Electroweak baryon number violation and a “topological condensate”

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Baryon asymmetry in the Universe:
Needs baryon number non-conservation
→ Non-perturbative “Sphaleron” processes in the electroweak vacuum
as candidate mechanism
Consistency of local Ward identities and non-local topological structure
→ formation of a “topological condensate” in the early Universe

QCD version of this physics provides an elegant “solution” to the proton spin puzzle: quarks contribute just 30% of the proton’s spin

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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

- **Here: Focus on sphaleron induced electroweak baryon number violation**

A Key Issue: What is baryon number ?

- **Definition of baryon number in e-weak theory is 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

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

$$\partial^\mu J_\mu^{\rm con} = 0$$

Anomalous commutators

- Consider the charges

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

- Gauge invariant baryon number B is defined through the commutators

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

despite gauge dependence of the operator

- 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

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

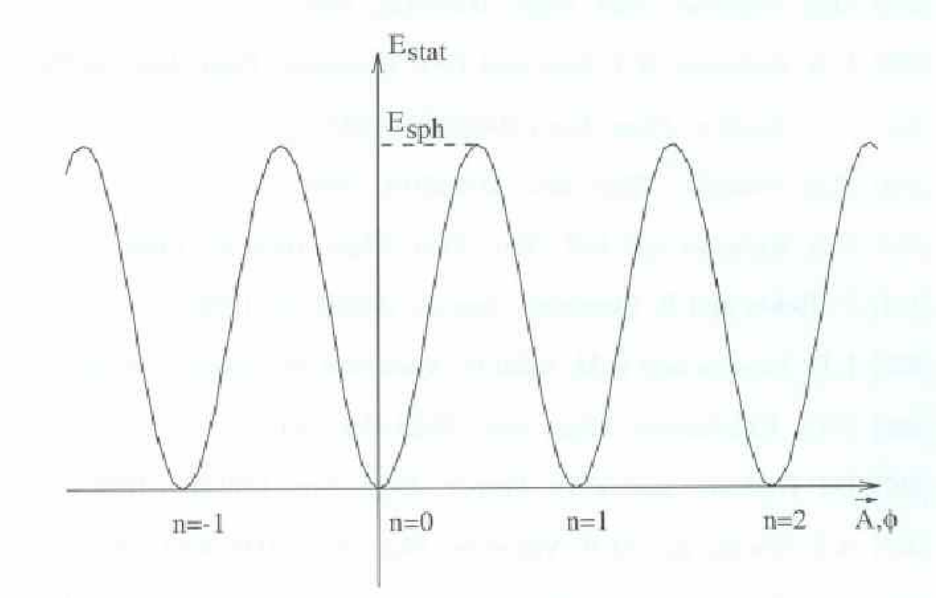
and

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

Instantons and Sphalerons

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

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



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

- B-L is conserved while B+L is violated

- Fermion levels are shifted in the |m> state relative to the |m+1> state:
  - total „baryon number" (measured by the gauge invariant current) of each |m> state is zero when we sum over gauge topology and B contributions
  - each |m> 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 equations

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

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

Vacuum transitions II

- Start from $\Delta Y = \Delta B - n_f m.$
- **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 !
  - B+L violation goes for finite-momentum fermions
  - Zero momentum modes (vacuum) restores conservation laws
- The B definition → formation of a zero-momentum „topological condensate" which accompanies the change in B baryon number
- For the Y charge definition one needs to introduce a a zero mode „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“**
  - » **vector component associated with vector current**
- **(Presumably) still there today with accompanying B violation !**
  - → **Phenomenological and cosmological implications ??**

QCD: the Spin Structure of the Proton

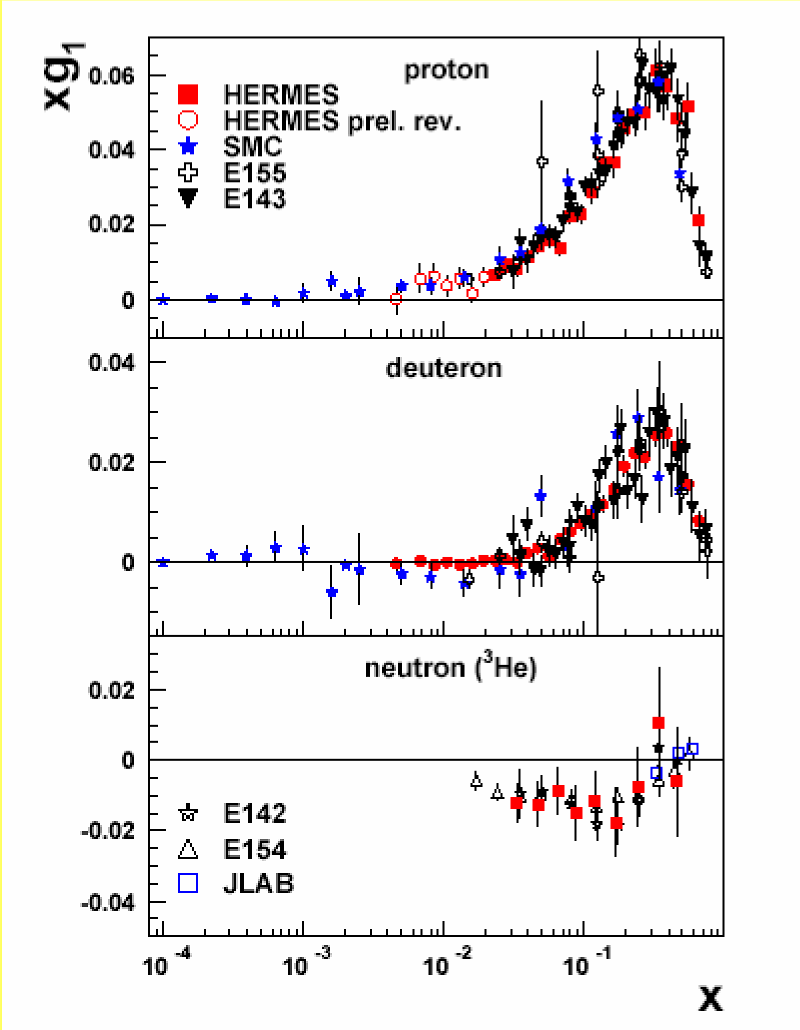
- Polarized Deep Inelastic Scattering
  - Measure g_1 spin structure function
  - First moment → Quark spin content ~ 0.3
  - Where is the „missing spin" ?

- Spawned vast EP program-many exciting ideas being tested: gluon, valence and sea quark polarization … (COMPASS, RHIC, HERMES)

- 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)



Conclusions

- Topological condensate: the vacuum has structure
- Spin independent, vector component → SSB of Lorentz invariance (?)
- Sign of baryon number violation in sphaleron models
- QCD version of this has important phenomenology in the proton spin and axial U(1) problems