Baryogenesis
and
Searches for Nucleon Decay

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TRIUMF

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Japan-North America Collaboration

4.6 × 10^6
944 735 km^2

27.5 × 10^6
695 662 km^2

127 × 10^6
377 962 km^2
Invitation to TRIUMF

• TRIUMF is Canada’s national laboratory for particle and nuclear physics and accelerator-based science.
Invitation to TRIUMF

- TRIUMF is Canada’s national laboratory for particle and nuclear physics and accelerator-based science.

- On-site program is driven by a 500 MeV proton cyclotron:
  - rare-isotope beams for fundamental nuclear physics
  - ultra-cold neutron facility (with Osaka U)
  - muons for materials science
  - nuclear medicine and isotope production

- Off-site program is very diverse:
  - ATLAS, T2K, SNOLab projects, EXO/nEXO, NA62, ...
Some Areas of Collaboration

• particle and nuclear physics theory
• ATLAS collaboration
• T2K/HyperK collaboration
• accelerator technology for a linear collider and more
• EXO/nEXO, DEAP, SuperCDMS, ...
• RIKEN-TRIUMF shared offices
• TRIUMF-Osaka project on ultra-cold neutrons
• J-PARC-TRIUMF (g-2) experiment
Baryons
and
Baryogenesis
Energy Content of the Universe

Ordinary Matter = baryons, mostly free H and He

- Dark Matter: 26.8%
- Ordinary Matter: 4.9%
- Dark Energy: 68.3%

[ESA]
Baryons in the Universe: CMB

\[
\frac{\rho_B}{\rho_{\text{tot}}} \equiv \Omega_B = 0.047(3)
\]
Baryons in the Universe: Nucleosynthesis

CMB value
Baryons vs. Antibaryons

• We only see baryons today, not antibaryons.

• Questions:
  • Why the asymmetry?
  • Can we explain the density of baryons with the SM?

• Inflation is expected to wash out any “initial” asymmetry.

• A mechanism for Baryogenesis is needed to address these questions.

• Note: \( \frac{\rho_B}{\rho_{\text{tot}}} = 0.047 \Rightarrow \frac{n_B}{n_\gamma} = 6.1 \times 10^{-10} \)

Doesn’t seem so hard...
The Story of Baryons

1. Inflation and reheating happens.
   The universe emerges very hot and very uniform.

2. Baryogenesis happens.
   More baryons are created than antibaryons.

3. Baryons and antibaryons annihilate leaving only the asym.

   \[ (10^{10} + 1) B + 10^{10} \bar{B} = 1 B \]

4. Baryons go on to form light elements, stars, us, ...
Baryogenesis Ingredients  [Sakharov '67]

1. Baryon Number Violation:
   \[ |B = 0\rangle \rightarrow |B \neq 0\rangle \text{ requires } B \text{ violation.} \]

2. C and CP Violation:
   Without both, B violation makes just as many baryons as anti-baryons.

3. Departure from Equilibrium
   \[ \langle B \rangle = \text{constant in equilibrium, since also have reverse.} \]

All three are present in the Standard Model!
Baryogenesis Ingredients in the SM

1. Baryon Number Violation:
   Occurs efficiently at high temperatures, $T > 100$ GeV.

2. C and CP Violation:
   From chiral fermions and phase in the CKM matrix.

3. Departure from Equilibrium:
   Non-zero cosmological expansion rate makes this possible.

All three are present in the Standard Model!
Violation of B in the Standard Model?

- Baryon number is a symmetry of the classical action.
- It is broken by quantum tunneling transitions between different $SU(2)_L$ vacua. [Belavin, Polyakov, Schwartz, Tyupkin '75]
- Each transition violates $(B + L)$ by 3 units: ['t Hooft '76]

![Diagram showing the violation of Baryon number](image)
Violation of B in the Standard Model?

• B-violation today is unmeasurably slow: ['t Hooft '76]

\[
\frac{\Gamma}{V} \propto e^{-16\pi^2/g_W^2} \sim 10^{-320}
\]

• At high temperature, transitions can also occur via thermal “sphaleron” fluctuations over the barrier. [Klinkhamer + Manton '84]

\[
\frac{\Gamma}{V} \sim \begin{cases} 
(\alpha_w T)^4 & \langle H \rangle = 0 \text{ (fast)} \\
T^4 \exp(-8\pi \langle H \rangle/g_w T) & \langle H \rangle \neq 0 \text{ (slow)}
\end{cases}
\]

• \( \langle H \rangle \) is the background value of the Higgs field.
It also determines the weak scale: \( m_W = g_W \langle H \rangle / \sqrt{2} \).
Violation of B in the Standard Model?

- Rate of (SM) B violation in the early Universe:

\[ h_{\text{Higgs transition}} = 0 \Rightarrow h_{\text{Higgs transition}} \approx 174 \text{ GeV} \]

- Higgs transition: \[ \langle H \rangle = 0 \Rightarrow \langle H \rangle \approx 174 \text{ GeV} \]
Baryogenesis Ingredients

Ingredients are not enough.

A mechanism for baryogenesis is needed. No known mechanism works in the Standard Model.
Some Baryogenesis Mechanisms

• Grand Unified Theory (GUT) Baryogenesis: [Weinberg ‘74, Dimopoulos+Susskind ‘75]
  B violation from decays of heavy GUT states
  Often induces nucleon decay close to current limits.

• Baryogenesis via Leptogenesis: [Fukugita + Yanagida ‘86]
  Heavy neutrino decays make L, converted to B by sphalerons.
  Can produce signals in neutrino oscillations and $0\nu\beta\beta$.

• Electroweak Baryogenesis: [Kuzmin, Rubakov, Shaposhnikov ‘85]
  Baryons are produced by sphalerons in the Higgs transition.
  Leads to new signals at the LHC and in electric dipole moments.

• Low-Temperature Baryogenesis:
  Any mechanism that operates at temperatures below $T < 100$ GeV
  Requires new sources of B violation.
Low-Temp. Baryogenesis and Searches for Nucleon Decay
Hylogenesis: A Low-Temp. BG Mechanism

[Blincov, Davoudiasl, DM, Sigurdson, Tulin’10, ’11, ’12, ’14]

• Cosmological Densities:

\[ \rho_{DM} \approx 5 \rho_B \]

Maybe this is more than a coincidence?

• Idea: hide missing “antibaryons” in Dark Matter.

• Experimental Implication: dark matter can destroy baryons by inelastic scattering.

⇒ new signal to look for in nucleon decay searches!
Setup

• New SM-Singlet States:
  • $X_1$, $X_2$ heavier Dirac fermions, $\tilde{B} = +1$
  • $Y$ lighter Dirac fermion, $\tilde{B} = y$
  • $\Phi$ lighter complex scalar, $\tilde{B} = -(1 + y)$

• Interactions:

$$ -\mathcal{L} \supset \frac{\lambda_i}{M^2} (X_i d)_R (\bar{u}^c d)_R + \zeta_i^* \Phi \bar{Y}^c X_i + (h.c.) $$

Preserves the generalized baryon number $\tilde{B}$. 
Matter Genesis

• Three easy steps:

1. Equal numbers of $X_1$ and $\overline{X}_1$ are created non-thermally.
2. $X_1$ decays with CP violation into $udd$ and $\overline{Y}\Phi^*$. 
3. Annihilation erases everything but the asymmetries.

• Leftover $Y$ and $\Phi$ are stable and make up the dark matter.

• They carry (generalized) anti-baryon number, and lead to signals in nucleon decay searches.
Step 1: X Production

- Equal densities of $X$ and $\bar{X}$ are created non-thermally. e.g. reheating after inflation or moduli domination.
- This is a departure from equilibrium for large densities.
- No net production of $\tilde{B}$ has occurred.
Step 2: $X$ Decay with CP Violation

- $X \rightarrow udd$ or $X \rightarrow \overline{Y} \Phi^*$, $\overline{X} \rightarrow udd$ or $\overline{X} \rightarrow Y \Phi$.

- CP violation alters partial decay widths:

$$
\Gamma(X \rightarrow 3Q) = \Gamma_{3Q} + \epsilon \Gamma_{tot}
$$
$$
\Gamma(X \rightarrow \overline{Y} \overline{\Phi}) = \Gamma_{Y \Phi} - \epsilon \Gamma_{tot}
$$
$$
\Gamma(\overline{X} \rightarrow 3\overline{Q}) = \Gamma_{3Q} - \epsilon \Gamma_{tot}
$$
$$
\Gamma(\overline{X} \rightarrow Y \Phi) = \Gamma_{Y \Phi} + \epsilon \Gamma_{tot}
$$

CPT requires $\Gamma(X \rightarrow all) = \Gamma(\overline{X} \rightarrow all)$
Step 2: $X$ Decay with CP Violation

- Asymmetries come from tree-loop interference:

\[
\epsilon = \frac{\Gamma(X \to 3Q) - \Gamma(\bar{X} \to 3\bar{Q})}{\Gamma(X \to all) + \Gamma(\bar{X} \to all)}
\]

\[
\simeq \frac{\text{Im}(\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*)}{256\pi^3 |\zeta_1|^2} \frac{m_{X_1}^5}{M^4 m_{X_2}}
\]
Step 2: $X$ Decay with CP Violation

- Decay asymmetries split $\tilde{B}$ in $3Q, Y\Phi$:

- Net $\tilde{B}$ number is zero.
Step 3: Annihilation

- Symmetric densities of $3Q$ and $Y\Phi$ annihilate away. All that is left are the equal and opposite asymmetries.

- $Y\Phi$ are hidden antibaryons. We want them to be stable.
Hidden Antibaryonic Dark Matter

- **Prediction:** \( n_Y = n_\Phi = n_B \)
- **Both** \( Y \) and \( \Phi \) **can be stable if**
  \[
  |m_Y - m_\Phi| < (m_p + m_e) < m_Y + m_\Phi
  \]
- **They provide the right DM density if**
  \[
  m_Y + m_\Phi = m_p \left( \frac{\rho_{DM}}{\rho_B} \right) \approx 4.5 \text{ GeV}
  \]
- **Possible mass ranges:**
  \[
  1.7 \text{ GeV} \leq m_{Y,\Phi} \leq 2.9 \text{ GeV}
  \]
Implication: DM-Nucleon Inelastic Scattering

- DM now carries a net charge of $\tilde{B} = -1$!
- Relic $Y$ or $\Phi$ can scatter inelastically off a nucleon:
  e.g.
  \[
  \begin{align*}
  \begin{array}{c}
  \text{\(p\)} \\
  \text{\(u\)} \\
  \text{\(u\)} \\
  \text{\(d\)} \\
  \end{array}
  \leftrightarrow
  \begin{array}{c}
  \text{\(\bar{s}\)} \\
  \text{\(d\)} \\
  \text{\(u\)} \\
  \text{\(u\)} \\
  \text{\(s\)}
  \end{array}
  \rightarrow
  \begin{array}{c}
  \text{\(K^+\)} \\
  \text{\(X_{1,2}\)} \\
  \Phi^*, \Phi \\
  \end{array}
  \]
Induced Nucleon Decay (IND)

- Inelastic DM scattering looks like nucleon decay.
- Event rates in a nucleon decay detector:
  \[ R_{\text{decay}} = \Gamma_{\text{decay}} N_{\text{nuc}} \]
  \[ R_{\text{IND}} = \sigma_{\text{IND}} \mathcal{F}_{\text{DM}} N_{\text{nuc}} \]
  \[ \mathcal{F}_{\text{DM}} = \text{local DM flux} \simeq (5 \times 10^6 \text{cm}^{-2}\text{s}^{-1}) (2 \text{ GeV}/m_{\text{DM}}) \]
  \[ \sigma_{\text{IND}} = \text{inelastic IND scattering cross section} \]
- Translate limits from nucleon decay searches:
  \[ \tau = \frac{1}{\Gamma} \quad \longleftrightarrow \quad \tau_{\text{eff}} \equiv \frac{1}{\sigma \mathcal{F}} \]
Induced Nucleon Decay (IND)

• IND “Lifetime”:
  \[ \tau_{eff} \approx 10^{32} \text{ yr} \left| \frac{m_X M^2 / \lambda^* \zeta}{\text{TeV}^3} \right|^2 \]

• Best current limits on nucleon decay are similar!
• But nucleon decay searches use meson momentum cuts.
• IND can have upscattering or downscattering, and meson momenta may lie outside cut ranges.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>( p^\text{dec}_M ) (MeV)</th>
<th>( p^{IND}_M ) (MeV)</th>
<th>bound (( \times 10^{32} ) yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N \rightarrow \pi )</td>
<td>460</td>
<td>800-1400</td>
<td>( \tau_p &gt; 0.16 ), ( \tau_n &gt; 1.12 )</td>
</tr>
<tr>
<td>( N \rightarrow K )</td>
<td>340</td>
<td>680-1360</td>
<td>( \tau_p &gt; 23 ), ( \tau_n &gt; 1.3 )</td>
</tr>
<tr>
<td>( N \rightarrow \eta )</td>
<td>310</td>
<td>650-1340</td>
<td>( \tau_n &gt; 1.58 )</td>
</tr>
</tbody>
</table>
Induced Nucleon Decay (IND)

- Meson momentum cuts at Super-Kamiokande:

\[ p \rightarrow e^+ \pi^0 \]
Induced Nucleon Decay (IND)

- Muon momentum cuts at Super-Kamiokande:

\[ p \rightarrow K^+ \nu \]

\[ K^+ \rightarrow \mu^+ \nu \]

[Takhistov for SuperK ’16]
Induced Nucleon Decay (IND)

- Muon momentum cuts at Super-Kamiokande:
  \[ p \rightarrow K^+ \nu \]
  
  \[ K^+ \rightarrow \mu^+ \nu \text{ with } ^{15}N^* \gamma \text{ de-excitation} \]
Induced Nucleon Decay Kinematics

- Nucleon decay searches do not probe the whole range.
- Example for $X U^c D^c S^c$ operator:

![Graph showing kinematics](image)
Other Signals of Hylogenesis

- DM direct detection from elastic scattering of $Y, \Phi$ with nucleons.
- Monojet signals at the LHC from $pp \rightarrow j + Y + \Phi^*$. 
- Modified stellar evolution from DM capture and IND.
Summary

• Baryogenesis is needed to explain the universe. It motivates new sources of B (and L) violation.

• Deep underground searches for nucleon decay, neutron-antineutron oscillation, and neutrinoless double beta decay are well motivated.

• More exotic mechanisms for baryogenesis could produce non-standard signals in these searches.

It is worth searching broadly!
Extra Slides
Baryons in the Universe

- “Regular” matter is mostly baryons, \( \rho_B / \rho_{\text{tot}} \approx 5\% \).
- It consists almost entirely of baryons, not antibaryons.
- Why: Baryogenesis.

[CMB]

[Garrett+Duda ’10]

[BBN]

[Cyburt et al. ’97]
Baryons in the Universe

• “Regular” matter is mostly baryons, $\rho_B/\rho_{tot} \simeq 5\%$.
• It consists almost entirely of baryons, not antibaryons.
• Why: Baryogenesis.

**Electroweak Baryogenesis (EWBG):**
→ baryon creation during the electroweak phase transition

• Requires new physics beyond the Standard Model, leads to modified Higgs properties and new light states.
• The LHC is currently testing this BG mechanism.
**EWBG Step 1: Electroweak Bubbles**

The effective Higgs potential is modified in the early Universe by thermal effects at temperature $T$:

$$V(\varphi, T) \simeq -\frac{1}{2}(\mu^2 - \xi T^2)\varphi^2 - \gamma T\varphi^3 + \frac{\lambda}{4}\varphi^4$$
EWBG Step 2: Particle Asymmetries

Particles in the plasma scatter off the bubbles. C+CP violation can lead to charge asymmetries.
**EWBG Step 3: Sphaleron Transitions**

Sphaleron = non-perturbative SU(2)$_L$ transition. Violates (B+L) by 3 units.

Active in the unbroken phase. Suppressed in the broken.

\[
\Gamma/V \sim \left\{ \begin{array}{l}
(\alpha_w T)^4 \\
T^4 \exp(-8\pi \langle \varphi \rangle / g_w T)
\end{array} \right.
\]