Experimental signatures of supersymmetric dark-matter Q-balls

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Abstract

Theories with low-energy supersymmetry predict the existence of stable non-topological solitons, Q-balls, that can contribute to dark matter. We discuss the experimental signatures, methods of detection, and the present limits on such dark matter candidates.

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Supersymmetric generalizations of the Standard Model, in particular the minimal version, MSSM, invariably predict the existence of non-topological solitons, dubbed Q-balls [1], with an arbitrary baryon number [2]. Supersymmetric Q-balls are coherent states of squarks, sleptons, and the Higgs fields. In theories with "flat directions" in the scalar potential, which are generic for supersymmetry, these objects may exhibit a number of interesting properties [3, 4]. In particular, solitons with a large baryon number are entirely stable [5] and can be copiously produced in the early universe [5]. This makes relic Q-balls an appealing candidate for cold dark matter [5]. In this Letter we will examine the implications of this speculative type of dark matter for detector experiments.

Flat potentials $U(\phi)$, $i.\,e.$, those that grow slower than the second power of the scalar VEV ϕ, arise naturally in theories with low-energy supersymmetry breaking (see, $e.\,g.$, Refs. [6, 7] and discussion in Ref. [3]). For example, if $U(\phi) \sim m^4 = const$ for large ϕ, the mass of a soliton with charge (baryon number) Q_B is $M_Q \simeq (4\pi\sqrt{2}/3)\, m\, Q_B^{3/4}$, its radius is $R_Q \simeq (1/\sqrt{2})\, m^{-1} Q_B^{1/4}$, and the maximal scalar VEV inside is $\phi_Q \simeq (1/\sqrt{2})\, m\, Q_B^{1/4}$. We will assume these relations and neglect the logarithmic corrections to the flat potentials that appear in realistic theories [6, 7]. One assumes m to be from 100 GeV to 100 TeV, higher values being disfavored by the naturalness arguments. For a specific model of supersymmetry breaking studied in Ref. [7], $m \sim 1$ TeV.

The baryon number Q_B of a stable soliton must be greater than $10^{15}(m/1\mathrm{TeV})^4$ [5]. Larger solitons cannot decay into the matter fermions because the energy per unit baryon number is less than the proton mass. Q-balls with a much greater global charge, in excess of 10^{20}, can be produced in the early universe from the breakdown of a coherent scalar condensate [5]. Formation of such condensate, being the starting point of the Affleck–Dine scenario for baryogenesis [8], may also explain the baryon asymmetry of the universe, in which case the initial baryon number stored in the condensate is distributed between the matter baryons and Q-balls. If the ordinary baryonic matter and the dark matter share the same origin [5], one may hope to explain why the two have, roughly, the same density in the Universe.

The flux of cosmic Q-balls falling on Earth can be estimated under the assumption that they make a sizeable contribution to the missing matter of the universe. As follows from Ref. [5], Q-balls produced from the breakdown of a primordial condensate have a very narrow distribution of charges. We will assume, therefore, that all dark-matter solitons have the same mass. Q-balls can be of interest as dark matter candidates if their mass density in the galactic halo is of order $\rho_{DM} \approx 0.3$ GeV/cm^3, which corresponds to the number density

$$n_Q \sim \frac{\rho_{DM}}{M_Q} \sim 5 \times 10^{-5} Q_B^{-3/4} \left(\frac{1 \text{TeV}}{m} \right) \text{cm}^{-3}. \tag{1}$$

We assume the average velocity for Q-balls $v \sim 10^{-3} c$. Then the flux is $F \simeq (1/4\pi) n_Q v \sim 10^2 Q_B^{-3/4} \left(\frac{1 \text{TeV}}{m} \right) \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. For example, the total surface area of the water tank used in the Super-Kamiokande experiment [9] is 7.5×10^7 cm^2. If all or most of the dark matter is made up of solitons with charge Q_B, some Q-balls must go through this detector at the rate

$$N \sim \left(\frac{10^{24}}{Q_B} \right)^{3/4} \left(\frac{1 \text{TeV}}{m} \right) \text{yr}^{-1}. \tag{2}$$

Q-balls can also produce a signal, at a comparable rate, at the Baikal Deep Underwater Neutrino Experiment [10], as well as other experiments.

Let us consider the interactions of baryonic solitons with ordinary matter. The interior of a large Q-ball can be thought of as a spherically-symmetric region filled with a non-standard vacuum that breaks spontaneously the baryonic $U(1)_B$ symmetry. The scalar VEV inside a stable soliton extends along a flat direction in the MSSM scalar potential and carries the corresponding quantum numbers.

If supersymmetry is exact (which we assume to be the case for sufficiently large VEV, as in theories with SUSY breaking communicated at low energy), the MSSM has a very large space of degenerate vacua, the flat directions, labelled by the corresponding gauge-invariant holomorphic polynomials of the chiral superfields [11, 12]. They have been enumerated and catalogued in Ref. [13, 14]. Each flat direction is parameterized

by a gauge-invariant scalar VEV. Those that carry some baryon number can give rise to stable Q-balls, and may also play a central role in generating baryon asymmetry of the Universe [8, 7, 13].

Inside a Q-ball the SU(3)×SU(2)×U(1) gauge symmetry may be broken by the VEV of squarks, sleptons, and the Higgs fields. In the absence of fundamental SU(3)-singlet baryons in the MSSM, any baryonic Q-ball has a broken SU(3) inside. In contrast, the electroweak symmetry may be restored if the only fields that have non-zero VEV are SU(2) singlets. This is the case for Q-balls that have a scalar VEV aligned, for example, with the *udd* flat direction (notation of Ref. [14]). Although baryon number is violated by the instantons, the rate is suppressed because the the size of the instantons that fit inside a Q-ball is small.

A baryonic Q-ball must have a non-zero VEV $\phi_Q \sim m\,Q_B^{1/4}$ of scalar quarks in its interior. It may or may not be accompanied by the VEV's of sleptons and the Higgs fields. Matter fermions cannot penetrate inside some Q-balls because their masses inside may be increased by the large Higgs VEV, as well as through their mixing with gauge fermions. However, the outer region of any Q-ball has a layer near its boundary where (i) the quark masses are less than Λ_{QCD} and (ii) the gauge SU(3) symmetry is broken spontaneously by the VEV's of squarks. When a nucleon enters this region, where the QCD deconfinement takes place, it dissociates into quarks. The energy released in such process, roughly 1 GeV per nucleon, is emitted in pions. This process is the basis for the experimental detection of the dark-matter Q-balls.

As an electrically neutral Q-ball passes through matter, it absorbs the nuclei with a cross-section determined entirely by the soliton's size, $\sigma \sim 10^{-33}\,Q_B^{1/2}(1\mathrm{TeV}/m)^2$ cm^2. The corresponding mean free path in matter with density ρ is

$$\lambda_0 \sim 10^{-3}\,A\left(\frac{10^{24}}{Q_B}\right)^{1/2}\left(\frac{m}{1\ \mathrm{TeV}}\right)^2\left(\frac{1\ \mathrm{g/cm}^3}{\rho}\right)\ \mathrm{cm}, \qquad (3)$$

where A is the weight of the nucleus in atomic units. The quarks caught in the deconfining coat of a Q-ball are absorbed into the condensate eventually via the reaction $qq \to \tilde{q}\tilde{q}$ that proceeds with a (heavy) gluino exchange. The reason this process is energetically

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allowed is, of course, because the squarks in the condensate are nearly massless. The rate of conversion is suppressed by the square of the gluino mass. If the condensate in the Q-ball is different in flavor from the quarks, an additional CKM suppression takes place. In any case, the absorption of quarks into the condensate occurs at a much higher rate than the collisions of Q-balls with nuclei characterized by λ_0 in equation (3).

For energetic reasons, large Q-balls comprise an electrically neutral scalar condensate. However, unless the electrons are trapped by the Q-ball, the process described above proceeds through the formation of a bound state of the Q-ball to quarks which has a positive electric charge. If this is the case, the electrons can be captured eventually in an electroweak process $ue \rightarrow d\nu$ which, we note in passing, is very fast inside those Q-balls that restore the $SU(2)$ gauge symmetry because the W boson is massless.

However, the electrons cannot penetrate inside those Q-balls, whose scalar VEV gives them a large mass. For example, the simultaneously large VEV's of both the left-handed (L_e) and the right-handed (e) selectrons along the $QQQLLLe$ flat direction give rise to a large electron mass through mixing with the gauginos. The locked out electrons can form bound states in the Coulomb field of the (now electrically charged) soliton. The resulting system is similar to an atom with an enormously heavy nucleus. Based on their ability to retain electric charge, the relic solitons can be separated in two classes: Supersymmetric Electrically Neutral Solitons (SENS) and Supersymmetric Electrically Charged Solitons (SECS). The interactions of Q-balls with matter, and, hence, the modes of their detection, differ drastically depending on whether the dark matter comprises SENS or SECS.

First, the Coulomb barrier can prevent the absorption of the incoming nuclei by SECS. A Q-ball with baryon number Q_B and electric charge Z_Q cannot imbibe protons moving with velocity $v \sim 10^{-3}c$ if $Q_B \lesssim 10^{29} Z_Q^4 (m/1\,\mathrm{TeV})^4$. Second, the scattering cross-section of an electrically charged Q-ball passing through matter is now determined by, roughly, the Bohr's radius, rather than the Q-ball size: $\sigma \sim \pi r_B^2 \sim 10^{-16} cm^2$. The corresponding mean free path is

$$\lambda_e \sim 10^{-8} A \left(\frac{1 \text{ g/cm}^3}{\rho} \right) \text{ cm.} \qquad (4)$$

By numerical coincidence, the total energy released per unit length of the track in the medium of density ρ is, roughly, the same for SENS and SECS, $dE/dl \sim 100 \left(\rho/1 \text{ g cm}^{-3} \right)$ GeV/cm. However, the former takes in nuclei and emits pions, while the latter dissipates its energy in collisions with the matter atoms. Signatures of baryonic and anti-baryonic solitons are expected to be similar.

A passage of a Q-ball with baryon number $Q_B \sim 10^{24}$ through a detector, associated with emission of, roughly, 10 GeV per millimeter can make a spectacular signature. Of course, depending on the mass parameter m and the charge Q_B, the frequency of such events can be small; for some values, too small to be detected. As is evident from equation (2) the generic values of parameters are not ruled out, and are consistent with observation of relic Q-balls at the existing and future facilities. Since the anticipated tracks are very energetic and unmistakable, it is the surface area of the detector, rather than its fiducial volume, that is important. A large-area detector (LAD) would, in general, be more effective in searching for Q-balls than a more compact machine with the same volume.

The present experimental limit on the flux of SECS is set by the MACRO search [15] for "nuclearites" [16], which have similar interactions with matter: $F < 1.1 \times 10^{-14}$ cm^{-2} s^{-1} sr^{-1}. This translates into the lower limit on the baryon number of dark-matter Q-balls, $Q_B \gtrsim 10^{21}$. Signatures of SENS are similar to those expected from the Grand Unified monopoles that catalyze the proton decay. If one translates the current experimental limits from Baikal [10] on the monopole flux, one can set a limit on the charge of SENS, $Q_B \gtrsim 3 \times 10^{22}$, for $m = 1$ TeV. Non-observation of Q-balls at the Super-Kamiokande after a year of running would improve this limit by two orders of magnitude. Of course, this does not preclude the existence of smaller Q-balls with lower abundances that give negligible contribution to the matter density of the universe.

Electrically charged Q-balls with a smaller baryon number can dissipate energy so efficiently that they may never reach the detector. SECS with baryon number $Q_B \lesssim$

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$10^{13}(m/1\,\mathrm{TeV})^{-4/3}$ can be stopped by the 1000 m of water equivalent matter shielding. Such solitons could not have been observed by the underground detectors. Therefore, in the window of $Q_B \sim 10^{12}...10^{13}$ the flux of SECS appears to be virtually unconstrained.

For completeness, we will briefly review some astrophysical constraints. A SENS that passes through Earth with velocity $10^{-3}\,c$ looses a negligible part of its kinetic energy to collisions with the matter particles. The total change in its velocity is $\delta v/v \sim 10^{-2} Q_B^{-1/4}(1\,\mathrm{TeV}/m)^3$. Therefore, SENS do not accumulate inside ordinary stars and planets. A neutron star is sufficiently dense to stop a Q-ball of any kind. During the period of 10^8 years (the age of the oldest observed pulsars) of order $\sim 10^{33} Q_B^{-3/4}(1\,\mathrm{TeV}/m)$ relic solitons are captured by a neutron star. Since the nuclear matter is very dense, the energy released in the capture of nucleons by the Q-balls is significantly higher than that in the ordinary matter. The interactions of the relic Q-balls with neutron stars and white dwarfs are studied in Ref. [17].

However, the combined heat from all Q-balls captured in 100 Myr can lead to an increase in temperature of the neutron star by only $\lesssim 0.01 (Q_B/10^{24})^{-1/16}$ keV, too small to have any observable consequences.

SECS's do accumulate in ordinary stars. However, the Coulomb barrier prevents a rapid absorption of nuclei and inhibits the production of pions. Therefore, in contrast to the case of monopoles, there is no constraint on the abundance of SECS from observations of the low-energy solar neutrinos.

It should also be mentioned that, because of its very large mass, a Q-ball passing through the atmosphere cannot create an extensive shower typical for the high-energy cosmic rays. The effectiveness of the wide-array detectors in searching for Q-balls is, therefore, limited by the total area of their counters. Searches for stable ultra-heavy nuclei in matter [18], which may be suitable for detecting smaller Q-balls (with charges $10^{12}...10^{13}$), afford no limit at present because the mass range of interest, $m_Q \gtrsim 10^{12}$ GeV, has never been explored.

It would be interesting to see if some of the exotic events in the cosmic rays, $e.\,g.$, the so called Centauro events [19], the penetrating halo event of the Pamir experiment [20,

19], and the ultra-high energy cosmic rays that appear to defy the GZK bound [21], may be related to the relic Q-balls.

In summary, Q-ball is an appealing dark matter candidate predicted by supersymmetry. Baryonic Q-balls have strong interactions with matter and can be detected in present or future experiments. Observational signatures of the baryonic solitons are characterized by a substantial energy release along a straight track with no attenuation throughout the detector. The present experimental lower bound on the baryon number $Q_B \gtrsim 10^{21}$ is consistent with theoretical expectations [5] for the cosmologically interesting range of Q-balls in dark matter. In addition, smaller Q-balls, with the abundances much lower than that in equation (1), can be present in the universe. Although their contribution to Ω_{DM} is negligible, their detection could help unveil the history of the universe in the early post-inflationary epoch. Since the breakdown of a coherent scalar condensate [5] is the only conceivable mechanism that could lead to the formation of Q-balls with large global charges, the observation of any Q-balls would seem to speak unambiguously in favor of such process having taken place. This would, in turn, have far-reaching implications for understanding the origin of the baryon asymmetry of the universe, for the theory of inflation, and for cosmology in general.

References

[1] S. Coleman, Nucl. Phys. **B262**, 263 (1985).

[2] A. Kusenko, Phys. Lett. **B405**, 108 (1997).

[3] G. Dvali, A. Kusenko and M. Shaposhnikov, Phys. Lett. **B417**, 99 (1998).

[4] A. Kusenko, Phys. Lett. **B404**, 285 (1997); *ibid.* **B406**, 26 (1997).

[5] A. Kusenko and M. Shaposhnikov, Phys. Lett. **B418**, 46 (1998).

[6] G. Dvali, Q. Shafi and R. Schaefer, Phys. Rev. Lett. **73**, 1886 (1994); G. Dvali, Phys. Lett. **B387**, 471 (1996).

[7] A. de Gouvêa, T. Moroi and H. Murayama, Phys. Rev. **D56**, 1281 (1997).

[8] I. Affleck and M. Dine, Nucl. Phys. **B249**, 361 (1985).

[9] For a review of the current status, see, *e. g.*, K. Young, talk presented at the APS meeting, Washington, D. C., April 1997.

[10] For a review of current status, see, *e. g.*, V. A. Balkanov, *et al.*, talk presented at NANP-97, Russia, July 1997 (astro-ph/9709070).

[11] F. Buccella, J. P. Derendinger, S. Ferrara, C. A. Savoy, Phys. Lett. **B115**, 375 (1982); I. Affleck, M. Dine and N. Seiberg, Nucl. Phys., **B241**, 493 (1984); *ibid.* **B256**, 557 (1985).

[12] M. A. Luty and W. Taylor, Phys. Rev. **D53**, 3399 (1996).

[13] M. Dine, L. Randall and S. Thomas, Nucl. Phys. **B458**, 291 (1996).

[14] T. Gherghetta, C. Kolda, and S. P. Martin, Nucl. Phys. **B468**, 37 (1996); G. Cleaver, M. Cvetic, J. R. Espinosa, L. Everett, and P. Langacker, hep-th/9711178.

[15] S. Ahlen *et al.*, Phys. Rev. Lett. **69**, 1860 (1992).

[16] E. Witten, Phys. Rev. **D 30**, 272 (1984); A. De Rújula and S. L. Glashow, Nature **312**, 734 (1984).

[17] A. Kusenko, M. Shaposhnikov, P. G. Tinyakov, and I. I. Tkachev, Phys. Lett. **B**, in press (hep-ph/9801212).

[18] T. Yamagata *et al.*, Phys. Rev. **D 47**, 1231 (1993); T. K. Hemmick *et al.*, Phys. Rev. **D 41**, 2074 (1990); P. F. Smith *et al.*, Nucl. Phys. **B206**, 333 (1982).

[19] C. M. G. Lattes, Y. Fujimoto, and S. Hasegawa, Phys. Rep. **65** 151 (1980).

[20] S. G. Bayburina *et al.*, Proc. 16th Intern. Cosmic Ray Conf., **7**, 279 (1979).

[21] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, Pisma Zh. Eksp. Theor. Fiz. **4**, 114 (1966).