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Search for magnetic monopoles and nuclearites with the ANTARES experiment

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ABSTRACT

We report on the search for magnetic monopoles and nuclearites with the ANTARES experiment, using data collected in 2007 and 2008. Both magnetic monopoles and nuclearites are expected to produce a large signal inside the detector. The analysis of data yielded no exotic candidates, and upper limits were set on the flux of fast upgoing magnetic monopoles and of slow downgoing nuclearites.

1. Introduction

ANTARES is a detector designed for neutrino astronomy, that can also contribute to the search for hypothetical massive particles [1,2], such as magnetic monopoles [3,4] and nuclearites [5]. Magnetic monopoles were initially predicted by Dirac in 1931, in order to explain the quantization of the electric charge. They were rediscovered almost 40 years later by 't Hooft and Polyakov, as a natural occurrence in GUT theories. Since then, monopoles were intensively searched for in various experimental facilities, like MACRO [6], Baikal [7], AMANDA-II [8], but no such particle was detected. Nuclearites are hypothetical lumps of strange quark matter, that may be present in the cosmic radiation. The most representative upper limit on the nuclearite flux, for the mass range expected at the ANTARES depth, was that established by MACRO [9]. In this paper, dedicated analyses and their results for relativistic magnetic monopoles and slow nuclearites are presented for 116 and 310 active days, respectively.

2. The ANTARES detector

ANTARES is located in the Mediterranean Sea, at 2475 m depth, 40 km south of Toulon [10]. It is an array of 885 optical modules (OMs), arranged in triplets on 12 lines anchored to the sea bed. An OM consists of a glass sphere housing a 10″ Hamamatsu photomultiplier (PMT). Each line is connected to the main junction box, which is linked to the shore station. Until the completion with 12 lines 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) [11]. 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 coincidence (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.

The muon triggers used are the so-called directional trigger (DT), operational both in 2007 and 2008, and the cluster trigger (CT), implemented since 2008. DT requires at least 5 L1 hits correlated in space and time, while 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 paper 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 ($\sim 15\%$) of the available data.

3. Magnetic monopoles

According to Grand Unified Theories (GUT), magnetic monopoles may have formed in the early Universe. It was shown by 't Hooft [12] and Polyakov [13] that they appear 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 $g_D = \hbar c/2e$, where e is the elementary electric charge, $\hbar$ the Planck's constant and c the speed of light.

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Fast monopoles can lose a large amount of energy in the terrestrial environment. Nevertheless, magnetic monopoles with mass below $\sim 10^{14}$ GeV could be accelerated to relativistic velocities by cosmic magnetic fields, and thus could reach the ANTARES detector from below.

3.1. Magnetic monopole signal in water

Depending on the velocity, the light signal can be produced either as direct Cherenkov emission, for magnetic monopoles with $\beta > 0.74$ or as indirect Cherenkov emission, for $\beta > 0.51$, by means of the knock-out electrons (δ-rays) pulled out from the atoms by the magnetic monopole. Thus, a monopole with one Dirac charge may emit about 8500 more photons than a muon with the same velocity, as shown in Fig. 1.

3.2. Magnetic monopole analysis

For this analysis, data taken in 2008 with 9, 10 and 12 line configurations were used, with a total livetime of 136 days. 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 simulated events were processed using the active triggers, along with the dead channel information and the optical background rates 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 [14] was modified by implementing the velocity as a free parameter and by optimizing it for the crossing of magnetic monopoles [4]. 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.

Both MC events and a 15% data sample (~ 20 days active time) have been reconstructed with the modified algorithm. Then data-MC comparisons were performed using various parameters and preliminary cuts were defined. These cuts require events with reconstructed $\beta > 0.60$ and zenith angle $< 90^\circ$.

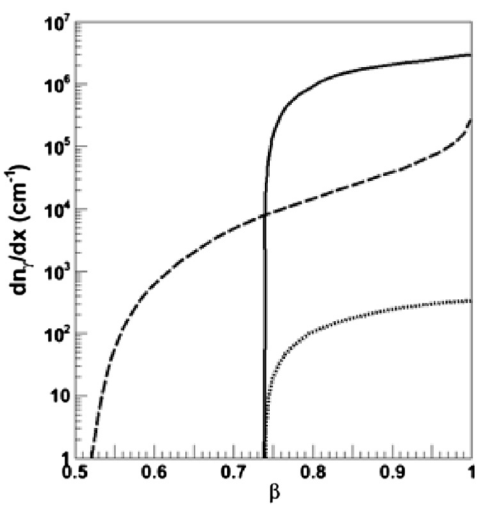

Fig. 1. Expected light yield in the 300–600 nm wavelength range in sea water from magnetic monopoles with unit Dirac charge (solid line), from δ-rays produced along the monopole path (dashed line) and from muons (dotted line), as a function of velocity.

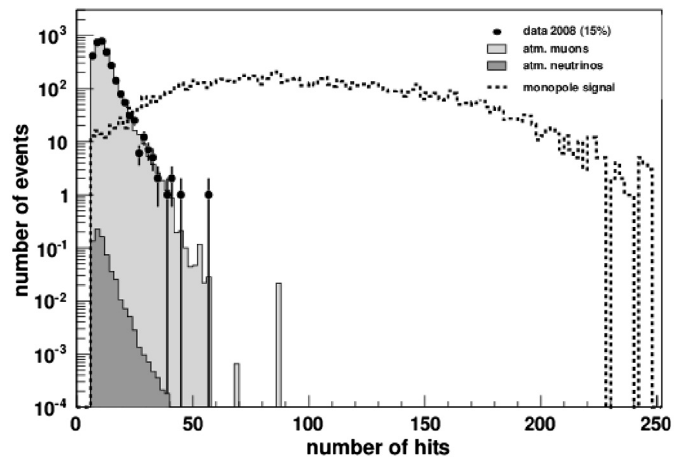

Fig. 2. Distribution of the number of hits for MC magnetic monopoles (dashed line) reconstructed with $\beta_{rec} = [0.775, 0.825]$. Comparisons of simulated atmospheric downgoing muons (light gray) and upgoing neutrinos (medium gray) with 15% data samples (solid dots) are also shown.

For the final event selection, discriminative variables were defined. The first discriminative variable is the number of hits used in the reconstruction, nhit. A data-MC comparison of the nhit distributions is shown in Fig. 2. The second variable is the so-called λ 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 (nhit, λ) defined for every region of reconstructed velocities was optimized by minimizing the Model Discovery Factor for a 5σ discovery at 90% probability.

4. Results

After unblinding, a very good data-MC agreement is obtained for the remaining 85% of data. The final results obtained after applying the selection cuts on the unblinded data are shown in Table 1.

One event survived the selection cuts in the interval $\beta_{rec} = [0.675, 0.725]$. Given the expected background of 0.13, which requires five events for a 5σ deviation, the observation is compatible with the background-only hypothesis.

The Feldman–Cousins 90% C.L. upper limit obtained for this interval considers the observed event as background [4]. 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 Fig. 3. This is the most stringent upper limit for upgoing magnetic monopoles in the velocity range $0.625 < \beta < 0.995$ ($\gamma = 10$) [4].

5. Nuclearites

Nuclearites are hypothetical massive particles of up, down and strange quarks in approximately equal proportions. They may have formed in the early Universe [16], or in high energy astrophysical phenomena, like supernovae and strange star collisions [17]. Their velocity is assumed to be $\beta \simeq 10^{-3}$, the typical velocity of gravitationally trapped objects inside the galaxy. Nuclearites with masses larger than $\sim 3 \times 10^{13}$ GeV could reach the ANTARES depth from above and could be detected by means