Charged Q-balls in gauge mediated SUSY breaking models

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Motivations

• After Affleck-Dine baryogenesis, spatial inhomogeneities of Affleck-Dine field grow into non-topological solitons called **Q-balls**, which are typically neutral.

• We hope Q-balls survive until present universe and contribute to Dark Matter.

• In **Gauge Mediated SUSY Breaking Models**, Q-balls are stable against decay into nuclei, but may decay into leptons, which are typically lighter than nuclei.

  - Decay into charged leptons
    → Q-balls are electrically charged
    : **Charged Q-balls**
  - Stability of baryonic component
    → Charged Q-balls may survive in the universe.

  : **Charged Q-balls as Dark Matter?**
Affleck-Dine Baryogenesis

Affleck, Dine (1985)

- Dynamics in phase direction of Baryonic(Leptonic) scalar fields in MSSM(squark, slepton) can generate Baryon Asymmetry.

\[ n_B \sim i(\phi^* \dot{\phi} - \dot{\phi}^* \phi) \]
\[ \sim r^2 \dot{\theta} \quad (\phi = re^{i\theta}) \]

: analogous to angular momentum
Q-ball formation


• After Affleck-Dine baryogenesis, spatial inhomogeneities of the scalar field grow into non-topological solitons called Q-balls.

• Conserved Charge: Baryon(Lepton) number

T. Hiramatsu, M. Kawasaki, F. Takahashi (2010)
Gauge Mediation Type Q-ball

Dvali Kusenko Shaposhnikov (1998)

\[ E = \frac{4\pi \sqrt{2}}{3} M_F Q^{3/4}, \]

\[ \omega \equiv \frac{dE}{dQ} = \sqrt{2\pi} M_F Q^{-1/4} \quad < \text{proton mass}(Q>>1) \]

: Stable against decay into nuclei

\[ R = \frac{\pi}{\omega} \quad (M_F \sim 10^6 \text{GeV}) \]
Charged(Gauged) Q-ball(1-scalar)


• Baryonic(Leptonic) scalar field with local U(1) charge + U(1) gauge field
• As a U(1) gauge field, consider only Coulomb potential, neglecting magnetic field, or electric current.
  : Neglect electrodynamical effects, and consider only electrostatic solutions.
Charged(Gauged) Q-ball(1-scalar)


• Gauge Mediation Model

Field Values

\begin{align*}
E &= 2.47 \times 10^4 \\
Q &= 2.73 \times 10^4
\end{align*}

Field Values

\begin{align*}
E &= 7.00 \times 10^4 \\
Q &= 6.43 \times 10^4
\end{align*}

Pushed outward by electric repulsion

\[ r \]
Charged Q-ball(2-scalar)

• Baryonic(Leptonic) scalar fields

\[ \Phi_1, \Phi_2 \leftrightarrow L=1 \]

\[ B=1 \]

Local U(1) Charge= (+1, -1)

+ U(1) gauge field (Coulomb potential, neglecting magnetic field or electric current)
Leptonic decay

\begin{align*}
E &= 7.1 \times 10^4 \\
B &= 8.4 \times 10^4 \\
L &= 8.4 \times 10^4 \\
Q &= B - L = 0
\end{align*}

\begin{align*}
E &= 6.9 \times 10^4 \\
B &= 8.4 \times 10^4 \\
L &= 7.1 \times 10^4 \\
Q &= B - L = 1.4 \times 10^4
\end{align*}

\begin{align*}
E &= 8.4 \times 10^4 \\
B &= 8.4 \times 10^4 \\
L &= 2.6 \times 10^4 \\
Q &= B - L = 5.8 \times 10^4
\end{align*}

\begin{align*}
E &= 9.6 \times 10^4 \\
B &= 8.4 \times 10^4 \\
L &= 7.1 \times 10^3 \\
Q &= B - L = 7.7 \times 10^4
\end{align*}

\[
\text{Coulomb potential arises.}
\]
Leptonic decay

**Field Values**

- **$E = 7.1 \times 10^4$**
- **$B = 8.4 \times 10^4$**
- **$L = 8.4 \times 10^4$**
- **$Q = B - L = 0$**

$\phi_1$

$\phi_2$

$A_0$

$\frac{dE}{dL} > 0$

$\Rightarrow$ decay into particles

$\Rightarrow$ form a bound state

$\Rightarrow$ a Leptonic cloud is formed.
Leptonic decay

neutral Q-ball
Leptonic decay

\( (\frac{\partial E}{\partial L})_B = 0 \)

\( 0 = \left( \frac{\partial E}{\partial L} \right)_B \approx \omega_0 L - \frac{e^2 Q}{4\pi R_L} \)

\( \approx \omega_0 L - \frac{e^2 Q}{4\pi^2} \omega_0 L, \)

\( Q = \frac{4\pi^2}{e^2}. \)

\( (e^2 = 0.002) \)
Extension to larger Q-balls

• Large Q-balls cannot form the cloud:
  Q-ball size $> \text{Cloud radius} (\sim \text{Bohr radius})$

• Threshold: Q-ball size $\sim \text{Bohr radius}$
  \[ B \sim 10^{36} (M_F/10^6 \text{GeV})^4 \]
  : For $B \gtrsim 10^{36} (M_F/10^6 \text{GeV})^4$, evolution stops at $Q = 4\pi^2/e^2$, so that charged Q-balls with $Q = 4\pi^2/e^2$ survive in the universe.
Extension to larger Q-balls

- Large electric field $\rightarrow$ electron-positron pair production (Schwinger process).

: prevents further growth of the electric charge of the Q-ball.

\[
E_S = \frac{m_e^2}{e} = \frac{eQ_S}{4\pi R^2}
\]
\[
= \frac{eQ_S}{4\pi^3} \omega_0^2
\]
\[
= \frac{eQ_S}{2\pi} M_F^2 B^{-1/2},
\]

\[
Q_S \sim \frac{4\pi^2}{e^2} \left( \frac{M_F}{10^6 \text{GeV}} \right)^{-2} \left( \frac{B}{10^{39}} \right)^{1/2}
\]
Extension to larger Q-balls

• Pair creation occurs at spatial interval about Compton length.

→ When the size of Q-ball becomes smaller than Compton length \((R < 1/m_e \Leftrightarrow B \lesssim 10^{38})\), the electric charge of the Q-ball can grow until

\[
E_S = \frac{m_e^2}{e} = \frac{eQ_S}{4\pi(1/m_e)^2},
\]

\[
Q_S = \frac{4\pi}{e^2}
\]
Conclusions

\[(\partial E/\partial B)_L = m_p\]

\[(e^2=0.002)\]

\[4\pi^2/e^2(B/10^{39})^{1/2}\]

\[4\pi^2/e^2\]

((\partial E/\partial L)_B = 0)