Search for massive exotic particles with the ANTARES neutrino telescope

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Abstract. A report is presented on the search for magnetic monopoles and nuclearites with the ANTARES experiment, using data collected in 2007 and 2008. A large light signal is expected from these presumably rare particles. The analysis of data yielded no exotic candidates, thus upper limits were set on the flux of fast upgoing magnetic monopoles and of slow downgoing nuclearites.

1. Introduction
Besides the search for cosmic neutrinos, the ANTARES detector can contribute to the search for magnetic monopoles [1] and nuclearites [2]. Magnetic monopoles were initially predicted by Dirac in 1931, and rediscovered almost 40 years later by ’t Hooft and Polyakov, as a natural occurrence in GUT theories. Nuclearites are hypothetical lumps of strange quark matter, that may be present in the cosmic radiation. Upper limits on their fluxes were provided by MACRO [3, 4], Baikal [5], AMANDA-II [6] experiments. In this paper, dedicated analyses and their results for relativistic magnetic monopoles and slow nuclearites are presented.

2. The ANTARES detector
ANTARES is a tridimensional array of 885 photomultipliers (PMTs), located in the Mediterranean Sea, at 2475 m depth, near the French town Toulon [7]. The PMTs are contained in glass spheres and are arranged in triplets on 12 lines anchored on the sea bed. Until its 12 line completion in mid-2008, ANTARES took data in partial configurations of 5 lines (2007), 9 and 10 lines (2008).

The data acquisition system sends to shore all PMT signals above a pre-defined threshold, typically 0.3 photoelectrons (pe) [8]. Then the raw signals are filtered by various triggers and stored. The time and charge information of the PMT signals is digitized into “hits”, labeled L0 hits. The standard algorithms used to identify muon events are based on local coincidences. A local concidence (or L1 hit) is defined either as two L0 hits on the same storey, within 20 ns, or as a single hit with a large charge, usually above either 3 or 10 pe threshold. Thus, the so-called directional trigger (DT) requires at least 5 L1 hits correlated in space and time, while the cluster trigger (CT) looks for a pair of clusters of two L1 hits in 2 out of 3 consecutive storeys, within a 2.2 μs time window, the characteristic time of a relativistic particle to cross the detector.

Both analyses presented in this article are using a blinding strategy. This requires the definition and optimization of the selection criteria using Monte Carlo simulations and the validation of the simulations on a fraction (∼ 15%) of the available data.
3. Magnetic monopoles

According to 't Hooft [9] and Polyakov [10], magnetic monopoles may have formed in the early Universe, as a result of the spontaneous breaking of a semi-simple gauge group that contains the U(1)_{E.M.} subgroup. Their magnetic charge \( g \) is defined as a multiple integer of the Dirac charge \( g_D = \frac{\hbar c}{2e} \), where \( e \) is the elementary electric charge, \( \hbar \) the Planck’s constant and \( c \) the speed of light. Monopoles of intermediate GUT mass (below \( \sim 10^{14} \) GeV) could be accelerated to relativistic velocities by cosmic magnetic fields, and thus may reach the ANTARES detector from any direction.

The light signal of monopoles in water can be produced either as direct Cherenkov emission, for \( \beta > 0.74 \) or as indirect Cherenkov emission, for \( \beta > 0.51 \), by means of the knock-out electrons (\( \delta \)-rays) pulled out from the atoms. Thus, a monopole with one Dirac charge may emit about 8500 more photons than a muon with the same velocity.

For this analysis, 136 days of data taken in 2008 were used. Upgoing magnetic monopoles were simulated for 10 velocity ranges within \( \beta = [0.550, 0.995] \). Monte Carlo upgoing atmospheric neutrinos and downgoing atmospheric muons were considered for background. The MC events were processed with the active triggers, along with background information extracted from a group of experimental runs for each detector configuration. In order to account for the different velocities of simulated monopoles, one of the ANTARES track reconstruction algorithms [11] was modified by implementing the velocity as a free parameter and by optimizing it for the crossing of magnetic monopoles [1]. This algorithm is based on the minimization of the time residuals using the least square method, with a very stringent hit selection. The Gaussian resolution obtained for the reconstructed monopole velocity is \( \sigma_\beta \sim 0.003 \) for \( \beta > 0.8 \) and \( \sigma_\beta \sim 0.03 \) for lower velocities.

Data - MC comparisons were performed for events reconstructed with the modified algorithm, using a 15% data sample. In a first step, only upgoing events with zenith angle \( < 90^\circ \) and reconstructed \( \beta > 0.60 \) are selected. For the final event selection, discriminative variables were defined.

The first discriminative variable is the number of hits used in the reconstruction, \( n_{hit} \). The second variable is the so-called \( \lambda \) parameter, defined as the logarithmic ratio between the track quality factors \( Q_t(\beta_{rec} = 1) \) and \( Q_t(\beta_{rec} = \text{free}) \), obtained from the standard muon reconstruction and from the modified reconstruction, respectively. The quality factor is the sum over the number of hits of squared time residuals plus an adjusting term for distant hits with large charge. The cut parameter space (\( n_{hit}, \lambda \)) defined for every region of reconstructed velocities was optimized by minimizing the Model Discovery Factor for a 5\( \sigma \) discovery at 90% probability.

After unblinding, a very good data-MC agreement is obtained for the remaining 85% of data. For most velocity ranges, no event survived the selection cuts, except for one event in the interval \( \beta_{rec} = [0.675, 0.725] \). Given the expected background of 0.13, which requires five events for a 5\( \sigma \) deviation, the observation is compatible with the background-only hypothesis. The upper flux limit for upgoing magnetic monopoles, obtained for 116 days of ANTARES data (corresponding to 85% of the unblinded data), is shown in figure 1. This is the most stringent upper limit for upgoing magnetic monopoles in the velocity range \( 0.625 < \beta < 0.995 \) (\( \gamma = 10 \)) [1].

4. Nuclearites

Nuclearites are hypothetical massive particles of up, down and strange quarks in approximately equal proportions. They may have formed in the early Universe [13], or in high energy astrophysical phenomena, like supernovae and strange star collisions [14]. Their velocity is assumed to be \( \beta \approx 10^{-3} \), the typical velocity of gravitationally trapped objects inside the galaxy. Nuclearites would interact through elastic collisions with the atoms of the medium.
Nuclearites with masses larger than $\sim 3 \times 10^{13}$ GeV could reach the ANTARES depth from above and could be detected by means of the black-body radiation from their overheated path in the traversed medium [15]. The number of visible photons emitted by downgoing nuclearites can be a few orders of magnitude higher than the number of Cherenkov photons emitted by a muon with $\beta \sim 1$.

For this analysis, 310 days of data taken during 2007 and 2008 were considered. Downgoing nuclearites were simulated inside a hemispherical volume of 548 m radius surrounding the ANTARES vertical symmetry axis, in the mass range $3 \times 10^{13} - 10^{17}$ GeV, and considering an initial velocity outside the Earth atmosphere of $\beta = 10^{-3}$. At the ANTARES depth, the dominant background for nuclearites is caused by the downgoing atmospheric muons. The muons were simulated with the MUPAGE code [16]. Both MC nuclearites and muons were processed using the triggers described in section 2.

Characteristic of the nuclearite signal is the long duration of the event inside the detector (about 1 ms) compared to the typical duration of a muon event (about 2.2 $\mu$s). When a muon event is triggered, all hits are recorded in an enlarged snapshot containing 2.2 $\mu$s before and after the cluster of L1 hits, while a typical nuclearite event will produce a sequence of multiple enlarged snapshots within 1 ms.

The discriminative variable used for the nuclearite signal selection is the snapshot duration $dt$, defined as the time difference between the last and the first L1 hit producing a trigger. Optimized C1 cuts were established by minimizing the upper flux limits obtainable if no signal is found. A few events from the 15% data sample used for the data-MC comparison survived the C1 cuts, their investigation revealing the presence of bioluminescence bursts due to marine organisms. In order to remove the bioluminescence background, a second level cut was introduced, requiring either events with multiple snapshots within 1 ms or single snapshot events with a duration larger than twice the value of the C1 cut.

Seven events from the unblinded data survived the cuts. The visual and topological investigations showed that three of them were due to sparking OMs and the other four were products of bioluminescence bursts, so they were excluded. The preliminary ANTARES upper limit for a flux of downgoing nuclearites obtained for 310 days of data is presented in figure 2, and compared with the MACRO [4] and SLIM [17] limits.

![Graph showing flux limits for different experiments](image)

**Figure 1.** The preliminary ANTARES 90% C.L. upper limit for upgoing magnetic monopoles, compared to the upper limits set by MACRO, Baikal and AMANDA II, and the theoretical Parker bound [12].
5. Conclusions
The first results of the searches for relativistic magnetic monopoles and slow nuclearites with the ANTARES detector were presented. The ANTARES upper flux limit for upgoing magnetic monopoles in the velocity range $0.625 < \beta < 0.995$ is the most stringent up to date. The upper limit for a flux of downgoing nuclearites improves the MACRO result and is the best present limit for the $10^{14} - 10^{17}$ GeV nuclearite mass range.

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