THE EXPERIMENTAL LIMITS ON Q-BALL FLUX WITH THE BAIKAL DEEP UNDERWATER ARRAY “GYRLYANDA”

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Abstract

Supersymmetric models allow for stable non-topological solitons, Q-balls, which can be
produced in the early Universe and contribute to dark matter. Experimental signature
of electrically neutral Q-balls is, in fact, the same as is expected for superheavy mag-
netic monopoles catalyzing baryon decay. Here we use the upper limits on monopole
flux obtained with the deep underwater Cherenkov array Gyrlyanda which operated in
the Baikal lake in 1984-90 with 267 days of live time to obtain the limit on Q-ball flux.
The last has been found to be equal to $3.9 \times 10^{-16}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ (90% CL). This
result is discussed and compared with other restrictions.
1 Introduction

Supersymmetric models allow for a new class of objects, which were named Q-balls\(^{[1]}\). These stable non-topological solitons can be produced in the early Universe and contribute to dark matter\(^{[1],[2],[3]}\). The possible experimental signatures of Q-balls were considered recently by Kusenko, Kuzmin, Shaposhnikov and Tinyakov\(^{[4]}\). The interactions of Q-balls with matter were shown in their work to differ essentially on whether they are electrically neutral (SENS) or charged (SECS). Q-balls of SENS type absorb the nuclei with a cross-section

\[
\sigma \sim 10^{-33} Q^{1/2} (1 \text{TeV}/m)^2 \text{cm}^2 ,
\]  

(1)

were \(m\) is assumed to be in the range of 0.1 ÷ 100 TeV and \(Q\) is a soliton charge (baryon number) which must be not less than \(\simeq 10^{15}(m/1\text{TeV})^4\) and may be much greater\(^{[4]}\). The released energy (\(\sim 1\) GeV per nucleon) is emitted in pions which (together with their decay products) may become the sources of the Cherenkov radiation in a transparent media. The Coulomb barrier prevents the absorption of the incoming nuclei by Q-ball of SECS type, which dissipates its energy in collisions with the matter atoms. In spite of enormous energy released by SECS passing, e.g., the water (\(\sim 100\) GeV/cm) it does not result in the Cherenkov light.

So, SENS passing the water media look very much like the monopoles catalyzing baryon decay\(^{[5]}\) for which the strong experimental flux limits were set with the Baikal deep underwater Cherenkov array Gyrylyanda\(^{[6]}\). In this short note we give the upper limit on Q-ball (SENS) flux which was recalculated from monopole flux limits obtained with Gyrylyanda in 1984-90. Though no experimental restrictions on Q-ball flux have been published by other group so far we compare the Gyrylyanda results with those that can be set using the monopole flux limits.

2 Upper limits on monopole flux with the “Gyrylyanda” array

The deep underwater array Gyrylyanda was constructed within the framework of the Baikal project which is devoted to creation of a large scale Cherenkov neutrino telescope in Siberian Lake Baikal\(^{[7]}\). It operated from April, 1984, till February, 1990, with live time of 267 days. Being modified after each year of operation it consisted of 12–36 PMTs placed at the single vertical string at depths of 900–1200 m. The distance between upper and lower PMTs was in the range of 30–250 m. The number of PMTs involved in the monopole search experiment fluctuated from 2 to 24 depending on year with \(\approx 10\) as an averaged value over the whole data taking period.

The detailed description of the Gyrylyanda array and monopole search experiment can be found in Ref.\(^{[6]}\). The basic idea is as follows: track of magnetic monopole catalyzing baryon decay in passage through a water media should look as a chain of flashes with a Cherenkov spectrum and, hence, objects of such kind can be detected by a short-time excesses of PMTs counting rate. The main advantage of array which operates in the open water volume is that the effective area is determined mainly by catalysis cross-section and water optical characteristics (in contrast to underground detectors whose effective area is limited by their geometrical sizes) and for catalysis
cross-section $\sigma > 10^{-23}$ cm$^2$ may be as large as $10^3$–$10^5$ m$^2$ even for considerable small single-string array like Gyryanda.

The upper limits set on the monopole flux in Ref.\cite{6} lie within a range of $\approx 10^{-17}$ – $10^{-14}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ depending on monopole velocity $\beta$ and catalysis cross-section $\sigma$ which were considered to be within intervals of $10^{-5}$–$10^{-3}$ and $10^{-23}$ cm$^2$–$10^{-17}$ cm$^2$, respectively.

3 Upper limits on Q-ball flux from “Gyrlyanda” monopole results

Q-balls of SECS type passing through the water seem to be not able to generate the light flux which would be intensive enough to be detected by an underwater array. Due to large energy losses it should generate $\sim 2 \times 10^4$ photons per 1 cm path via water luminescence\cite{8,9}. It is the same order of magnitude as is expected for SENS type of Q-balls with the nuclei absorption cross-section $\sigma \sim 10^{-24}$ cm$^2$ and lies under threshold of sensitivity for Gyryanda array.

SENS, in contrast to SECS, can produce much more impressive light show moving in water media. In according to (1), e.g., cross section of nuclei absorption $\sigma > 10^{-23}$ cm$^2$ if $m = 1$ TeV and $Q > 10^{20}$. This means dozens, hundreds, thousands and even much more (depending on $m$ and $Q$ values) absorbed nuclei per 1 cm of Q-ball path. Each event becomes a source of the Cherenkov radiation which is emitted both by pions and their daughter and grand-daughter particles (muons, $e^+e^-$ pairs etc.). The pions multiplicity distribution has not been numerically calculated so far but should be of the same kind that one for proton-antiproton annihilation\cite{9}.

Basing on results reported in Ref.\cite{10} one can expect 2–3 pions on average per each absorbed nucleon. Conservative estimates give at least $3 \times 10^4$ Cherenkov photons with wavelength interval $300$ nm < $\lambda$ < $600$ nm from each N – Q-ball interaction.

Thus due to absolutely similar effects which are produced by Q-ball of SENS type and magnetic monopole catalyzing proton decay in the water media it is possible to apply the results of Ref.\cite{6} to SENS. If Q-balls of SENS type are responsible for dark matter halo of Galaxy their velocities should be $\beta \sim 10^{-3}$\cite{11}. There are two experimental limits for monopoles catalyzing baryon decay and moving with velocity

\textit{On the one hand it is of $\sim 50$ times more than the Cherenkov light flux generated by relativistic muon which is well detectable object for underwater arrays. But, on the other hand, due to low velocity of heavy Q-ball of SECS type the number of photons generated within some time interval is much less than the corresponding value for the muon. It determines very low value of Gyryanda’s effective area for SECS.}

\textit{The sun rotates around the center of Galaxy with a velocity of $\beta = 7.3 \times 10^{-4}$. But there should be some distributions (which are unknown, in fact) both for Q-balls velocities and their motion directions. This must cause to some distribution for Earth – Q-balls relative velocities which spreads over the range from $\beta \sim 0$ to $\beta \sim 2 \times 10^{-3}$.}

Some fraction of SENS from the halo of Galaxy might loose velocity passing, e.g., through giant planet and be gravitationally captured by Sun. Such scenario was considered for GUT monopoles\cite{11} and can be applied to SENS as well. Due to large accumulation time which is equal to solar system age ($\sim 5$ Gyr) it might result in remarkable fraction of SENS with velocities of $\beta \sim 10^{-4}$ even in spite of negligible part of SENS’s kinetic energy which should be lost by passing through the matter.

Nevertheless we assume here simply $\beta = 10^{-3}$ for relative Earth – Q-ball velocity because, firstly one is lacking in information to use more sophisticated model and, secondly because the more detailed analysis is beyond the scope of the present work.
\[ \beta = 10^{-3} \] obtained with Gyrllyanda data. The first limit relates to proton decay channel with luminosity \( L = 1.1 \times 10^5 \) Cherenkov photons in the spectral interval \( 300 \text{ nm} < \lambda < 600 \text{ nm} \), the second one does to \( L = 3.0 \times 10^4 \). Both results were obtained for the effective (averaged for all protons and neutrons forming both hydrogen and oxygen nuclei) catalysis cross-section \( \sigma = 1.9 \times 10^{-22} \text{ cm}^2 \). Choosing the conservative estimation for single N – SENS interaction luminosity \( L = 3.0 \times 10^4 \) we obtain the upper limit for SENS flux:

\[
F = 3.9 \times 10^{-16} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} (90\% CL) \tag{2}
\]

for nuclei absorption cross-section

\[
\sigma > 1.9 \times 10^{-22} \text{ cm}^2. \tag{3}
\]

For \( \beta = 10^{-4} \) and the same values of \( \sigma \) the limit is of \( \simeq 10\% \) more strong.

4 Discussion

One should emphasize that for \( \sigma > 1.9 \times 10^{-22} \text{ cm}^2 \) the limits are obviously more strong than (2). Moreover for smaller cross-sections the restriction becomes more soft rather smoothly. But there were no numerical calculated results in Ref. 6 for other \( \sigma \) values and, therefore one is not able to obtain the flux limit dependence on cross-section. Following by the most conservative way let’s consider the upper limit (2) to be constant for all cross-sections which are equal or greater than those that is determined by (3) and to be not valid for smaller cross-sections. Using (1) it is easy to obtain the inequality

\[
Q^{1/2}(1\text{ TeV/m})^2 > 1.9 \times 10^{11}, \tag{4}
\]

which repeats (3) in another terms. The upper limits for SENS flux obtained here are shown in fig.1 by thick lines 1a, 1b, 1c and 1d. One can see that for smaller \( m \) the limit is valid for more wide range of \( Q \). E.g. for \( m = 0.1 \text{ TeV} \) and \( m = 100 \text{ TeV} \) the flux limit (2) is valid for \( Q > 3.6 \times 10^{18} \) and \( Q > 3.6 \times 10^{30} \), respectively (lines 1a and 1d). At the same plot the limits which are caused by dark matter density in the galactic halo are shown by four sloping lines (for four different values of \( m \)). They are resulting from the obvious condition \( \rho_Q \leq \rho_{DM} \) where \( \rho_{DM} \) is galactic halo dark matter density in the Sun neighborhood and \( \rho_Q \) is Q-ball density. Assuming Q-ball mass to be equal to \( M \simeq (4\pi\sqrt{2}/3)mQ^{3/4} \) (Ref. 8) and \( \rho_{DM} \simeq 10^{-2} \text{ M}_\odot \text{ pc}^{-3} \) (see, e.g., Ref. 12), we obtain

\[
F < 1.5 \times 10^2 Q^{-3/4}(1\text{ TeV/m}) \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}. \tag{5}
\]

One can see that Gyrllyanda flux limits lie below this limit in rather narrow range of \( Q \) and for small values of \( m \) only.

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*This limit is actual only under assumption that dark matter is uniformly distributed along the galactic latitude. Generally saying, this assumption may be rather far from reality. If so, there may be, e.g., short periods when the Earth crosses the galactic areas with \( \rho_{DM} \gg 10^{-2} \text{ M}_\odot \text{ pc}^{-3} \) and, on the contrary, long periods when Earth is inside areas with \( \rho_{DM} \ll 10^{-2} \text{ M}_\odot \text{ pc}^{-3} \).*
The result which has obtained by the Baksan telescope for magnetic monopoles and should be valid for Q-balls of both SENS and SECS types are shown in fig.1 by the thin lines 2a, 2b, 2c, and 2d. It is only slightly stronger comparing with Baikal result but is valid for much more wide range of $Q$. The Baksan telescope is able to detect SENS if $\sigma \geq 5 \times 10^{-26}$ cm$^2$ (compare to (3)). The large multi-string deep underwater neutrino telescope NT-200 is currently under construction in the Lake Baikal. The reported limits which can be set with its data on monopole flux are one or two orders of magnitude lower than Gyrlyanda’s one. These limits will be able to be applied to SENS flux, too. Due to more phototubes and more smart electronics one can expect the less values of $\sigma$ (and, consequently, the less values of $Q$) for which these more strong limits will be valid. The experimental upper limits on monopole flux obtained by IMB, Kamiokanda and MACRO can be also applied to Q-balls, but resulting limits are still less strong comparing to both Gyrlyanda and Baksan results. The most strong limit on Q-balls of SECS type seems to be set by the GUT monopole search experiment with “ancient mica” and is equal to $4 \times 10^{-19}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$. If this limit will be confirmed to be valid for Q-balls of SECS type it will be out of the ability of underground/water detectors for a long time.

Now let’s have look at the Gyrlyanda limits by another way. For $m$ and $Q$ above the thick slopping line (fig. 2) the limit (2) is valid. The shaded area below the dotted line contains $m$ and $Q$ for which experimental limit (2) is more strong than restriction (5) obtained from allowed DM density in galactic halo. So, if one assumes SENS to be entirely responsible for DM density in halo, one can consider shaded triangle as a region for $Q$ and $m$ values which are excluded by Gyrlyanda results. One can see that for presented limit (2) all $Q$ values have not been excluded for $m$ greater than $\simeq 1.5$ TeV. To cover the remaining region both larger effective area and ability to detect SENS which absorb the nuclei with smaller cross-section are neccessary.

5 Conclusion

The upper limit on Q-ball flux of SENS type has been set by revising the old monopole limits obtained by Baikal deep underwater Cherenkov array Gyrlyanda: $F = 3.9 \times 10^{-16}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ (90% CL). It is valid for nuclei absorption cross-section $\sigma > 1.9 \times 10^{-22}$ cm$^2$. It is still above the limit obtained for SENS by Baksan telescope but can be improved with the deep underwater neutrino telescope NT-200 which is currently under construction in the Baikal Lake.

The main advantage of underwater arrays operating in the open water volume and searching for the objects like magnetic monopoles and Q-balls which are expected to generate the intensive light flux passing through a water media is that the effective area is determined mainly by light flux intensity and water optical characteristics (in contrast to underground detectors whose effective area is limited by their geometrical sizes) and may be as large as $10^3$–$10^5$ m$^2$ even for considerable small arrays.

$d$ It is our conclusion which seems to be obvious but, strongly saying, it has to be confirmed by Baksan group.

e The effective area of the Baksan telescope for Q-balls is much less than Gyrlyanda’s one but Baksan’s data taking period is of 20 times longer.
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Figure 1: Slopping lines: the upper limits on Q-ball flux which are resulting from condition $\rho_Q \leq \rho_{DM}$ where $\rho_{DM}$ is galactic halo dark matter density in the Sun neighborhood and $\rho_Q$ is Q-ball density ($\rho_{DM}$ is assumed to be equal to $10^{-2} M_\odot$ pc$^{-3}$). Thick lines 1: the upper limits (90% CL) on Q-ball of SENS type flux obtained with Baikal deep underwater Cherenkov array Gyryanda for $m = 0.1$ TeV (1a), 1 TeV (1b), 10 TeV (1c), 100 TeV (1d) (this preprint and Ref. 6). Thin lines 2: the upper limit for Q-balls (both SENS and SECS type) obtained with Baksan telescope (90% CL) for $m = 0.1$ TeV (2a), 1 TeV (2b), 10 TeV (2c), 100 TeV (2d) 8. See text for the further explanations.
Figure 2: For $m$ and $Q$ above the thick sloping line (including the shaded triangle) the limit (2) is valid. The shaded area below the dotted line contains $m$ and $Q$ for which experimental limit (2) is more strong than restriction (5) obtained from allowed DM density in galactic halo. Thus, if one assumes SENS to be entirely responsible for DM density in halo, one can consider shaded area as a region for $Q$ and $m$ values which are excluded by Gyryanda results.