Electroweak baryon number violation and a “topological condensate”

Steven Bass / Innsbruck

Baryon asymmetry in the Universe:
Needs baryon number non-conservation
→ Non-perturbative “Sphaleron” processes in the electroweak vacuum as candidate mechanism
NEW: electroweak baryon number non-conservation accompanied by formation of a spin-independent “topological condensate” in the Standard Model vacuum
QCD version of the key physics input also provides elegant “solution” of the proton spin puzzle, testable in elastic neutrino-proton scattering

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Baryon asymmetry in the Universe

- What is observed ?
  - » $n_B / n_{gamma} = 10^{-10}$
- Sakharov´s conditions (1966)
  - Baryon number non-conservation
    - (non-perturbative e-weak processes or „new physics“)
  - C and CP violation
    - Need different rate of reactions with particles and antiparticles
  - Deviations from thermal equilibrium
    - Otherwise, if the initial baryon number were zero at the start of Universe it would stay zero

- Baryon number violating processes: can investigate in (very) high energy colliders (?)

- This talk: new developments in the physics of electroweak baryon number violation [SDB, Phys. Lett. B590 (2004) 115]

A Key Issue: What is baryon number ?

- Definition of baryon number in e-weak theory quite subtle because of the axial anomaly

$$J_\mu = \bar{\Psi}\gamma_\mu\Psi$$
$$= \bar{\Psi}\gamma_\mu\frac{1}{2}(1-\gamma_5)\Psi + \bar{\Psi}\gamma_\mu\frac{1}{2}(1+\gamma_5)\Psi.$$

- SU(2) gauge bosons couple only to left handed quarks → axial anomaly is important!

$$\partial^\mu J_\mu = n_f\left(-\partial^\mu K_\mu + \partial^\mu k_\mu\right).$$

$$\partial^\mu K_\mu = \frac{g^2}{32\pi^2} W_{\mu\nu}\tilde{W}^{\mu\nu}$$

- Suggests choice of currents to define baryon number:
  (1) the gauge invariant renormalized current
  OR
  (2) (gauge invariant observables associated with) the conserved (but gauge dependent) current

$$J^{\text{con}}_\mu = J_\mu - n_f(-K_\mu + k_\mu)$$

$$\partial^\mu J^{\text{con}}_\mu = 0$$

Anomalous commutators

- Consider the charges

$$Y(t) = \int d^3z\, J_0(z), \qquad B = \int d^3z\, J_0^{\rm con}(z).$$

- Gauge invariant baryon number B is defined through the commutators

$$[B, \mathcal{O}]_- = \mathcal{B}\mathcal{O}$$

  despite gauge dependence of the operator

- Can show: B charge is renormalization scale invariant (as baryon number should be!) whereas Y is not. Also, the time derivative of the spatial components of the W boson field has zero B charge and non-zero Y charge

$$[B, \partial_0 A_i]_- = 0$$

and

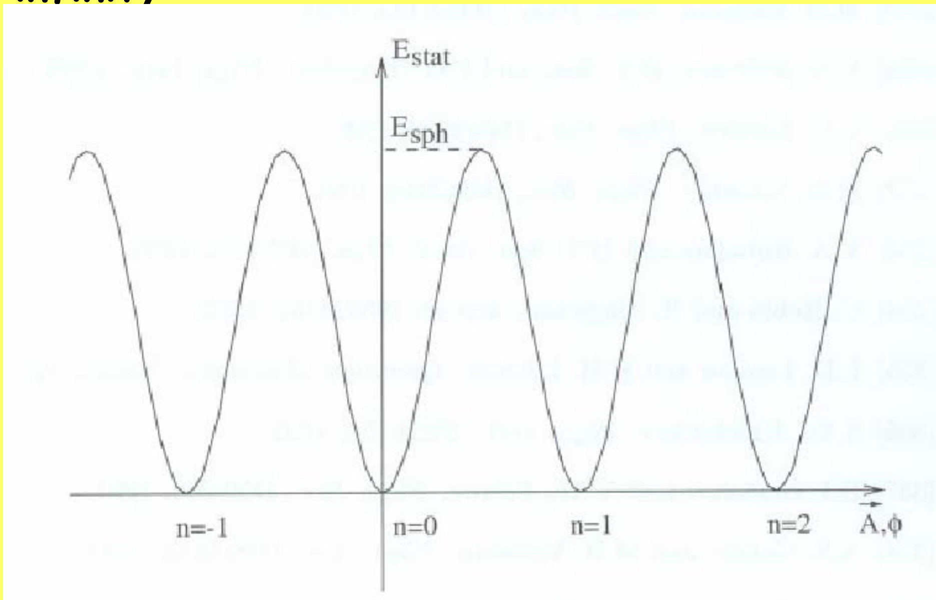
$$\lim_{t' \to t} \big[Y(t'), \partial_0 A_i(\vec{x}, t)\big]_- = \frac{i n_f g^2}{4\pi^2} \tilde{W}_{0i} + O\big(g^4 \ln|t' - t|\big)$$

Instantons and Sphalerons

- **Vacuum as Bloch superposition of vacuum states with different topological winding number, from –infinity up to +infinity**

$$|\theta_1, \theta_2\rangle = \sum_m \sum_n \mathrm{e}^{i(m\theta_1 + n\theta_2)} |m\rangle_{\mathrm{EW}} |n\rangle_{\mathrm{QCD}}$$

$$\Delta B = \Delta L = \pm 3 n_f$$



- **The fermion levels are shifted in the |m> state relative to the |m+1> state so that the total „baryon number" (measured by the gauge invariant current) of each |m> state is zero when we sum over gauge topology and B contributions; also each state carries zero net electric charge**

- **Tunneling and vacuum transitions can yield baryon number non-conservation**

$$q + q \rightarrow 7\bar{q} + 3\bar{l},$$

Vacuum transition processes

- E-weak instanton tunneling processes strongly suppressed

$$e^{-4\pi \sin^2\theta_W/\alpha} \sim 10^{-170}$$

- BUT at high temperatures of order the potential barrier (multi TeV) in the early Universe thermal fluctuations can induce vacuum transitions „Sphalerons" and the suppression factor goes away
- Key equation

$$\Delta Y = \Delta B - n_f m.$$

- Choice of baryon number current essential → yields different and interesting physics
- Two solutions (for m=1) $\Delta B = n_f \text{ and } \Delta Y = 0$ OR $\Delta Y = -n_f \text{ and } \Delta B = 0.$
- Essential physics is in zero momentum modes. Vacuum transitions involve zero momentum physics !
- The B definition implies the formation of a zero-momentum „topological condensate" which accompanies the change in B baryon number quantum numbers.
- The Y charge definition involves a zero momentum „schizon" which absorbs B charge in the vacuum → no net condensate.

The real world: QCD + E-weak

- E-weak Sphalerons involve only left handed fermions
- Also have QCD Sphalerons plus scalar Higgs couplings → flip the spin/chiralities of the left handed quarks produced by the e-weak sphalerons. Net result is spin independent baryon number violation PLUS spin independent „topological condensate“
- (Presumably) still there today with accompanying B violation!

  → Phenomenological and cosmological implications ??

- Collider tests:
  - Cross sections (Ringwald) expected about 10^{-3} fb at VHLC energies (200 TeV)

- Key physics may also explain the proton spin problem: testable signature in neutrino proton elastic scattering …

The Spin Structure of the Proton

- Polarized Deep Inelastic Scattering
  - Measure g_1 spin structure function
  - First moment → Sigma ~ 0.15 – 0.35
  - Where is the „missing spin" ?

- Spawned vast EP program-many exciting ideas being tested: gluon polarization, quark sea, orbital angular momentum …

- Key result [SDB]:
  Transition from current to constituent quarks
  → Polarized Condensate (x=0)

Testable through elastic neutrino-proton scattering (measures everything, including x=0 contributions)