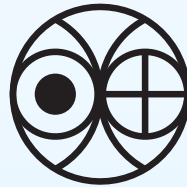


Baryogenesis without Baryon number violation

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Outline of Talk

- Baryon Asymmetry of the Universe
- Framework of Model
- Baryogenesis in the model
- Background A_0 profile
- Reflection Coefficients
- Conclusion and Summary

Baryon Asymmetry of the Universe

Framework of Model

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Baryon Asymmetry of the Universe

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- Universe is baryon asymmetric
- Present baryon asymmetry of the universe:

$$\frac{n_q - n_{\bar{q}}}{n_\gamma} \simeq 10^{-10}$$

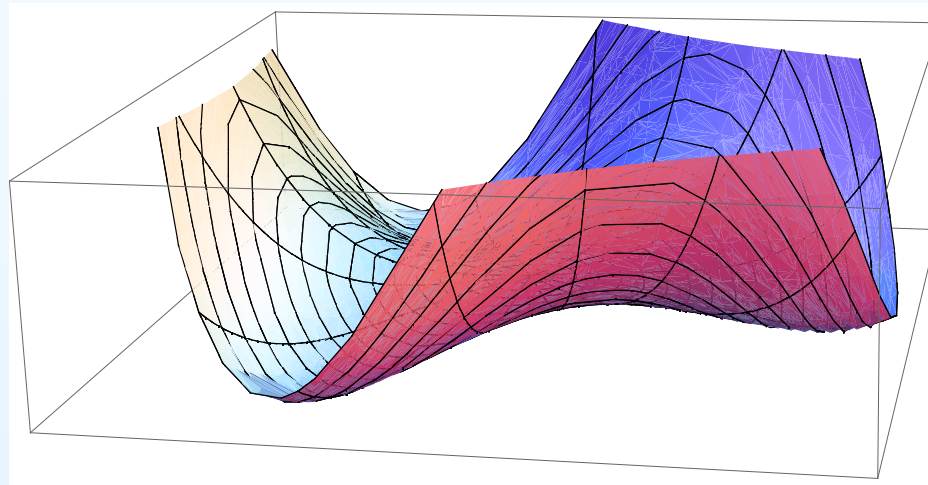
- Solution: Baryogenesis
- Sakharov Conditions:
 - Baryon number violation
 - C and CP violation
 - Out of equilibrium condition



Framework of Model

- Baryon Asymmetry of the Universe
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- Start with pure $SU(3)$ gauge theory: No quarks
- A global $Z(3)$ symmetry is a symmetry of local $SU(3)$ gauge theory.





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Framework of Model

- In pure gluon theory, an order parameter can be constructed

$$l(x) = \frac{1}{3} \text{Tr} \left[\mathbf{P} \exp \left(ig \int_0^\beta A_0(\vec{x}, \tau) d\tau \right) \right]$$

where we are working in the imaginary time formalism.

[G. 't Hooft, NPB 153, 141 (1979)]

$l(x)$ = is called the Polyakov loop,

A_0 = is the zeroth component of the gauge field,

$$\beta = 1/T$$

- The Polyakov loop is interpreted as the free energy of an infinitely heavy test quark. i.e. $\langle l \rangle = \exp(-\Delta F/T)$.
- For confining phase, free quark cannot exist, and so $\Delta F \rightarrow \infty$. Thus $\langle l \rangle = 0$.
- For deconfining phase, free quarks can exist, and so $\Delta F = \text{finite}$. Thus $\langle l \rangle \neq 0$.



Framework of Model

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- For a pure gluon theory, $l(x)$ has $Z(3)$ symmetry i.e it has 3 identical vacua.

$$l(x) \rightarrow \exp\left(\frac{2\pi i j}{3}\right) l(x), \quad j = 0, 1, 2$$

- With the addition of **dynamical quarks**, the stable vacuum is the one with $j = 0$ state i.e for which $\langle l \rangle$ is real.
- Due to quarks pressure in the vacua with $j \neq 0$ states are less than the one with $j = 0$ state. As such they are unstable vacua.
- If these unstable vacua are metastable these lead to interesting physics.



Baryogenesis in the model

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- Domain Wall formation
 - $Z(3)$ bubbles of different vacua nucleate randomly.
 - They expand and coalesce to form domain walls between different vacua.
 - Regions of true vacuum ($l(x) = 1$) will expand, metastable vacua ($l(x) \neq 1$) will shrink.
- Scattering From Interfaces
 - Due to CP violating effects, quarks and anti-quarks scatter differently from interfaces.
 - Shrinking domains will have a net anti-baryon number.
 - Possibility of forming stable Baryonic Lumps.
 - Results in segregation of Baryon number.



Background A_0 profile

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- To prove the CP violating effects one needs to calculate the reflection and transmission coefficients of quarks and anti-quarks
- For this we need to formulate the A_0 profile for which $l(x)$ acquires different vacua.
- For $l(x) = 1$, state $A_0 = 0$, is a trivial solution.
- For the other vacua, **gauge choice**

$$A_0 = \frac{2\pi T}{g} (a\lambda_3 + b\lambda_8),$$

where, a and b are constants, λ_3 and λ_8 are GellMann matrices. [Altes, Lee, Pisarski, PRL, 73, 1754 (1994)]



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- **Potential** form of $l(x)$ [R. D. Pisarski, PRD 62, 111501 (2000)]

$$V(l) = \left(-\frac{b_2}{2} |l|^2 - \frac{b_3}{6} (l^3 + (l^*)^3) + \frac{1}{4} (|l|^2)^2 \right) b_4 T^4.$$

- For $T > T_c$ second term leads to 3 degenerate vacua corresponding to the three $\langle l(x) \rangle$ values.
- However vacuum to vacuum transition or domain wall solutions is non-trivial for $Z(3)$.



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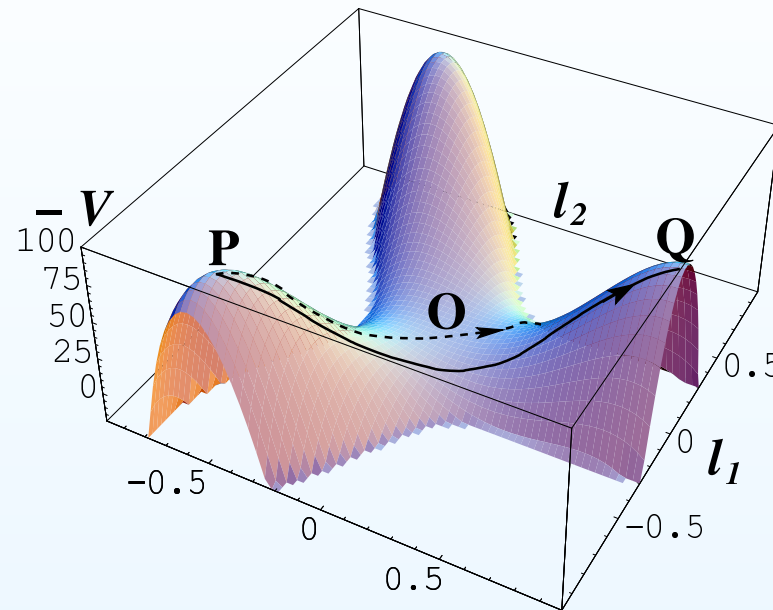


Image showing the inverted potential $-V(l_1, l_2)$, where $l = l_1 + il_2$ [Layek, Mishra, Srivastava PRD, 71, 074015 (2005).]

- Domain wall (DW) solution corresponds to particle trajectory starting from top of one hill to top of another hill for inverted potential $-V$.



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- The figure showed, DW solutions cannot go through $l = 0$.
- Particle starting at P, rolling down to $l = 0$ cannot turn back to end up at Q.
- It will rather roll away downward as shown via dashed line.
- To end up at Q, the trajectory must loop back before reaching $l = 0$ as shown by solid curve.
- To obtain the particle trajectory (DW solutions $l(x)$) energy minimization is carried out numerically. [Layek, Mishra, Srivastava PRD 71, 070415 (2005).]
- This gave us the value of $l(x)$ from one vacua to another.

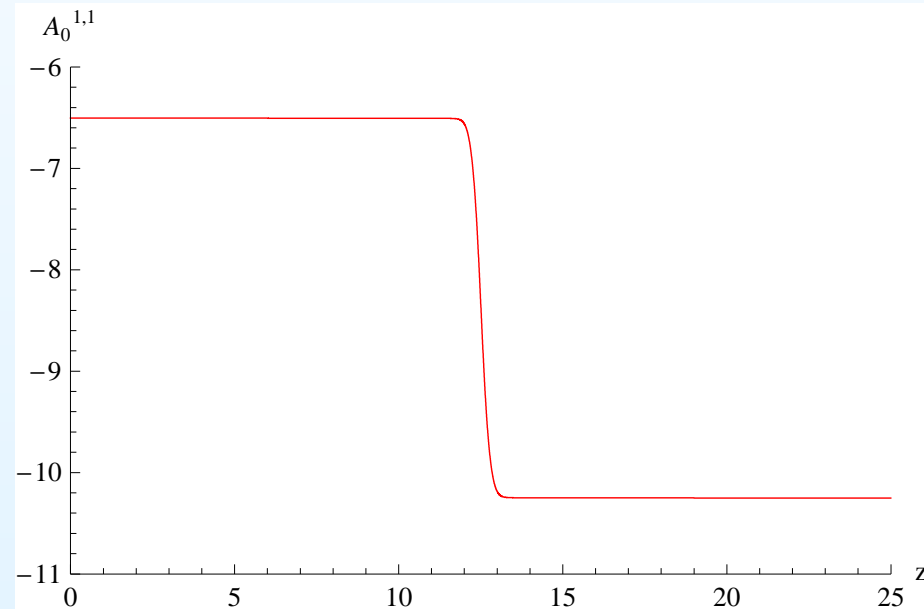


Background A_0 profile

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$$\text{Since, } l(x) = \frac{1}{3} \text{Tr} \left[\mathbf{P} \exp \left(ig \int_0^\beta A_0(\vec{x}, \tau) d\tau \right) \right]$$

- The a and b profiles are then calculated from the above $l(x)$ values demanding that the variation of A_0 is continuous.





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Reflection Coefficients

- For the purpose of simplicity, we approximate the profile with a step potential and then calculate the reflection coefficients.
- The reflection coeff. is given by

$$R = \frac{(1 - r)^2}{(1 + r)^2}$$

$$\text{where , } r = \left(\frac{\bar{p}}{p} \right) \frac{(E + m_0)}{E - V_0 + m}$$

where, p is the momentum of free quark, and \bar{p} is the momentum of quark in the potential.

- At $E = 1.55$ GeV
 $R = 0.00222868772$ for u quark
 $R = 6.28654781 \times 10^{-7}$ for u anti-quark.
- At $E = 1.55$ GeV
 $R = 0.0090536449$ for d quark
 $R = 2.51470843 \times 10^{-6}$ for d anti-quark.



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Reflection Coefficients

- At $E = 2.00$ GeV
 $R = 1.3964092 \times 10^{-5}$ for u quark
 $R = 2.86700612 \times 10^{-6}$ for u anti-quark.
- At $E = 2.00$ GeV
 $R = 5.58694075 \times 10^{-5}$ for d quark
 $R = 1.146829 \times 10^{-6}$ for d anti-quark.
- At $E = 2.00$ GeV
 $R = 0.0135854843$ for s quark
 $R = 0.000261228277$ for s anti-quark.
- At $E = 3.00$ GeV
 $R = 0.141079702$ for c quark
 $R = 0.00649715838$ for c anti-quark.
- From the above values we conclude that the CP violating effect is very dominant in the heavier quarks, namely strange and charm.



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Conclusion and Summary

- Conclusion
 - We have studied QCD $Z(3)$ interfaces at finite temp.
 - Calculated the A_0 profile.
 - Study the reflection and the transmission coefficients.
 - Proposed a Baryogenesis model without B violation.
- Outlook
 - Quantitatively produce the net baryon to photon ratio.
 - Study of signatures of formation of $Z(3)$ interfaces in RHIC.

Thank you



$Z(N)$ symmetries in $SU(N)$

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The Lagrangian of a $SU(N)$ theory is

$$\mathcal{L} = \frac{1}{2} \text{Tr} G_{\mu\nu}^2 + \bar{q}i \not{D}q, \quad G_{\mu\nu} = \frac{1}{-ig} [D_\mu, D_\nu].$$

The Lagrangian is invariant under $SU(N)$ transformations U

$$D_\mu \rightarrow U^\dagger D_\mu U, \quad q \rightarrow U^\dagger U.$$

U satisfies the relations: $\det U = 1$, $U^\dagger U = 1$.

A trivial gauge transformation U would be $U = e^{i\phi} \mathbf{1}$.

Since the $\det U$ has to be one, it must satisfy

$$\phi = \frac{2\pi j}{N}, \quad j = 0, 1, \dots, (N - 1).$$

This defines a global $Z(N)$ symmetry since the integer cannot change continuously.



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Spontaneous breaking of $Z(N)$ symmetry

- Bosons and Fermions follow the boundary conditions

$$A_\mu(\vec{x}, \beta) = +A_\mu(\vec{x}, 0), \quad q(\vec{x}, \beta) = -q(\vec{x}, 0)$$

- However, one can consider more general gauge transformation [’t Hooft 1978].

$$U(\vec{x}, \beta) = U_c, \quad U(\vec{x}, 0) = 1.$$

- Under these general gauge transformations

$$A_\mu^U(\vec{x}, \beta) = U_c^\dagger A_\mu(\vec{x}, \beta) U_c = A_\mu(\vec{x}, \beta) = A_\mu(\vec{x}, 0)$$

$$q^U(\vec{x}, \beta) = U_c^\dagger q(\vec{x}, \beta) = e^{-i\phi} q(\vec{x}, \beta) \neq q(\vec{x}, 0)$$

- Thus, addition of quarks **breaks** the $Z(N)$ symmetry.



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Pisarski Potential

- Effective Lagrangian

$$\mathcal{L} = \frac{N}{g^2} |\partial_\mu l|^2 T^2 - V(l), \quad N = 3 \text{ for } SU(3)$$

- The **Pisarski** potential is [R. D. Pisarski, PRD 62, 111501 (2000)]

$$V(l) = \left(-\frac{b_2}{2} |l|^2 - \frac{b_3}{6} (l^3 + (l^*)^3) + \frac{1}{4} (|l|^2)^2 \right) b_4 T^4.$$

- The coefficients b_2, b_3, b_4 are fixed¹ from lattice results².

$$b_3 = 2.0, b_4 = 0.606147.5/16$$

$$b_2 = (1 - 1.11/x)(1 + 0.265/x)^2(1 + 0.300/x)^3 - 0.478$$

$$\text{where, } x = T/T_c, T_c \sim 182 \text{ MeV.}$$

¹Dimitru and Pisarski, PLB 504, (2001); PRD 66, (2000); NPA 698 (2002)

²G. Boyd *et. al.*, NPB 469, 419 (1996); M. Okamoto *et. al.*, PRD 60 094510 (1999)



Pisarski Potential

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- As $T \rightarrow \infty$, $\langle l(x) \rangle \rightarrow y = b_3/2 + \frac{1}{2} \sqrt{b_3^2 + 4b_2} |_{T \rightarrow \infty}$

- Various quantities are rescaled as

$$l(x) \rightarrow l(x)/y, b_2 \rightarrow b_2/y^2, b_3 \rightarrow b_3/y \text{ and } b_4 \rightarrow b_4 y^4$$

- $\langle l(x) \rangle \rightarrow 1$, as, $T \rightarrow \infty$



A_0 parametrization

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- In non-Abelian theory only the eigenvalue of the matrix $l(x)$ are **gauge invariant**.
- These eigenvalues lies in the space of mutually commuting generators of the group.
- This mutually commuting sub-algebra is called the Cartan subalgebra.
- Cartan subalgebra is a set of linear combinations of the mutually commuting generators λ_3 and λ_8 .