Q-BALLS IN THE MSSM

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In the MSSM with gravity mediated supersymmetry breaking, there may exist unstable but long-lived solitons carrying large baryonic charge, or B-balls. These decay well after the electroweak phase transition, giving rise to B-ball baryogenesis. Being made of squarks, B-ball decays produce also LSPs and hence can be the source for all cold dark matter.

A Q-ball is a stable, charge Q soliton in a scalar field theory with a spontaneously broken global $U(1)$ symmetry. The Q-ball solution arises provided the scalar potential $V(\phi)$ is such that $V(\phi)/|\phi|^2$ has a minimum at non-zero $\phi$. In the MSSM such solitons are necessarily part of the spectrum of the theory, as was first pointed out by Kusenko. This is due to the form of the MSSM scalar potential and the fact that squarks and sleptons carry a global $B-L$ charge. The crucial question is whether B-balls and/or L-balls can be copiously created in the early Universe and whether they could naturally be sufficiently long-lived to have important consequences for cosmology.

An interesting possibility for Q-ball formation is provided by the fact that there are many flat directions in the MSSM. During inflation the MSSM scalar fields are free to fluctuate along these flat directions and to form condensates. This is closely related to Affleck-Dine (AD) baryogenesis, in which a B violating scalar condensate forms along a D-flat direction of the MSSM scalar potential composed of squark and possibly of slepton fields. The difference now is that the condensate is naturally unstable with respect to the formation of Q-balls with a very large charge.

The properties of the MSSM Q-balls will depend upon the scalar potential associated with the condensate scalar, which in turn depends upon the SUSY breaking mechanism and on the order $d$ at which the non-renormalizable terms lift the degeneracy of the potential; examples are the $H_u L$-direction with $d=4$ and $u^c d^c d'^c$-direction with $d=6$. If SUSY breaking occurs at low energy scales, via gauge mediated SUSY breaking, Q-balls will be stable. Stable B-balls could have a wide range of astrophysical, experimental and practical implications.

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A more conservative possibility is that SUSY breaking occurs via the supergravity hidden sector. In this case the potential is not flat, but nevertheless radiative corrections to the $\phi^2$-type condensate potential allow B-balls to form. Such B-balls can decay at temperatures less than that of the electroweak phase transition, $T_{ew}$, and consequently they could have important implications for baryogenesis.

A particularly promising case is the $d=6$ $u^c u^c d^c d^c$ flat direction, along which the potential reads

$$V_6 \simeq m^2_S |\phi|^2 + \frac{\lambda^2 |\phi|^{10}}{M_p^6} + \left( A_\lambda \frac{\lambda \phi^6}{M_p^3} + h.c. \right),$$ (1)

where $\lambda$ and $A$ are coupling constants and the SUSY breaking mass $m^2_S \simeq m^2_0 [1 + K \log(|\phi|^2/\phi^2_0)]$, where $\phi_0$ is the reference point and $K$ a negative constant (and mainly due to gauginos), decreases as $\phi$ grows, thus allowing B-balls to form. The potential is stabilized by the non-renormalizable term so that the condensate field takes the value $\phi \simeq 4 \times 10^{14}$ GeV. The decreasing of the effective mass term is also responsible for the growth of any initial perturbation. In particular, there are perturbations in the condensate field inherited from the inflationary period. As was discussed in ref. 11, these will grow and become non-linear when $H \simeq 2 |K| m_S \alpha^{-1}$, where $\alpha \simeq -\log(\delta \phi(\lambda_0)/\phi_0)$ with $\lambda$ the length scale of the perturbation at $H \approx m_S$, and $\phi_0$ is the value of $\phi$ when the condensate oscillations begin. The charge of the condensate lump is determined by the baryon asymmetry of the Universe at $H_i$ and the initial size of the perturbation when it goes non-linear.

The formation of B-balls from the AD condensate can be shown to be generally effective if the charge density inside the initial lump is small enough;
this can be translated to a condition on the reheating temperature which reads

\[
T_R \gtrsim \frac{\eta B m \mu^2}{8\pi \phi_0^2} = 0.23 \left( \frac{m_S}{100\text{ GeV}} \right). \tag{4}
\]

After the formation B-balls could be dissociated by the bombardment of thermal particles, or dissolve by charge escaping from the outer layers. Both problems can be avoided provided \(T_R \lesssim 10^3 - 10^5\) GeV for \(|K|\) in the range 0.01 to 0.1. It then follows from Eq. (5) that the surviving B-balls must have very large charges, \(B \gtrsim 10^{14}\). The decay rate of the B-ball also depends on its charge; it has been estimated to have an upper bound, which is likely to be saturated for B-balls with \(\phi_0\) much larger than \(m_0\) (as in the case of \(d=6\) B-balls), and is given by

\[
\frac{dB}{dt} = -f_s \frac{\omega^3 A}{192\pi^2}, \tag{5}
\]

where \(A\) is the area of the B-ball, \(\omega \approx m_0\) for \(|K|\) small compared with 1, and \(f_s\) is a possible enhancement factor due to condensate decaying into scalars. We expect that \(f_s \lesssim 10^3\), although it is quite possible that the B-ball is made of the lightest squark, in which case only \(f_s = 1\). In the latter case the resulting decay temperature is depicted in the Figure as a function of the Q-ball charge for both thin and thick-wall Q-balls, which have different surface areas (\(d=6\) B-ball is of the thick-wall variety). As can be seen, for \(B \gtrsim 10^{14}\), B-balls will indeed decay well below the electroweak phase transition temperature, providing a new source of baryon asymmetry not washed away by sphaleron interactions. The only requirement is relatively low reheating temperature after inflation, typically of the order of 1 GeV, which is fixed by the observed baryon asymmetry when the CP violating phase responsible for the baryon asymmetry is of the order of \(10^{-12}\). In particular, this is expected to be true for D-term inflation models.

Being made of squarks, B-balls initially decay to LSPs and baryons with a similar number density (with three units of R-parity produced for each unit of baryon number). Given the efficiency, \(f_B\), by which B-balls are created from the collapsing AD condensate, the B-ball produced LSP and baryonic densities will be related by

\[
\Omega_{BB} = \frac{3f_B m_{\text{LSP}}}{m_N} \Omega_B. \tag{6}
\]

If the reheating temperature is smaller than the the freeze-out temperature of the LSPs, given by \(T_f \simeq m_{\text{LSP}}/20\), then B-balls would be the only source for cold dark matter. If \(T_R \gtrsim T_f\), a relic LSP density would exist, with interesting implications for the sparticle spectrum. Hence B-balls promise to provide a novel and complete alternative to the more conventional cosmological scenario.
Figure 1: Q-ball decay temperature $T$ vs. the charge $Q$ for $d=4$ and $d=6$ Q-balls. The regions where L-balls and B-balls exist are also indicated.

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