SIGNATURES OF SUPERSYMMETRIC Q-BALLS

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ABSTRACT

In many supersymmetric extensions of the Standard Model the spectrum of states contains stable non-topological solitons, Q-balls. If formed in the Early Universe in sufficient amounts, Q-balls now contribute to cold dark matter. We discuss their experimental signatures and astrophysical implications.
1. **Q-balls in SUSY theories.** In theories where scalar fields carry a conserved global charge, \( Q \), there may exist non-topological solitons which are stabilized by the charge conservation\(^1\). Under certain assumptions about the self-interaction of the scalar fields these solitons, which are called Q-balls\(^2\), are absolutely stable. The prototype model\(^3\) containing absolutely stable Q-balls has one complex scalar field \( \phi \) with the potential \( V(|\phi|) \) which is asymptotically flat as shown in Fig.1a. The Q-ball solution has the form \( \phi(t, x) = \exp(i \omega t) \phi(r) \), where \( \omega \) and \( \phi(r) \) are found by minimizing the energy in the sector of fixed charge \( Q \). The profile \( \phi(r) \) is shown schematically in Fig.1b. In the interior region \( \phi(r) \) satisfies massive free field equation, \( \phi(r) = \phi_0 \sin(\omega r)/\omega r \). At \( r \approx R = \pi/\omega \) there is a transition region where the field smoothly goes to zero in a way determined by the shape of the potential at small fields. The Q-ball mass \( M_Q \) and size \( R \), as well as the parameters \( \omega \) and \( \phi_0 \) are functions of its charge \( Q \). In particular,

\[
M_Q = \frac{4\pi \sqrt{2}}{3M_s} Q^{3/4}, \\
R = \frac{1}{\sqrt{2}} M_s^{-1} Q^{1/4},
\]

where \( M_s \) is determined the asymptotic value of the potential, \( V \simeq M_s^4 \).

The conditions for existence of absolutely stable Q-balls are naturally satisfied\(^3\) in supersymmetric theories with low energy supersymmetry breaking. The role of conserved charge is played by the baryon number \( B \), while scalar fields carrying the charge are certain combinations of squark, slepton and Higgs fields associated with flat directions of scalar potential (for the list of flat directions of the MSSM see\(^4\)). The mass parameter \( M_s \) is of the order of the SUSY breaking scale. For definiteness we take \( M_s = 1 \) TeV. The condition of absolute stability \( M_Q < Qm_p \), where \( m_p \) is the proton mass, is satisfied for charges \( Q > 10^{15} (M_s/1\text{TeV})^4 \).

Among known forms of baryonic matter Q-balls are the most energetically favorable one. Being absolutely stable, baryonic Q-balls are viable candidates for the dark matter\(^5\). They can be produced in cosmologically significant amounts in the early Universe\(^6\) through the decay of the Affleck-Dine condensate\(^6\). In this talk which is based on refs.\(^7,8,9\) we discuss modes of detection of relic Q-balls, as well as their possible role in the evolution of neutron stars.

2. **Experimental detection of Q-balls.** If exist, relic Q-balls are concentrated in galactic halos and have velocities of order \( v \sim 10^{-3}c \). Assuming that Q-balls constitute cold dark matter with \( \rho_{DM} \simeq 0.3 \) GeV/cm\(^3\) one finds their number density

\[
n_Q \sim \frac{\rho_{DM}}{M_Q} \sim 3 \times 10^{-4} Q^{-3/4} \left( \frac{1\text{TeV}}{M_s} \right) \text{cm}^{-3},
\]
Consider the interaction of baryonic Q-balls with ordinary matter. The interior of a baryonic Q-ball is characterized by large VEV of certain squark (and, possibly, slepton and Higgs) fields. Therefore, color SU(3) is broken and de-confinement takes place inside a Q-ball. Simultaneously, quarks and possibly some leptons get masses through mixing with gluinos. Since masses are proportional to VEV’s the outer region of a baryonic Q-ball has a layer where quarks are lighter than $\Lambda_{QCD}$ and are not confined. When a nucleon enters this region, it dissociates into quarks which later get absorbed into condensate via the reaction $qq \rightarrow \tilde{q}\tilde{q}$. The cross section of this reaction which goes through the gluino exchange can be parameterized as $\sigma(qq \rightarrow \tilde{q}\tilde{q}) = \beta/M_s^2$, where $\beta$ is dimensionless parameter to be treated phenomenologically. In total, the reaction looks as

$$(Q) + N \rightarrow (Q + 1) + \text{pions}, \quad (3)$$

where $N$ denotes a nucleon and it is assumed that, like in typical hadronic process, the released energy (of order 1 GeV per nucleon) is carried out predominantly by pions.

Since nuclei in ordinary matter are electrically charged, a Q-ball resulting from the reaction (3) is (with some probability) positively charged and further absorption is suppressed by the Coulomb barrier. Depending on their ability to retain electric charge, Q-balls associated with
different flat directions of the MSSM can be divided into two general classes: Supersymmetric Electrically Neutral Solitons (SENS) which rapidly neutralize, and Supersymmetric Electrically Charged Solitons (SECS) which stay charged much longer than the time between successive collisions. An example of SECS is a Q-ball associated with $(QQQLLe)$ flat direction. A non-zero VEV of both left $(L)$ and right $(e)$ selectron along this direction makes electron heavy so that it is repelled by the Q-ball.

The cross section of the reaction (3) is determined by the Q-ball size $R$, $\sigma \sim 10^{-33}Q^{1/2} (1\text{TeV}/m)^2 \text{cm}^2$. With this cross section, a SENS passing through ordinary matter with density $\rho$ experiences roughly $100 \times (Q/10^{24})^{1/2} \rho/(1 \text{g/cm}^3)$ collisions with nuclei per centimeter of track. Large amount of energy (of order $100 \times (Q/10^{24})^{1/2}$ GeV/cm) released in pions is the main signature of these events.

Events produced by SECS would look totally different. After few first collisions SECS becomes electrically charged; from that point on its interaction with nuclei becomes elastic. The corresponding cross section is determined by the Bohr radius, $\sigma \sim \pi r_B^2 \sim 10^{-16} \text{cm}^2$. SECS propagation through matter results in similar energy release, $\sim 100$ GeV/cm, but now mainly in the form of heat with only $\sim 10^{-5}$ fraction of visible light.

The present experimental limit on the flux of SECS, $F < 1.1 \times 10^{-14} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, is set by the MACRO search for “nuclearites”, which have similar interactions with matter. This translates into the lower limit on the baryon charge of dark-matter Q-balls, $Q \gtrsim 10^{21}$. 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 on the monopole flux, one can set a limit on the charge of SENS, $Q \gtrsim 3 \times 10^{22}$, for $m = 1$ TeV. 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.

### 3. Astrophysical implications

Since Q-balls are the most energetically favorable state of baryonic matter, one would naturally expect them to play role in stellar evolution. This role is, however, limited by the low density of ordinary matter and small size of Q-balls. In fact, the only place where they may be essential is the evolution of neutron stars.

The neutron star is sufficiently dense to stop both SECS and SENS. We will not make difference between them in subsequent discussion since both absorb neutrons with comparable rates. Captured Q-balls reach the center of the star in a matter of seconds where they finally merge forming a large central Q-ball. When the charge of the central Q-ball exceeds $\sim 10^{30}$
further accumulation of relic Q-balls can be neglected. Therefore, the ultimate fate of the neutron star does not depend on the flux of Q-balls as long as at least one Q-ball is captured during the lifetime of a star.

The growth of the central Q-ball in a neutron star is determined by the infall rate of neutrons on the Q-ball and the rate of processing of quarks into condensate, whichever is smaller. Since both rates are proportional to the surface area of Q-ball, the resulting change of the Q-ball charge obeys the equation

\[ \frac{dQ}{dt} = \alpha Q^{1/2}, \]

where \( \alpha \) is a phenomenological parameter. The magnitude of \( \alpha \) is limited by the infall rate at the level of \( \sim 10^{16} \text{ s}^{-1} \). With this value of \( \alpha \) the neutron star would live only \( \sim 10^5 \) years. More realistic value of \( \alpha \) is obtained when the conversion rate is taken into account. Writing the cross section of the reaction \( qq \rightarrow \bar{q}\bar{q} \) as above, one gets an estimate \( \alpha = 10^8(M_s/1\text{TeV})^{-5/2}\beta\text{s}^{-1} \), which implies for the lifetime of a star

\[ t_s \sim \frac{1}{\beta} \times \left( \frac{m}{200\text{ GeV}} \right)^5 \text{ Gyr}. \]

The lifetime can be as low as \( 10^{-2} \) Gyr for \( m \sim 100 \text{ GeV} \), or can exceed the age of the universe for \( m \gtrsim 300 \text{ GeV} \), if \( \beta \sim 1 \). Since neutron stars with ages around 0.1 Gyr are known to exist, there is a lower bound on \( t_s \) and, correspondingly, on \( m^5/\beta \). If \( \beta \ll 1 \) and \( m \) is in the TeV range then the lifetime of a neutron star exceeds the age of the Universe and the relic Q-balls play no role in the stellar evolution at present time.

Neutron stars are only stable in a certain range of masses\(^4\). When the mass of a star becomes smaller than \( \sim 0.2M_\odot \) (the mass and gravitational effect of the Q-ball can be neglected), the star becomes unstable and explodes. The energy released in this process is of order \( \sim 10^{52} \ldots 10^{53} \) erg. The emission of gamma rays associated with the explosion can, in principle, account for observed gamma-ray bursts. Whether this mechanism can also explain the duration and spectrum of observed gamma ray bursts remains to be seen.

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