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Affleck-Dine baryogenesis, Q-balls and braneworld

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AD Baryogenesis in models with Large Extra Dim.(LED)

- *Hybridized Affleck-Dine baryogenesis* Phys.Rev.D67(2003)127302
- *Affleck-Dine baryogenesis after thermal brane inflation*, Phys.Rev.D65(2002)103501
- *Affleck-Dine baryogenesis in local domain* Phys.Rev.D65(2002)103502

Brane Q-balls

- *Brane Q Ball, branonium and brane Q ball inflation* JCAP0410:014,2004
- *Formation of monopoles and domain walls...* JHEP 0410(2004)042

Q-ball inflation

- *Q-ball Inflation, Phys.Rev.D68(2003)127302*

Author: T.Matsuda

In this talk we discuss about...

1. Baryogenesis in models with LED.
    - Non-equilibrium decay of heavy X-particle
    - Affleck-Dine
2. Brane Q-balls

Why we consider these issues?

- Baryogenesis with LED requires non-trivial cosmological scenarios that might be distinguishable.
- Brane Q-balls are distinguishable by their decay mode

Strong desire for higher dimensional physics

Problems unsolved;

- Cosmological Constant
- Quantization of the gravity
- Ultimate theory for Unification, etc...

It is unlikely that [Standard Model]+[4D general relativity] can solve the above problems.

Beyond standard model;

- Expanding (gauge or global) symmetry groups
- more than four dimensions
- adding exotic particles,
- etc...

There are too many issues to be discussed.

Phenomenological Models and baryogenesis

Model\ Mechanism	X-decay	AD	leptogenesis
SUSY-GUT	**A**	**B**	**C**
Large extra dim.	**D**	**E**	**F**

- **A** GUT baryogenesis in SUSY-GUT

  Non-equilibrium decay of heavy particles(X→ ql, qq)

  $$\left.\begin{array}{l}\text{Thermal production of heavy particles} \rightarrow T_R > M_{GUT} \\ \text{Gravitino problem} \rightarrow T_R < 10^9 \text{ GeV}\end{array}\right\} \rightarrow \text{Contradiction}$$

  Parametric Resonance, Cosmic string decay, etc...

  Production of heavy particles requires non-trivial mechanisms.(safe)

- **B** Affleck-Dine baryogenesis in SUSY-GUT

  Model-dependent problems(example)

  $$\left\{\begin{array}{l}\underline{\text{Q-ball problem}}\ : \\ \text{Initial charge density is too large} \rightarrow \text{lifetime of Q-balls become too long} \\ \underline{\text{Early Oscillation}}\ : \\ \text{Thermal effect} \rightarrow \text{early oscillation} \rightarrow \text{AD is unsuccessful}\end{array}\right.$$

  There are many solutions.(safe)

- **C** leptogenesis in SUSY-GUT

  Right-handed neutrino could remove difficulties in conventional GUT baryogenesis.(advantage)

- **D** GUT baryogenesis in Large extra dim.

$$\begin{cases} \text{Heavy particles are not heavy } (M_X < M_*) \\ \text{Small } M_* \text{ requires additional mechanisms} \end{cases}$$

Example : $M_* \ll M_{GUT}$

$$\left.\begin{array}{l} \text{Proton stability} \rightarrow \text{additional mechanism or symmetry} \\ \text{Baryogenesis} \rightarrow \text{enhanced baryon number violation} \end{array}\right\} \text{"both" are needed}$$

Baryon number violation is suppressed in the true vacuum, while it must be enhanced “somewhere” and “sometime”.

→ “Defects” are needed

- **E** Affleck-Dine baryogenesis in LED

Serious problems for small M_*!

MSSM Flat Direction on “our” brane cannot produce baryon number

  - AD after thermal brane inflation(Matsuda)
  - AD field is a bulk field(Mazumdar)

- **F** Leptogenesis and LED.

$$\left.\begin{array}{l} \text{Sphalerons cannot be activated if } (T_{RH} < T_{EW}) \\ \text{Small } M_* \rightarrow \text{small } T_{RH}(T_{RH} < T_{EW}) \end{array}\right\} \text{Contradiction}$$

How one can convert leptons into baryons?

(Additional mechanism for L→B is required)

Finding “signatures of branes” in observations is important

Baryogenesis and defects in brane models might be important to find “signatures of branes”

- Baryogenesis in LED

  Suppressed couplings $qqql$ from non-trivial mechanisms

  Low reheat temperature...

  → Baryogenesis requires non-trivial mechanism which could be distinguishable in future observations

- Defects in brane models(3 types)

  1. Defects are produced by brane creation.

     Brane inflation → tachyon condensation

     → brane creation = defect production

     → baryogenesis, UHECR, etc...

  2. Defects = deformed branes.

     Spatial fluctuation of the “position”

     → domain walls, strings, Q-balls, etc

  3. Localized fields are shifted in the defect.

     → Enhanced baryon number violation in the core

     → baryogenesis etc

These ideas are important to find “branes”.

Baryogenesis from X-decay (particles or defects) in LED

$M_* \simeq O(TeV)$

Decay of a heavy particle $X \rightarrow qq, ql$

$$\mathcal{L} \;=\; \lambda_1 X \overline{q}\overline{q} + \lambda_2 X l q$$

X-decay(Branching ratio r) and $\overline{X}$-decay(Branching ratio $\overline{r}$) $\rightarrow n_B \sim (r - \overline{r})$

***Difference is important.**

Large $X \rightarrow \overline{q}\overline{q}$ does not mean large baryon asymmetry.

In conventional scenario, $\lambda_i \sim O(1)$, the ratio($\epsilon = r - \overline{r}$) is determined by CP breaking parameters.

$$\frac{n_B}{s} \simeq \epsilon O(\lambda_i) \frac{T_R}{M_X} \tag{1}$$

However,

$M_* < M_{GUT}$ (Large Extra dimensions) $\rightarrow \lambda_i \ll 1$!! (to suppress p^+ decay)

Even the most efficient mechanism (Inflaton decays directly into X) cannot explain baryon asymmetry of the Universe if $\lambda_i \ll 1$!!

→ So we need non-trivial mechanism. λ_i must be enhanced sometime and somewhere!! → We consider cosmic defect

Before we discuss baryogenesis, we should review the mechanism...

How one could obtain $\lambda_i \ll 1$?

Wavefunction localization → $\lambda_i \ll 1$

Lagrangian

$$
\begin{aligned}
\mathcal{L} &= \overline{\psi_i}\left(i\,\partial\!\!\!/_5 + g_i\phi_A(y) + m_{5,i}\right)\psi_i \\
&\quad +\frac{1}{2}\partial_\nu\phi_A\partial^\nu\phi_A \\
&\quad -V(\phi_A), \qquad (2)
\end{aligned}
$$

→ Wave function becomes the Gaussian function localized at the zeros of $g_i\phi_A(y) + m_{5,i}$.

→ λ_i is suppressed by the factor e^{-r}; r is the distance

Two Solutions

1. λ_i could be enhanced in the early Universe(Assumption)(Chung & Dent)
2. Local structure (defect) could enhance baryon number violation in low temperature.(T.Matsuda)

Candidates for the "local structure": here we consider two

1. **False Vacuum Domain (Domain walls)**
2. **String Core**

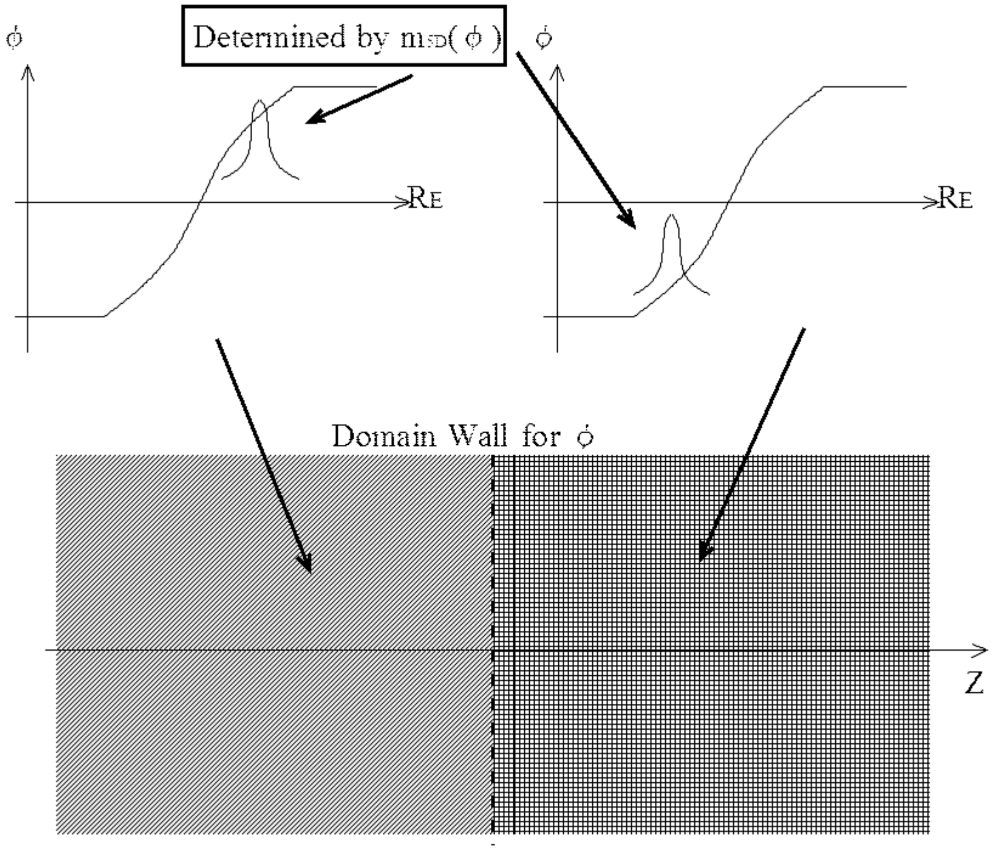

Figure 1: Localization and defects

The center of localization is determined by the mass $m_{5D}(\phi)$. If the VEV. of ϕ is shifted by the defect, the center of localization is shifted.

Idea: Enhanced λ_i

Let us assume that the five-dimensional mass depends on a field ϕ_B.

$\rightarrow m(\phi_B)_{5,i}$ is shifted **if** ϕ_B forms defects in the uncompactified space.

→ The center of the wavefunction is shifted.

$\rightarrow \lambda_i$ could be enhanced.

Example 1 False Vacuum Domain

$\phi_B = \pm v(\text{Two vacua : quasi-degenerated})$

→ In the "false vacuum" the shift of the "distance(r)" between q and l is $O(1)$

→ If $r' = r/2$, the suppression factor becomes $e^{-\mu^2 r^2} = 10^{-33} \rightarrow 10^{-8}$.

(Suppression factor is sensitive to the shift)

Result:

If the shift is $r' = r/2$, about 10^{25} **times enhancement!!** and cosmologically safe.

Enough to explain Baryogenesis by the non-equilibrium decay of X particles

Example 2 GUT string (decay and scattering)

Baryon number violation induced by (conventional) GUT strings and monopoles is an old issue.

Lagrangian (GUT) contains Yukawa interactions;

$$\mathcal{L} = -\lambda(\phi_X \overline{\chi}\psi + \phi_X^* \overline{\psi}\chi) \tag{3}$$

ψ and χ are fermions which have the charge of B or L.

String scattering cross section is already known for the above interactions. Dirac equations have off-diagonal elements $\lambda < \phi_X >$, which induces mixings in the core.

$$\begin{pmatrix} i\not{\partial} - i\not{A} - m_\psi & \lambda < \phi_X >^* \\ \lambda < \phi_X >^* & i\not{\partial} - i\not{A} - m_\chi \end{pmatrix} \begin{pmatrix} \psi \\ \chi \end{pmatrix} = 0 \tag{4}$$

where

$$A = \frac{1}{gr^2}\begin{pmatrix} 0 \\ -y \\ x \end{pmatrix}, \quad \lambda < \phi_X >= \begin{cases} 0, & for\ [r > R] \\ v, & for\ [r < R]. \end{cases} \tag{5}$$

It is easy to calculate the transition rate on the above potential by using the explicit form of the incoming waves and outgoing waves.

($B \leftrightarrow L$ scatterings are effective in GUT strings)

Then, what happens if we apply the same calculation to models of large extra dimensions?

Unfortunatelly, the suppression in the cross term, which comes from $\lambda_i \simeq O(M_*^2/M_p^2) << 1$ is crucial. The scattering cross section is negligible!!

→ Here we use "the idea"!! Then, something interesting happens.

Let us consider strings of the field ϕ_B.

- If $\lambda_i \simeq 1$ in the core, the scattering cross section is not negligible.
- Even if M_* is as small as TeV, the defects can affect the physics after inflation.

For example, let us consider a low-energy GUT model.

$$\begin{aligned} \bar{5}\,(g_5 < \Sigma > + M_5 + \phi_A)\, 5 &= 0 \\ \overline{10}\,(g_{10} < \Sigma > + M_{10} + \phi_A)\, 10 &= 0. \end{aligned} \tag{6}$$

Gut strings are formed by $< \Sigma >= v \times diag(2,2,2,-3,-3)$. In this case $< \Sigma >$ plays the role of ϕ_B, and in the core of the GUT strings the enhancement occurs naturally!!

($B \leftrightarrow L$ scatterings are effective)

Summary of baryogenesis in LED

($M_* \sim O(TeV)$ baryogenesis from X decay, and leptogenesis)

- Conventional baryogenesis is unsuccessful because of the tiny coupling constants $\lambda_i \sim 10^{-33}$
- X-decay (Defect-mediated)
  - In the false vacuum domain→ baryogenesis is successful
  - String decay → baryon number production is still too small
- leptgenesis
  - Scatterng from Strings ($L \leftrightarrow B$) is effective.

    → Leptogenesis without sphalerons could be successful.

AD + Large Extra Dimension

Problems

We assume that AD flat directions are MSSM flat directions on a brane.

1. To destabilize MSSM flat directions, we need $H > m_{soft}$.

   $\rightarrow V_{Infla} > (10^{10} GeV)^4 \rightarrow M_* > 10^{10} GeV$?

2. Initial value of the AD must be large($\phi_{AD} > 10^{10} GeV$).

   $\rightarrow M_* > 10^{10} GeV$?

3. Small energy density

$$\frac{n_b}{s} \approx \frac{n_b}{n_\chi} \frac{T_{\mathrm{r}}}{m_\chi} \frac{\rho_\chi}{\rho_{\mathrm{I}}}. \tag{7}$$

- The AD field is a brane-field, $\rightarrow \rho_\chi \approx m_\chi^2 M_*^2$ (Small !!).
- Effective four-dimensional energy density of the Bulk field $\rho_{\mathrm{I}} \approx M_{soft}^2 M_{\mathrm{p}}^2$ (Large !!)

$\rightarrow \frac{\rho_\chi}{\rho_{\mathrm{I}}} \ll 1$

Two Solutions

1. AD field = bulk field (Mazumdar et al.)

   - In LED, non-trivial bulk-brane field interactions are required.
   - If the bulk field is induced by the distance between branes

     → Brane Q-balls?

2. AD baryogenesis at late times(Matsuda)

   - AD after thermal brane inflation
   - Defect-mediated AD

Affleck-Dine baryogenesis after thermal brane inflation

Conventional Sugra

Soft terms

$$L_{soft} \sim \int d^4\theta \, \frac{1}{M_4^2} X^\dagger X Q^\dagger Q \tag{8}$$

Here X is a chiral superfield in the hidden sector whose F component F_X breaks supersymmetry. Q is a matter field in the visible sector.

A-terms

Higher dimensional operators in the superpotential $W_A \sim \frac{1}{M_p^{n+3}} \Phi^{n+3}$ produce A-terms and determines the phase of the AD direction at large $< \Phi >$.

$$L_A \sim \int d^4\theta \, \left(\frac{1}{M_4^{n+3}} X^\dagger X \Phi^{n+3} + h.c. \right) + \int d^2\theta \, \left(\frac{1}{M_4^{n+1}} X \Phi^{n+3} + h.c. \right) \tag{9}$$

where $n \geq 1$ and Φ represents the flat direction.

In conventional SUGRA, stabilized-destabilized phase transition is induced by H_{INF}, which requires large H_{INF}.

When matter fields are localized

Soft terms

$$V(\phi_{AD}) \sim \left[m_{soft}^2 + c \left(\frac{|F_X|}{M} \right)^2 e^{-M r_{susy}} \right] |\, \phi_{AD}|^2. \tag{10}$$

Here ϕ_{AD} is the flat direction of Affleck-Dine mechanism, and r_{susy} is the distance between the matter brane and the hidden supersymmetry-breaking brane on which F_X is localized. m_{soft} denotes the supersymmetry breaking induced on the matter brane, which is assumed to be a constant.

A-term

$$V_A \simeq \left(\frac{a_0 m_{soft}}{M_p} + \frac{a_1 |F_X| e^{-M r_{susy}}/M}{M} \right) \phi_{AD}^4 \tag{11}$$

where a_0 and a_1 are constants of O(1).

$\ast$ $O(H_{INF})$ terms are negligible ($H_{INF} \ll m_{soft}$)

During Thermal brane Inflation($r_{susy} = 0$)

Soft terms

$$V(\phi_{AD}) \sim \left[c\left(\frac{|F_X|}{M}\right)^2\right]\phi_{AD}|^2. \tag{12}$$

A-term

$$V_A \simeq \left(\frac{a_1|F_X|}{M}\right)\phi_{AD}^4 \tag{13}$$

These terms dominate soft and A-terms during thermal inflation, which induces the required displacements for the AD fields.

After Thermal Inflation($r_{susy} >> M_*^{-1}$)

Soft terms

$$V(\phi_{AD}) \sim m_{soft}^2|\,\phi_{AD}|^2. \tag{14}$$

A-term

$$V_A \simeq \left(\frac{a_0 m_{soft}}{M_p}\right)\phi_{AD}^4 \tag{15}$$

Baryogenesis

The sole difference is that the supersymmetry is not induced by the Hubble parameter, but is induced by the brane distance. The resultant baryon to entropy ratio is

$$\frac{n_B}{s} \sim \frac{T_{R2}}{M_p H_o \rho_I} |a m_{soft} (\phi^i_{AD})^4| \delta_{eff} \tag{16}$$

where T_{R2} is the reheating temperature after thermal brane inflation, and ϕ^i_{AD} is the initial amplitude of ϕ_{AD}. H_o denotes the Hubble parameter when the AD oscillation starts, which can be taken to be $H_o \leq H_I = M^2/M_p$. It is naturally assumed that the initial amplitude is $\phi^{ini}_{AD} \sim M$, and the inflaton density is still $\rho_I \sim M^4$ at the beginning of the oscillation. Then we obtain:

$$\frac{n_B}{s} \sim 10^{-10} \left(\frac{T_{R2}}{10 MeV} \right) \left(\frac{10^{-8} GeV}{H_o} \right) \tag{17}$$

which is the most naive result, but is enough to explain the origin of the baryon asymmetry of the present Universe.

Summary of AD Baryogenesis in LED

If the standard model fields are licalized on a wall-like structure,

- Conventional AD is unsuccessful
- AD field = Bulk field(Mazumdar) is successful but requires additional couplings.
- AD after thermal brane inflation lowers the energy density of the inflation field. → “successful”
- Defect-mediated AD is successful.

Before we explain the idea of brane Q-balls, we must start from the basic review of bare defects...

Brane Defects(1)

Brane = defect

∗ Defects do not always wrap the same compactified space as the mother brane.

	x_0	x_1	x_2	x_3	x_5	x_6	x_7	...
Cosmic String	+	+	-	-	/	/	/	...
Domain Wall	+	+	+	-	/	/	/	...

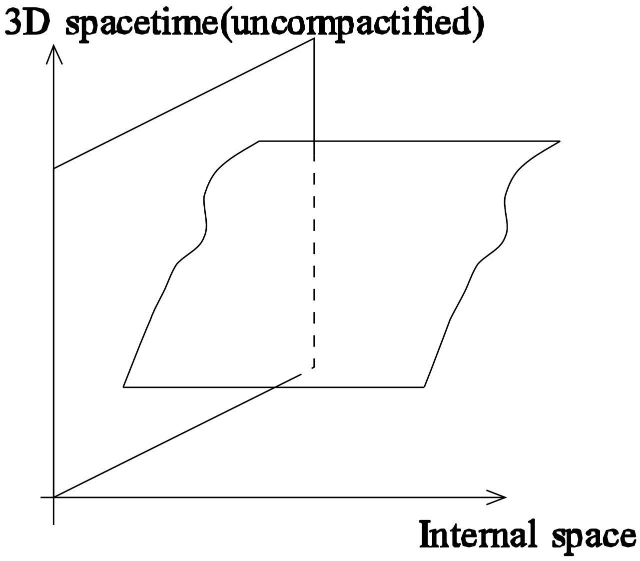

Figure 2:

There are **many** interesting topics in this field, which we cannot discuss in this talk....

1 Brane Defects(2)

Defect = Brane Deformation

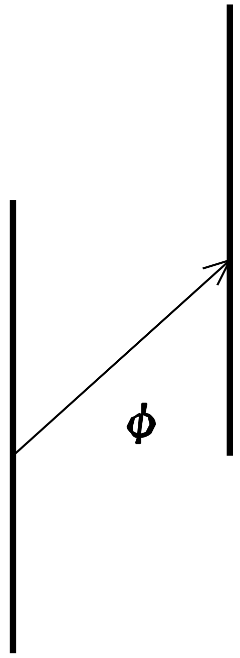

Figure 3:

Spatial variation of the field ϕ produces defects.

There are two ways to investigate...(complementary)

- Field-Theoretical constructions(Classical)

  (Branes=defects in higher dimensional gauge theory)

  → Useful to investigate higher-energy effects

  ("Smearing branes" etc.)

- Brane constructions (MQCD, etc.)

  → Useful to see quantum effects(anomaly)

  → Axionic strings, axionic domain walls, etc.

Branonium and Q-balls

It seems circumbendibus, however from historical reasons we must start from the discussions about why "Branonium" is unstable.

C.P.Burgess, P.Martineau, F.Quevedo, R.Rabadan (CERN), JHEP 0306:037,2003

J.Ellison, A.Lukas (Sussex U.), Phys.Rev.D70:083518,2004

C.P.Burgess, F.Quevedo, R.Rabadan, G.Tasinato, I.Zavala, JCAP 0402:008,2004

C.P.Burgess, N.E.Grandi, F.Quevedo, R.Rabadan, JHEP 0401:067,2004

Branonium is induced by the rotating branes.

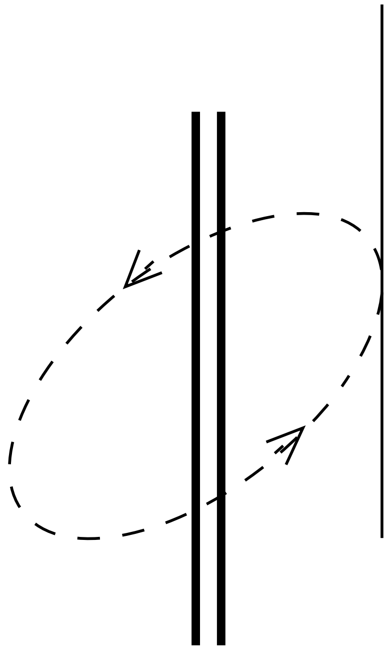

Figure 4: The simplest configuration of Branonium. A brane is rotating around the stack of heavy anti-branes.

To see "branonium" in the effective action, we include the field ϕ (corresponding to the relative distance between branes) and consider the effective action for $\phi = |\phi| e^{i\omega t}$.

- Kinetic term for the field ϕ:

$$\begin{aligned} S &\simeq -T_3 \int d^4\zeta \frac{1}{2} \partial^\mu X_a \partial_\mu X_a \\ &\equiv -\int d^4\zeta \frac{1}{2} \partial^\mu \phi \partial_\mu \phi. \end{aligned} \tag{18}$$

- Potential

$$V(\phi) = M_*^4 \left[1 - \frac{k M_*^4}{\phi^4}\right] + \text{soft terms}, \tag{19}$$

  where $M_*^4 \simeq T_{D3}$ is assumed, and k is a constant of $k < O(10^{-3})$.

From numerical simulation, we know that the same effective action induces clustering of charges (angular momentum) into "Q-balls".

- **What corresponds to "Q-balls" in the brane picture?**

- **Branonium is discussed to be stable.**

  → **Why? Is the reason appropriate?**

- Are Brane Q-balls identical to conventional Q-balls ? (NO!!)

  * Charged objects rotating each other

  → In brane picture, there must be radiation into the bulk

Let us see more details to show how **brane Q-balls** could be distinguished from conventional Q-balls.

Radiation from Brane Q-balls

Let us first consider the effective action for the simplest $D3\overline{D3}$ branonium.

- Kinetic term for the field ϕ:

$$\begin{aligned} S &\simeq -T_3 \int d^4\zeta \frac{1}{2}\partial^\mu X_a \partial_\mu X_a \\ &\equiv -\int d^4\zeta \frac{1}{2}\partial^\mu \phi \partial_\mu \phi. \end{aligned} \tag{20}$$

- Potential

$$V(\phi) = M_*^4 \left[1 - \frac{kM_*^4}{\phi^4}\right], \tag{21}$$

  where $M_*^4 \simeq T_{D3}$ is assumed, and k is a constant of $k < O(10^{-3})$.

- Conventional parameters for Q-balls

$$\begin{aligned} r_Q \simeq \frac{Q^{1/4}}{M_*}, &\quad \omega \simeq \frac{M_*}{Q^{1/4}} \\ \phi_Q \simeq M_* Q^{1/4}, &\quad E_Q \simeq M_* Q^{3/4} \end{aligned} \tag{22}$$

  where Q, r_Q, and E_Q denote the charge, the radius, and the energy of the Q-ball.

Now let us calculate the decay rate of the brane Q-balls!

- Normal decay (Well-known)

$$|\frac{dQ}{dt}| \leq \frac{\omega^3 A}{192\pi^2}. \tag{23}$$

Here $A = 4\pi r_Q^2$ is the surface area of the Q-ball. From eq.(23) and (22), we obtain the upper bound

$$\frac{dE_Q}{dt} \leq -c_q \frac{M_*^2}{Q^{1/2}}, \tag{24}$$

where the constant c_q is $c_q \leq O(10^{-3})$.

- Radiation into bulk

$$P \sim \frac{1}{8\pi} \left(\kappa_4 T_p V_p\right)^2 a_b^2, \tag{25}$$

where κ_4 and V_p are the 4-dimensional gravitational coupling and the spatial volume of the Dp-brane, respectively.

From the above equations;

The radiation into bulk dominates when the charge Q exceeds the critical value

$$Q_c^{3/2} \simeq c_1 \frac{M_p^2}{M_*^2}, \tag{26}$$

where $c_1 \simeq 10^{-2}$. Here the approximation $a_b \simeq \delta_{brane}\omega^2 \simeq (\phi_Q/M_*^2)\omega^2$ is used.

Result: The decay of brane Q-balls is dominated by the radiation into bulk during $Q > Q_c$, while it is dominated by the normal process during $Q < Q_c$.

*What happens in MQCD setups?

Ans : The radiation into bulk is always dominant.

Summary of brane Q-balls

1. The stability of branonium is discussed in the above papers and concluded that branonium is stable. **However**, the angular momentum (charge of Q-balls) was **assumed** to be homogeneous, then the stability of the brane distance is examined on this peculiar assumption!! Of course one cannot accept this result. Normally, branonium must fragment into Q-balls.
2. There is a distinctive radiation into the bulk, which can be used to distingish brane Q-balls from conventional Q-balls.

2 Conclusions and Discussions

Baryogenesis in LED models

- GUT models with small M_* requires additional mechanism to stabilize p^+.
- Small M_* requires small reheat temperature.
- Small M_* requires small $< \phi_{AD} >$.

→ Serious obstacles in “any” kind of baryogenesis

We have shown that defects could play important roles.

→ Could be Distinguishable in future observations

Brane Q-balls in brane models

- Brane Q-balls are distingishable