A new bound on supersymmetric Q-balls

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Abstract

Stable baryonic Q-balls, which appear in supersymmetric extensions of the Standard Model, could form at the end of cosmological inflation from fragmentation of the Affleck-Dine condensate. They can be dark matter. The existing bounds rely on the ability of Super-Kamiokande detector to trigger on a slowly moving bright source, which may be difficult for technical reasons. We present a weaker but more robust bound based on the flux of neutrinos produced by relic Q-balls interacting in Earth.

In the search for dark matter, supersymmetry (SUSY) provides two possible candidates: the lightest supersymmetric particle (for example, neutralino or gravitino), and stable Q-balls. SUSY Q-balls are nontopological solitons that carry baryon number [1]. Some Q-balls are stable or have lifetimes in excess of the age of the universe in theories with gauge-mediated SUSY breaking. They can form in the early universe from the fragmentation of the Affleck–Dine condensate [3] and they can presently exist as dark matter [2,4].

Because of the wide acceptance of supersymmetry as a candidate for physics beyond the standard model– and the corresponding implication of the existence of Q-balls– the desire to find experimental evidence for Q-balls is strong. However, there is a large range of uncertainty in the parameters involved, such as Q-ball mass, radius, cosmic abundance, and cross section. We therefore attempt to use extant experimental data to bound the region of future experimental interest.

Interactions of Q-balls in matter result in induced "proton decay" processes. A quark scattering off a Q-ball can reflect back as an antiquark with probability of order one [5]. The baryon number of the Q-ball changes in the process, so the overall baryon number of Q-ball and hadron is unchanged. However, a proton scattering off Q-ball can turn into an antiproton and can annihilate with one of the baryons in the ambient matter. Hence, a SUSY Q-ball passing...
through matter deposits as much as $\sim 10^3$ GeV of energy per 1 cm of track, and most of this energy is generated in the form of soft pions [6].

Astrophysical bounds based on stability of neutron stars are the strongest limits on many types of Q-balls [7]. A neutron star can be eaten away in a time shorter than the age of the universe if the Q-balls can grow big in its interior. However, depending on the structure of the operators that lift the MSSM flat directions, the baryon number violation can be triggered by a large VEV, which can stymie the further growth of Q-balls. For such Q-balls, the laboratory bounds are still the strongest.

The current laboratory bounds [8,10] rely on the abundance of relic SUSY Q-balls rely on the ability of Super-Kamiokande detector to register the passage of a slowly moving object producing a large amount of light. On entering the detector, the Q-ball would cause all its phototubes to saturate. Since all the tubes are effectively blinded, no further information is available. Events of this kind have happened in the past, both in Super-Kamiokande and in its predecessor, Kamiokande [9]. A clustering of low energy spallation events followed a bright flash saturating the detector’s phototubes. A Q-ball interacting within the detector could produce such results. To establish that this is not a SUSY Q-ball, one would have to analyze the data during the 0.1 millisecond time window subsequent to the onset of the bright flash. Relic Q-balls are expected to have a velocity $v \sim 10^{-3}c$. However, Super-Kamiokande routinely discards the data in the wake of various events because the signal would be plagued by multiple reflections of light inside the detector. Therefore, there is a possibility that the passages of SUSY Q-balls are not registered by Super-Kamiokande, except as events of the kind described in Ref. [9]. Similar effects have been reported by Pamir [11] and other experiments [12].

It is useful, therefore, to establish an independent limit even if such a limit is weaker than those presented in Refs. [8,10]. We will set a new limit based on the neutrinos SUSY Q-balls would produce interacting inside the Earth.

Several assumptions are made about Q-ball characteristics. A good review of the mathematics behind these assumptions can be found at Ref. [13].

1) In order to be a dark matter candidate, Q-balls must have baryon number $Q \sim 10^{24\pm5}$

2) $M(Q) \sim M_{SUSY} Q^{3/4}$

3) $M_{SUSY} \sim 1 - 10$ TeV

4) $\frac{M(Q)}{Q} < M_{proton}$

Condition (4) is a stability condition; if Q-ball mass per baryon number is
greater than the proton mass, the Q-ball is not stable and may decay into proton(s).

Taken together, these assumptions imply a Q-ball mass less than $10^{20}$ eV. Such Q-balls could exist in the form of relics from cosmological inflation. It is also possible that smaller Q-balls could be astrophysically accelerated to comparable energies.

The manner of Q-ball interaction with matter as described by Kusenko, et. al. is that Q-balls reflect incoming quarks as antiquarks with probability almost one [5]. In the Earth, a reflected antiproton will interact almost immediately with the surrounding matter. Proton-antiproton interactions in this energy regime are fairly well understood. At these energies, the interactions of neutrons are not significantly different from those of protons[14]. Therefore the approximation of a protonic earth is good.

Proton-antiproton interactions will create a host of pions. These pions will have time to interact with the surrounding matter before they decay, but at these (low) energies, only hard scatterings will occur. These scatterings will cause the charged pions to radiate some electromagnetic energy, but ultimately they will still decay into neutrinos. The neutrinos will escape from within the Earth and pass through surface neutrino detectors. Other products of p-pbar annihilation, such as photons and electrons, will be stopped by the Earth.

By comparing expected total neutrino flux to detector sensitivity, neutrino nondetection will set an upper bound on Q-ball abundance. Specifically, we know the detected flux of atmospheric neutrinos at the Super-K detector, which will act as a background to the desired detection, thus also as a benchmark for our predicted flux.

We will proceed through dimensional argument.

Flux is defined as the number of particles traversing a square area per unit time. We can find the flux of atmospheric neutrinos through Super-K at Ref. [15]. At 200 MeV, it is about $6 \text{cm}^{-2}\text{s}^{-1}$.

In the steady state, the rate of neutrino production within the volume of the Earth ($r_\nu$) must equal neutrino flux at the Earth’s surface.

$$4\pi R_{\text{Earth}}^2 \cdot F_\nu = r_\nu \quad (1)$$

The production rate of neutrinos within the Earth depends on the unknown Q-ball flux, $F_Q$.

We can convert the unknown Q-ball flux at the detector into a Q-ball density
in space by dividing by the velocity of the Q-ball, $v_Q$.

Given a density, we can multiply by the volume of the Earth, $V_E$ to get the total number of Q-balls in the Earth at a given time.

Multiplying the total number of Q-balls by the number of neutrinos per interaction times interactions per second gives the total number of neutrinos per second in the volume.

In the approximately uniform matter of the Earth, each second there are

$$\sigma \cdot n_p \cdot v$$

Q-ball interactions per second, where $n_p$ is the proton number density, $v$ is the velocity of the Q-ball, and the cross section is geometric

$$\sigma = \pi R_{Q\text{-ball}}^2$$

The radius of the Q-ball

$$R_{Q\text{-ball}} = \frac{Q^{1/4}}{M_{\text{SUSY}}} = 10^{-6}\text{eV}^{-1}$$

In the Earth, where $n_p \approx 3 \cdot 10^{24}\text{cm}^{-3}$, the number of interactions per second is then

$$\pi \cdot (10^{-6}\text{eV}^{-1})^2 \cdot 3 \cdot 10^{24}\text{cm}^{-3} \cdot v_{\text{cm/s}}$$

In each interaction

$$p + \bar{p} \rightarrow 5 \cdot (\pi_+ + \pi_- + \pi_0) \cdot \frac{1}{3}$$

5 pions are produced on average [6].

The pions share the energy of the 2 GeV annihilation (of the proton and anti-proton nearly at rest), resulting in about 400MeV/pion. As the charged pions decay (primary decay mode, 99.99%), neutrinos are produced in two subsequent steps

$$\pi_+ \rightarrow \mu_+ \nu_\mu$$
\[
\mu_+ \rightarrow e_+ \overline{\nu_e} \nu_\mu
\] (8)

Resulting in an average of 3.33 muon neutrinos at 200MeV and additional mu- and nu- neutrinos at about 1/3 this energy.

Finally, dividing by the surface area of the Earth, \(A_E\), we have the appropriate dimensions of \(m^{-2}s^{-1}\).

Algebraically,
\[
\frac{F_Q \cdot V_E \cdot \sigma \cdot n_p \cdot v \cdot 3.33}{v \cdot A_E} = r_\nu
\] (9)

Solving for \(F_Q\)
\[
F_Q = \frac{3}{6.4 \cdot 10^8 \text{cm} \cdot 3.33 \cdot 10^{-30} \text{cm}^2 \cdot 10^{24} \text{cm}^{-3}} \cdot \frac{6 \text{cm}^{-2}s^{-1}}{3.33 \cdot 10^{-30} \text{cm}^2 \cdot 10^{24} \text{cm}^{-3}}
\] (10)

where we assume a spherical earth for purposes of volume and surface area calculation. This calculation is independent of the velocity of the Q-ball, since that quantity cancels in the division.

Then we simply solve for \(F_Q\).
\[
F_Q \sim 10^{-2}\text{cm}^{-2}s^{-1}
\] (11)

Note that this argument remains good even in the relativistic case. For a gamma factor greater than 1, the output of such interactions will be beamed in a cone with opening angle \(\sim \frac{1}{\gamma}\), but because the arrival direction of the Q-balls is presumed to be symmetric, equal numbers of neutrinos are gained and lost through this effect.

At the beginning of this paper, several assumptions about the nature of Q-balls were made. This is, therefore, a bound on the abundance of Q-balls which are dark matter candidates by virtue of their mass, radius, and baryon number, around a total energy of \(10^{20}\text{eV}\). More energetic Q-balls, or less massive Q-balls with a higher gamma factor would produce more pions in their interactions with matter, resulting in more neutrinos and therefore a smaller upper bound.

1 Conclusions

Q-balls are a fundamental prediction of supersymmetry and have the power to explain many otherwise puzzling phenomena detected in the highest energy
regimes. Certain types of Q-balls are good candidates for dark matter, but have a large range of possible physical parameters. We have set a bound on the flux of Q-balls through detectors that is independent of the detector ability to recognize Q-ball events.

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