Energy losses of Q-balls in Matter, Earth and Detectors.

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Abstract

We present a study of the interactions of Q-balls with matter, and their energy losses in the earth, for a large range of velocities. These calculations are used to compute the fractional geometrical acceptance of underground detectors. Furthermore we computed the light yield in liquid scintillators, the ionization in streamer tubes and the Restricted Energy Loss in nuclear track detectors.

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1 Interaction of Q-balls with matter

1.1 Interaction with matter of Q-balls type SECS

SECS (Supersymmetric Electrically Charged Solitons) are Q-balls with a net positive electric charge which tends to be mainly in the outer layer. The charge of SECS originates from the unequal rates of absorption in the condensate\(^1\). The positive electric charge could be of one unit up to several tens. This positive electric charge may be neutralized by a surrounding cloud of electrons.

For small size Q-balls the positive charge interacts with matter (electrons and nuclei) via elastic or quasi elastic collisions\(^2\). The cross section is similar to the Bohr cross section of hydrogenoid atoms\(^3-4\)

\[
\sigma = \pi a_0^2 \sim 10^{-16} cm^2
\]  

(1)

where \(a_0\) is the Bohr radius.

The main energy losses\(^5\) of SECS passing through matter with velocities in the range \(10^{-4} < \beta < 10^{-2}\) are due to two contributions: \((i)\) the interaction of the SECS positive charge with the nuclei (nuclear contribution), and, \((ii)\) with the electrons of the traversed medium (electronic contribution). The total energy loss is the sum of the two contributions\(^5-6\).
Electronic energy losses of SECS: The electronic\(^5\) contribution to the energy loss of SECS may be computed with the following formula

\[
\frac{dE}{dx} = \frac{8\pi a_0 e^2 \beta}{\alpha} \frac{Z_Q^{7/6} N_e}{(Z_Q^{2/3} + Z^{2/3})^{3/2}}
\]

(2)

where \(\alpha\) is the fine structure constant, \(\beta = v/c\), \(Z_Q\) is the positive charge of SECS, \(Z\) is the atomic number of the medium and \(N_e\) is the density of electrons in the medium. Electronic losses dominate for \(\beta > 10^{-4}\) for the case of the \(dE/dx\) in the earth\(^5\).

Nuclear energy losses of SECS: The nuclear\(^5\) contribution to the energy loss of SECS is due to the interaction of the SECS positive core with the nuclei of the medium and it is given by

\[
\frac{dE}{dx} = \frac{\pi a^2 \gamma N E}{\epsilon} S_n(\epsilon)
\]

(3)

where

\[
S_n(\epsilon) \simeq \frac{0.56 \ln(1.2\epsilon)}{1.2\epsilon - (1.2\epsilon)^{-0.63}}, \quad \epsilon = \frac{a M E}{Z_Q Z e^2 M_Q}
\]

(4)

and

\[
a = 0.885 \frac{a_0}{(\sqrt{Z_Q} + \sqrt{Z})^{2/3}}, \quad \gamma = 4 M \frac{M_Q}{M}
\]

(5)

\(M_Q\) is the mass of the incident Q-ball; \(M\) is the mass of the target nucleus; \(Z_Q e\) and \(Z e\) are their electric charges; we assume that \(M_Q >> M\). Nuclear energy losses dominates for \(\beta \leq 10^{-4}\).

Using the energy losses of SECS discussed above, we can computed, for a specific velocity \(v = 250 \text{ km/s}\), the angular acceptance\(^6\) of a detector located at the underground Gran Sasso Laboratory in Italy (MACRO experiment).

1.2 Interaction with matter of Q-balls type SENS

The Q-ball interior of SENS (Supersymmetric Electrically Neutral Solitons) is characterized by a large Vacuum Expectation Value (VEV) of squarks, and may be of sleptons and Higgs fields. The \(SU(3)\) symmetry is broken and deconfinement takes place inside the Q-ball. If a nucleon enters this region of deconfinement, it dissociates into three quarks, some of which may then become absorbed in the supersymmetric condensate. The reaction looks like\(^3\)

\[
(Q) + \text{Nucleon} \rightarrow (Q + 1) + \text{pions}
\]

(6)
or less probably,

\((Q) + Nucleon \rightarrow (Q + 1) + kaons\) \hspace{1cm} (7)

The nucleon enter the \(\tilde{q}\) condensate and it gives rise to the process

\(qq \rightarrow \tilde{q}\tilde{q}\) \hspace{1cm} (8)

If it is assumed that the energy released in (6) and (7) is the same as in typical hadronic processes (about 1 GeV per nucleon), this energy is carried by 2 or 3 pions (or kaons). The cross section is determined by the Q-ball radius

\[ \sigma = \pi R_Q^2 = \frac{16\pi^2}{9} M_Q^{-2} Q^2 \sim 6 \times 10^{-34} Q^{1/2} \left( \frac{1 \text{ TeV}}{M_S} \right)^2 \text{ cm}^2 \] \hspace{1cm} (9)

The corresponding mean free path \(\lambda\) is

\[ \lambda = \frac{1}{\sigma N} \] \hspace{1cm} (10)

The energy loss of SENS moving with velocities in the range \(10^{-4} < \beta < 10^{-2}\) is constant and is given by

\[ \frac{dE}{dx} \sim \frac{\zeta}{\lambda} = \sigma N\zeta \] \hspace{1cm} (11)

where \(N\) is the number of atoms per \(\text{cm}^3\) in the traversed material; \(\zeta = 1 \left( \frac{\rho}{19 \text{ cm}^3} \right) \text{GeV}\) is the energy released in one reaction. Large mass SENS lose a small fraction of their kinetic energy and are able to traverse the earth without attenuation for all masses of our interest.

## 2 Energy losses of Q-balls in the earth

In general the energy losses in the earth are calculated using the density profile of the earth interior. One may observe three layers: the nucleus, the mantle and the crust. For our purposes it is sufficient to use a simpler model, in which the density and composition of each layer is uniform.

In the earth interior model the nucleus is made of iron, with a density of 11.5 g/cm\(^3\) and a conductivity of \(1.6 \times 10^{16} \text{ s}^{-1}\); the mantle is made of Si, with a density of 4.3 g/cm\(^3\). The radius of the nucleus is 0.54 earth radii. The crust may be neglected as long as we consider Q-balls arriving at underground detectors from below. The rock above is assumed to have the same composition of the mantle.

The energy losses of SECS in the earth mantle and earth core can be easily computed for different \(\beta\)-ranges and for different positive electric charges of the Q-ball core.
3 Energy losses of SECS in detectors

3.1 Light Yield of SECS in Scintillators

For SECS we distinguish two contributions to the light yield in scintillators: the primary light yield and the secondary light yield.

The primary light yield is due to the direct excitation (and ionization that occurs only for $\beta > 10^{-3}$) produced by the SECS in the medium. The energy loss in the MACRO liquid scintillator is computed from the energy loss of protons in hydrogen and carbon\(^{5-8}\)

* For electric charge $q = 1e$ the energy loss of SECS is calculated for two cases

  i) For $10^{-5} < \beta < 5 \times 10^{-3}$ we have the following formula

  $$(\frac{dE}{dx})_{SECS} = 1.3 \times 10^5 \beta \left[ 1 - \exp \left( \frac{\beta}{7 \times 10^{-4}} \right)^2 \right] \frac{MeV}{cm} \quad (12)$$

  ii) For $5 \times 10^{-3} < \beta < 10^{-2}$ we used the following formula

  $SP = SP_H + SP_C = (\frac{dE}{dx})_{SECS}$ \quad (13)

  where

  $$SP_H = \frac{SL_H \times SH_H}{SL_H + SH_H} \quad (14)$$

  $$SP_C = \frac{SL_C \times SH_C}{SL_C + SH_C} \quad (15)$$

  and

  $$SL = A_1 E^{0.45}, \quad SH = A_2 \ln \left( 1 + \frac{A_3}{E} + A_4 E \right) \quad (16)$$

  where ($A_i=1.4$) are constants obtained from experimental data, and $E$ is the energy of a proton with velocity $\beta$.

* For SECS with electric charge $q = Z_1 e$ the energy losses for $10^{-5} < \beta < 10^{-2}$ are given by\(^{9-11}\)

  $$\left( \frac{dE}{dx} \right)_{SECS} = \frac{8\pi e^2 a_0 \beta}{\alpha} \frac{Z_2^{7/6} N_e}{(Z_1^{2/3} + Z_2^{2/3})^{3/2}} \left[ 1 - \exp \left( \frac{-\beta}{7 \times 10^{-4}} \right)^2 \right] \quad (17)$$

  where $Z_2$ is the atomic number of the target atom, $N_e$ the density of electrons and $\alpha$ is the fine structure constant.
The primary light yield of SECS is given by

\[
\left( \frac{dL}{dx} \right)_{SECS} = A \left[ \frac{1}{1 + AB \frac{dE}{dx}} \right] \frac{dE}{dx}
\] (18)

where \( dE/dx \) is the total energy loss of SECS; \( A \) is a constant of conversion of the energy losses in photons (light yield) and \( B \) is the parameter describing the saturation of the light yield; both parameters depend only on the velocity of SECS.

The secondary light yield arises from recoiling particles: we consider the elastic or quasi-elastic recoil of hydrogen and carbon nuclei. The light yield \( L_p \) from a hydrogen or carbon nucleus of given initial energy \( E \) is computed as

\[
L_p(E) = \int_0^E \frac{dL}{dx}(\epsilon)S_{tot}^{-1} d\epsilon
\] (19)

where \( S_{tot} \) is the sum of electronic and nuclear energy losses. The secondary light yield is then

\[
\left( \frac{dL}{dx} \right)_{\text{secondary}} = N \int_0^{T_m} L_p(T) \frac{d\sigma}{dT} dT
\] (20)

where \( N \) is the number density of atoms in the medium \( T_m \) is the maximum energy transferred and \( \frac{d\sigma}{dT} \) is the differential scattering cross section.

### 3.2 Energy losses of SECS in streamer tubes

The composition of the gas in the MACRO limited streamer tubes is 73% helium and 27% n-pentane, in volume. The pressure is about one atmosphere and the resulting density is low (in comparison with the density of the other detectors): \( \rho_{\text{gas}} = 0.856 \text{ mg/cm}^3 \).

The ionization energy losses of SECS with \( 10^{-3} < \beta < 10^{-2} \) in the MACRO streamer tubes are computed with the same general procedure used for scintillators, using the density and the chemical composition of streamer tubes.

The threshold for ionizing n-pentane occurs for \( \beta \geq 2 \times 10^{-3} \).

### 3.3 Restricted Energy Losses of SECS in the Nuclear Track Detectors

The relevant parameter for nuclear track detectors is the Restricted Energy Loss (REL), that is, the energy deposited within \( \sim 100 \text{ Å} \) from the track.

The chemical composition of CR39 nuclear track detector is \( (C_{12}H_{18}O_7)_n \), and the density is 1.31 g/cm\(^3\). For the computation of the REL, only energy transfers
to atoms larger than 12 eV are considered, because it is estimated that 12 eV are necessary to break the molecular bonds.

At low velocities \((3 \times 10^{-5} < \beta < 10^{-2})\) there are two contributions to REL: the ionization and the atomic recoil contributions.

The *ionization contribution*, which become important only for \(\beta > 2 \times 10^{-3}\), was computed with Ziegler’s fit to the experimental data.

The *atomic recoil contribution*, important for low \(\beta\) values, and was calculated using the interaction potential between an atom and a SECS which is

\[
V(r) = \frac{Z_1 Z_2 e^2}{r} \phi(r)
\]  

(21)

where \(r\) is the distance between the core of SECS and the target atom, \(Z_1 e\) is the electric charge of the SECS core, \(Z_2\) is the atomic number of the target atom.

The Restricted Energy Losses are finally obtained by integrating the transferred energies as

\[
-\frac{dE}{dx} = N \int \sigma(K) dK
\]  

(22)

where \(N\) is the number density of atoms in the medium, \(\sigma(K)\) is the differential cross section as function of the transferred kinetic energy \(K\).

## 4 Conclusions

We computed for a large range of velocity the energy losses of Q-balls of type SENS and SECS in matter. Using these energy losses and a rough model of the earth’s composition and density profiles, we have computed the energy losses in the earth interior.

We also calculated the energy deposited in scintillators, streamer tubes and nuclear track detectors by SECS, in forms useful for their detection. In particular we computed the light yield in scintillators, the ionization in streamer tubes and the REL in nuclear track detectors.
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