeV $< m_{\text{stop}} < m_{\text{top}}$
    - LEP $- m_H > 114$ GeV
    - tight squeeze
  - in NMSSM
    - extra degrees of freedom
    - easier constraints
Our angle → Top down

• start from a string construction of SM-like effective field theory (we’ll use *intersecting brane models*)
  – is there a “natural” way to get baryogenesis in this class of models?
  – Start with IBM motivation, but not tied down to a specific model → “IBM motivated” but an EFT model

• IBM set-up → IIA compactified on orientifolded CY-3-fold – *N=1 SUSY*
  – D6-branes fill space-time, wrap 3-cycle
  – SM gauge theory on branes
    • $\text{SU}(3) \times \text{SU}(2)_L \times \text{U}(1)_Y \times \text{hidden}$
Branes and Matter

- **chiral matter** arises from strings living at topological intersection of branes
- divide up branes into two classes
  - "visible" sector branes $\rightarrow$ SM particles arise from strings which begin and end on these branes
  - "hidden" sector branes $\rightarrow$ the rest
- hidden sector branes are generic
  - we need them to cancel space-filling charges (RR tadpoles must vanish)

- $I_{ab}$ chiral multiplets in the bifundamental of $G_a \times G_b$
Generic anomalies

• but net chiral multiplets in bifund. of $G_a \times G_b$ gives a mixed anomaly $U(1)_a - G_b^2$

• is this generic? yes

• take $T^6/Z_2 \times Z_2$
  – generically, $I_{ab} \neq 0$

• also non-zero for more generic CY compactification
  – cycles $\alpha_i, \beta_i \rightarrow$ say a wraps $\alpha_1$
  – $I_{ab} = 0$ only if $b_1 = 0$

\[ I_{ab} = \prod_{i=1}^{3} (n_i^a m_i^b - m_i^a n_i^b) \]

\[ \int \int \Omega \wedge \overline{\Omega} = \delta_i^j \sum a^i \alpha_i + b^j \beta^j \]
So what’s the upshot?

- have brane stack “b” where SU(3)_{qcd} lives
  - U(1)_B is the diagonal subgroup of U(3)_{qcd}
- hidden sector group G lives on brane stack “g”
  - generically, l_{bg} is non-zero
  - chiral matter transforming under U(1)_B and G
  - U(1)_B-G^2 mixed anomaly
  - G-sphaleron/instanton processes violate baryon number
- can use this to get baryogenesis in IBM

\[ \partial_\mu J^\mu_B \propto \text{Tr}[F_G \wedge F_G] \]
What do we need?

• **all cubic anomalies must cancel**
  – automatic in IBM (RR-tadpole cancelation)

• **non-vanishing \( U(1)_B \)-\( G^2 \) anomaly**

• **vanishing \( U(1)_Y \) anomaly**
  – easy to arrange – \( U(1)_Y \) arises a lin. comb. of several \( U(1)'s \) – can find a set which is non-anomalous
  – needed for viable IBM

• **Yukawa coupling permitting exotic baryon decay to SM baryons**
  – can also arrange in IBM – fields with appropriate charge arise from generic intersections
    • **worldsheet instantons** generate coupling
Specific Model

- **4 stacks**
  - a – $U(3)_{qcd}$
  - b – $U(1)_{T3R}$
  - c – $U(1)_L$
  - g – hidden group $G$
- more hidden sectors to cancel RR-tadpoles
- exotic chiral mults. are $q$, $\lambda$, $\eta$, $\xi$
- $I_{ag}=2$, $I_{gb}=4$, $I_{gb'}=1$, $I_{cg}=1$
- no $U(1)_Y$ anomaly
- but $U(1)_B$, $U(1)_{B-L}$ anomaly

\[
U(1)_Y = \frac{1}{2} \left( U(1)_B - U(1)_L + U(1)_{T3R} - U(1)_G \right)
\]

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So what happens…?

- like in EWBG, T drops as universe expands
  - at $T=T_C$, we have a phase transition where $G$ either breaks or confines
    - needed for viable IBM, else chiral exotic fermions
- if transition is 1st order, nucleate bubbles of broken symmetry vacuum
  - at bubble walls, out of equilibrium
  - can have C and CP violation generically in G sector
    - G-sphalerons/instantons violate $B$
    - all Sakharov conditions satisfied
- so in this IBM scenario, baryon asymmetry can be generated
Points to note

• this is “natural” in IBMs
  – many hidden sectors
  – each generically has anomaly with $U(1)_B$
  – each must break/confine to avoid exotics (good IBM)
  – if even one has 1st order transition $\rightarrow$ it can work

• generic $U(1)_{B-L} - G^2$ anomaly
  – EW sphalerons cannot wash out asymmetry even if generated above weak scale
  – avoids trouble with GUT baryogenesis
  – B-L anomaly could vanish (say Pati-Salam), but still works if G breaks at or below EW scale – gravity mediation

• details (like strength of transition, transport mech., local or non-local, etc.) are model dependent
  – not boxed in the way EWBG is
Can also realize **HSB at inflation’s end**

- Louis discussed an inflation scenario in IBMs \( \rightarrow \) inflaton and waterfall fields are bi-fundamentals
- when waterfall field condenses, energy dumped into long-wavelength modes
  - tachyonic preheating (FGGKLT)
  - can excite sphaleron
- during tachyon condensation, out of equilibrium
- if \( I_{bg} \neq 0 \rightarrow U(1)_B G^2 \) mixed anomaly
  - baryon violation
  - with C and CP violation, can get baryogenesis
- Tranberg & Smit showed (numerically) that one can generate baryons in EWBG with tachyonic preheating
  - problem \( \rightarrow \) low inflation scale
- since HSB has \( U(1)_{B-L} G^2 \) mixed anomaly, can work at higher scale
- whether numerics work out is model specific....