Baryon Number Violation

Physic 290E Seminar
4/10/2019
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Why is there something rather than nothing?

Gottfried Leibniz: philosopher/co-inventor of calculus

Baryon Number (Asymmetry)

- B = +⅓ for quarks, B = -⅓ for antiquarks.
- B is an “accidental symmetry” of the SM.
- In the early universe, most particles were relativistic.
- Universe was in thermal equilibrium, so entropy constant.
- Particle density n_A scales with T^3.
- Relevant constant quantity:
- Easiest proxy for entropy density is photon density, estimated from CMB.
    - In actuality, Big Bang Nucleosynthesis (relative abundances of light elements) provides a much better estimate for η.

$$s = \frac{S}{V} = \frac{2\pi^2}{45} g_{*s} T^3$$

$$\frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{s}$$

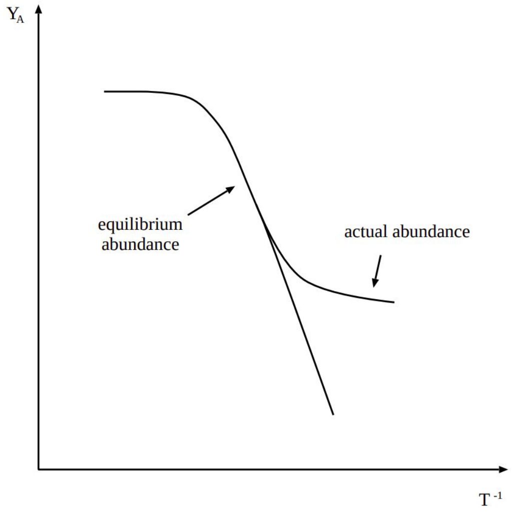
$$\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$$

Sakharov Conditions

- Universe contains more matter than antimatter.
- Three necessary conditions for Baryogenesis:
  - 1) Baryon Number Violation (for obvious reasons)
  - 2) CP Violation (so there won't be equal amounts of $\Delta B = +1$ and $\Delta B = -1$ violating processes).
  - 3) Thermal disequilibrium in the early universe (so the reverse reaction isn't equally likely).

Deviations from Thermal Equilibrium

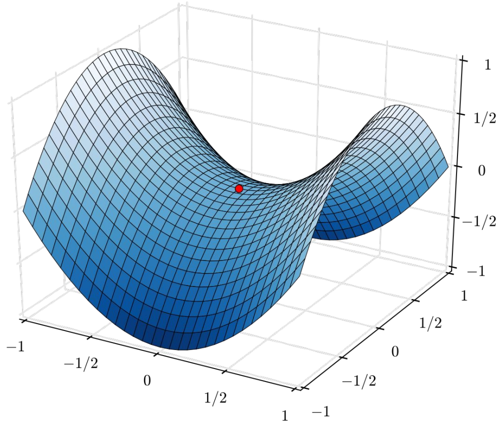
- Known departures are the freeze-out of various species like neutrinos, and nucleosynthesis.
- Inflation.
- WIMP decoupling.
- 1st order phase transitions.
- Occur when H > Γ for a species.



hep-ph/0205279

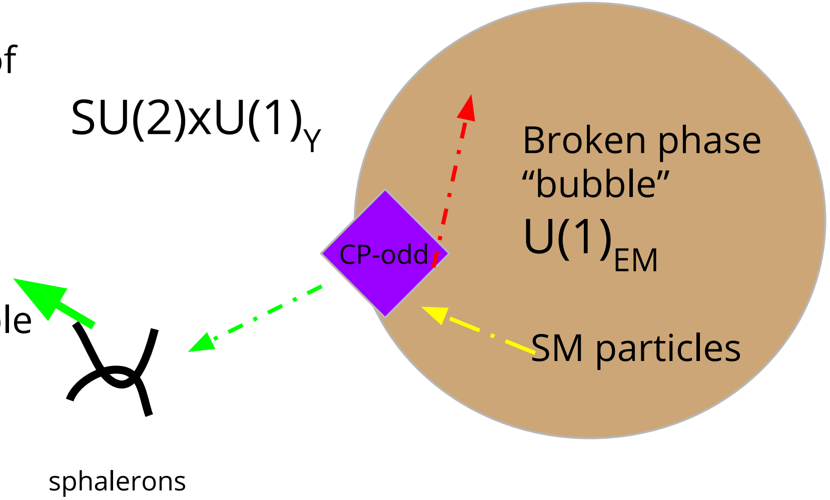
B-L and B+L Numbers

- B & L are both ≠0.
- B-odd processes need to put the energy somewhere, e.g. leptons or antileptions.
  - B-L=0 implies B->l
  - B+L=0 implies B -> l̄
- Sphalerons are saddle points in the electroweak potential. They have faster transitions than instantons and violate B+L (but preserve B-L).



Electroweak Baryosynthesis

1. During the EW phase transition, bubbles of different vacuum form.
2. Particles scatter with the bubble wall. If there's enough CP-violation, the phases obtain different net CP charges.
3. B+L violating sphalerons outside the bubble generate Baryon asymmetry.
4. The bubble catches up and captures the Baryons.



All of this is entirely within the standard model, but is highly non-perturbative.

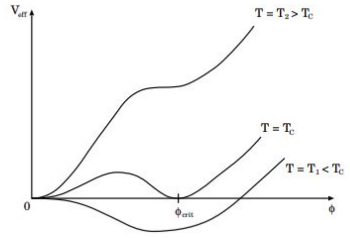
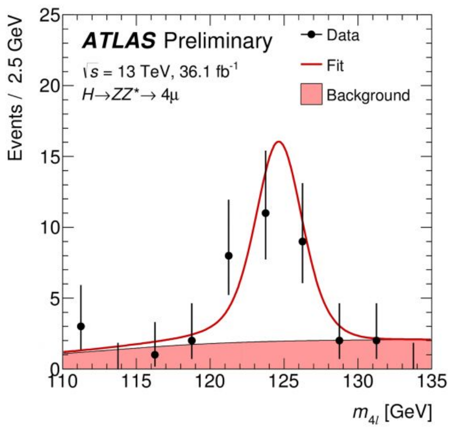


Figure 9: Behaviour of V_{eff} in the case of a first order phase transition.

Electroweak Baryosynthesis (problems)

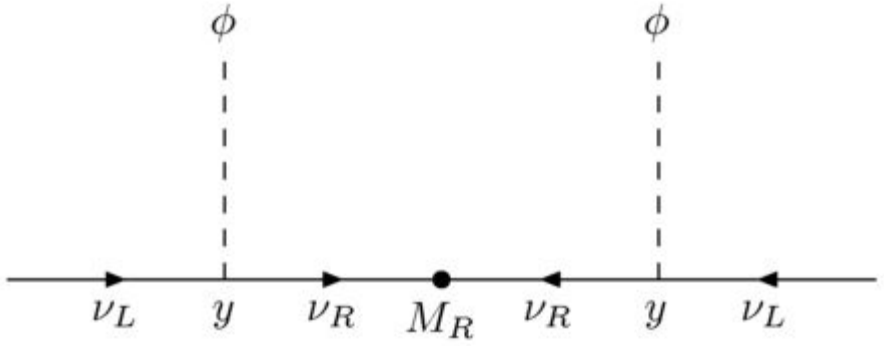
- The B+L violating sphalerons need to stop once the bubble expands, which only occurs with a strong first-order transition.
  - The Higgs mass is too large for this (m_H = 125 GeV > 70 GeV).
- CP violation is too weak.
  - Jarlskog invariant J (twice the area of the unitary triangle) ~ 3 x 10^{-5}.
- New physics required to remedy this.



$$\mathrm{Im}(V_{ij}V_{kl}V_{il}^*V_{kj}^*) = J\sum_{m,n}\epsilon_{ikm}\epsilon_{jln}$$

Leptogenesis

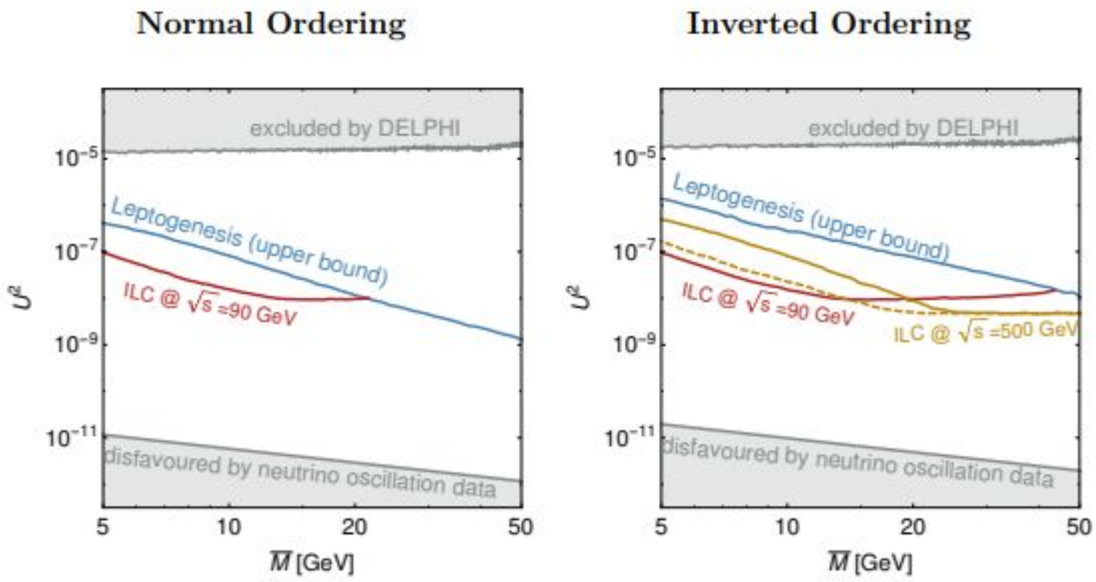
- Maybe CP violation in neutrino sector is responsible.
- Seesaw mechanism: light neutrinos couple to sterile neutrino with large Majorana mass, which violates lepton number.
    - CP violation would then lead to an excess of leptons.
    - Sphalerons convert leptons to baryons as in EWSB.



$$M = \begin{bmatrix} 0 & y \\ y & M_R \end{bmatrix}$$

International Linear Collider

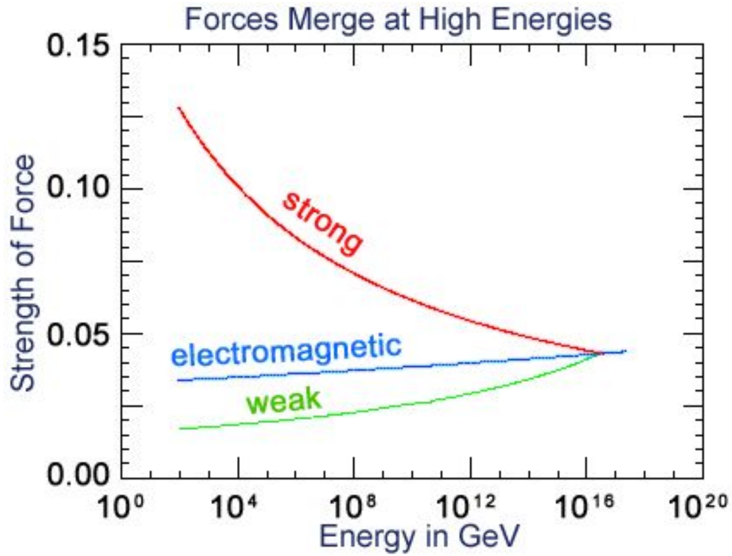
- Proposed e-e+ collider.
- Planned to operate at 500 GeV.
- Displaced vertex searches allow sensitivity below electroweak scale.
- Unfortunately, Japan didn't approve funding for the project.



From
arXiv:1801.06534 **[hep-ph]**

Grand Unified Theories (GUTs)

- These unify the forces into a larger group like SO(10).
- Quarks and leptons form a representation of this group.
    - Baryon number can be violated by one of the new interactions.
- Many require SUSY.



Proton Decay Searches and limits

- GUTs imply that protons can decay while conserving the rest of the quantum numbers.
- Proton to positron + pion will produce Cherenkov.
- Limit is t > 10^{34} years.
- ΔB = -1, ΔL = -1, so Δ(B-L) = 0.

$$p \to e^+\pi^0$$

Gauging B

- One could promote B from “accidental” symmetry to a real one.
- Like SU(2), it could be spontaneously broken, but at a very low energy scale.
- New B-charged fermions could be dark matter. B is conserved, B-L violated with some other mechanism, and sphalerons transfer B from standard model to dark matter.
- Long range forces would violate equivalence principle (inertial vs. gravitational mass) [3], so the couplings have to be very weak.
    - MICROSCOPE[4] says $|\alpha_B| < 10^{-11}$.

$$G = SU(3)\otimes SU(2)\otimes U(1)_Y\otimes U(1)_B\otimes U(1)_L$$

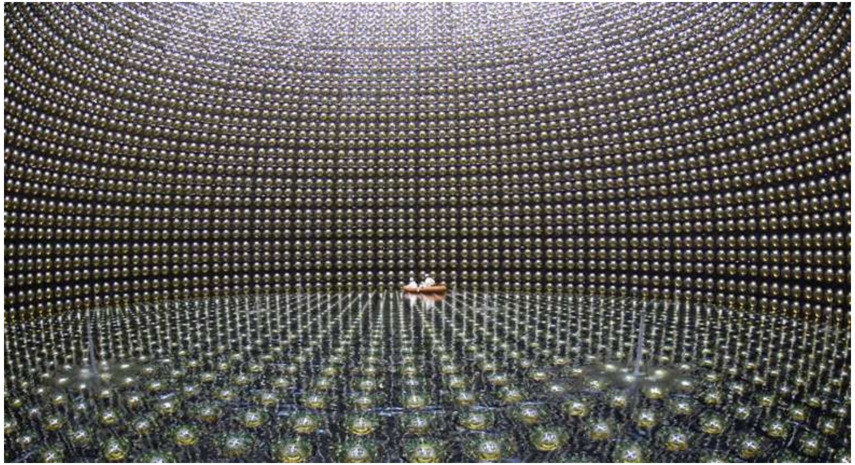
New fields and their quantum numbers [2]:

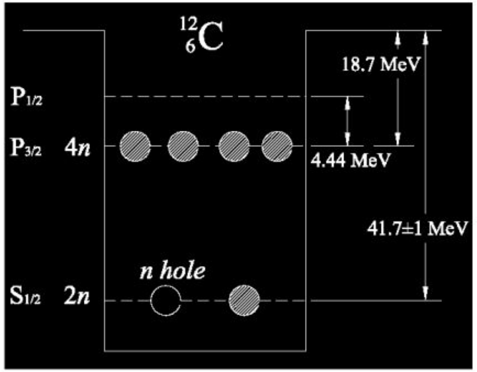
$\Psi_L \sim (1,2,-1/2,B_1)$; $\Psi_R \sim (1,2,-1/2,B_2)$;
$\eta_R \sim (1,1,-1,B_1)$; $\eta_L \sim (1,1,-1,B_2)$;
$\chi_R \sim (1,1,0,B_1)$; $\chi_L \sim (1,1,0,B_2)$;

Chiral anomaly cancellation requires:
$B_1 - B_2 = -3$

Dark Matter induced decays

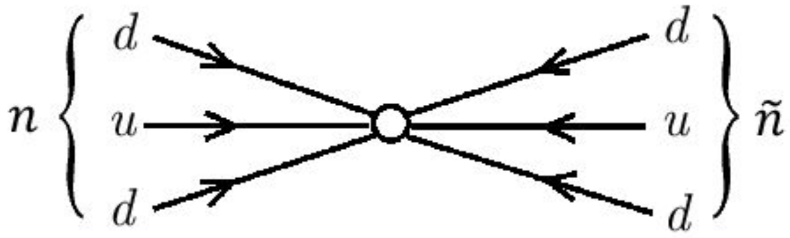
- (anti-) Baryonic dark matter would induce decays in matter via the new $U(1)_B$ coupling.
- Nucleon-> neutrino searches in Super-K constrain the mediator mass > 10^7 GeV.
- KamLand (liquid scintillator) set limits for invisible ^{12}C decays at $\tau(nn \to inv) > 1.4 \times 10^{30}$ years at 90% CL.





Neutron - Antineutron Oscillation

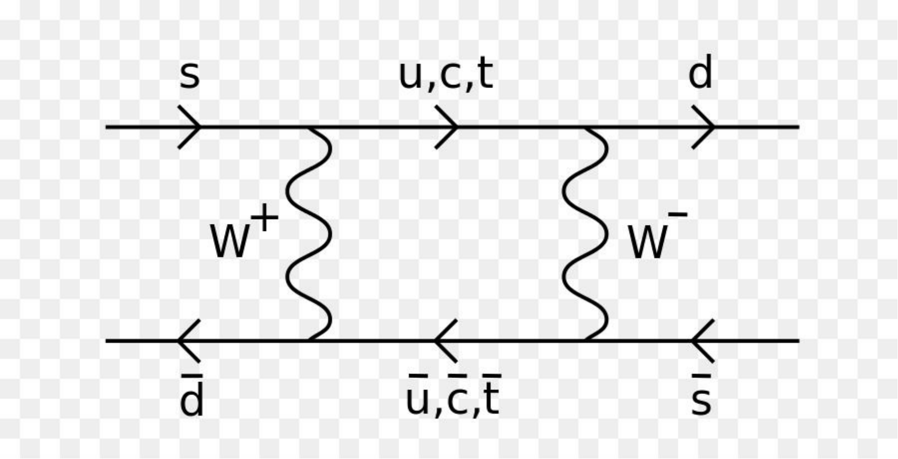
- B-asymmetry needs to be created and not destroyed at a later time.
- B+L violating sphalerons will tend to restore balance.
- B-L violating processes needed, preferably $|\Delta B| = 2$.
- Neutron oscillation n -> nbar fits the bill.
    - $|\Delta B| = 2$, $|\Delta L| = 0$.
- Early universe neutrons could oscillate, and the sphalerons could restore the B-L balance.



Neutral Meson Oscillation

$$H = \begin{bmatrix} E+\delta & \alpha \\ \alpha & E-\delta \end{bmatrix}$$

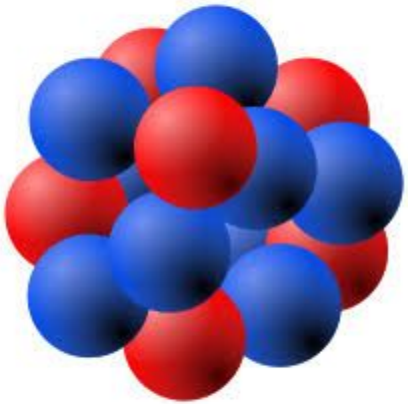
$$P(t) = \frac{\alpha^2}{\alpha^2+\delta^2}\sin^2[\frac{\sqrt{\alpha^2+\delta^2}}{\alpha^2}t]$$



Environmental Dependence

- Neutrons have no charge, but they have a magnetic dipole.
  - g_N = -3.826.
- Antineutrons with the same spin (e.g up or down) will have a dipole in the opposite direction.
- ANY magnetic field will create an energy split.
- Nuclear environment will also introduce energy splitting, and will suppress the transition time.
  - Suppression factor R ~$10^{22}s^{-1}$

$$\tau_A = R\tau_{n\bar{n}}^2$$



Neutron Oscillation Searches

- ILL in the 90s. Cold Neutron beam.
  - $\tau_{n-\bar{n}} > 0.86 \times 108$ s.
- Super-K did search for ^{16}O neutron oscillations. Antineutrons will annihilate into pions.
  - $T > 1.9 \times 10^{32}$ years.
- SNO did a search, but with the Deuterium neutrons (smaller correction factor).
  - $T > 1.8 \times 10^{18}$ years.
- Future searches focusing on building better:
  - cold neutron traps
  - Neutron reflectors
  - Magnetic shielding

Summary

- B-violation is an important process that needs to be identified in order to explain the matter dominance of the universe.
- The standard model satisfies the Sakharov conditions, but not enough.
- Proton decay is an active research area.
- NNBar oscillations are perhaps more attractive, and they are only limited by engineering at the moment.

References

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