Nuclearite search with the ANTARES neutrino telescope

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Abstract: We discuss the search for down-going nuclearites with the ANTARES neutrino telescope. After a very brief description of ANTARES, we explain the detection mechanism of slowly moving nuclearites. The search strategy, based on a blind analysis is then discussed. The search for nuclearites in data collected in 2007 and 2008 with different ANTARES configurations is ongoing.

Keywords: Nuclearites, ANTARES

1 Introduction

The ANTARES neutrino telescope was completely deployed in 2008 at a depth of 2475 meters, about 40 km South of Toulon, France. It is composed of 12 vertical lines, bearing a total of 885 optical modules (OMs) distributed in 25 storeys, at depths between 2050 and 2400 meters. A smaller instrumentation line is also present. The OMs, consisting of a glass sphere housing a 10" Hamamatsu photomultiplier (PMT) are arranged in triplets per storey, with the axes looking 45° downwards. Each line is connected by an electro-optical cable to the main junction box, and then to the shore station [1]. A secondary junction box is also present, ensuring the connection of various sea science experiments. All data above a certain threshold are sent to shore, where they are filtered by various triggers before being stored [2]. This is the so called "all data to shore" strategy.

ANTARES is optimized for the detection of upward going relativistic muons, but is also sensitive to a variety of exotic particles, as fast magnetic monopoles and slow nuclearites [3, 4]. In this paper we report on the status of nuclearite search with the ANTARES detector.

2 Nuclearite properties

If Strange Quark Matter (SQM) is the ground state of Quantum Chromodynamics (QCD), nuggets of SQM (so called "nuclearites") have to be present in the penetrating cosmic rays [5]. They could have been produced in the early Universe, or in violent astrophysical processes as binary strange star collapses [6]. The only phenomenological bound to the nuclearite flux in the galaxy is derived from the dark matter density [5]. The nuclearite detection in very large volume neutrino telescopes is possible through the black body emission from their over-heated path in water [5]. Nuclearites are known also as "strangelets"; in most cases this denomination refers to nuclear SQM nuggets with mass similar to that of heavy nuclei, "nuclearites", as used in this paper, refer to much heavier objects ($M \geq 10^{10}$ GeV). The density of SQM is estimated to be a little larger than that of ordinary nuclear matter, $\rho_N \simeq 3.6 \times 10^{14}$ g cm^{-3}. According to [5], the chemical potential difference between s and u or d quarks should induce a small residual positive charge for the finite size SQM. Nuclearites moving with typical velocities of gravitationally trapped objects in the Galaxy ($\beta = v/c \simeq 10^{-3}$) should have the residual charge compensated by an electron cloud, or/and by electrons in weak equilibrium inside the SQM [5].

2.1 Nuclearite energy loss in matter

For slowly moving nuclearites ($\beta \simeq 10^{-3}$) the dominant energy loss is through elastic collisions with the atoms in the traversed medium:

$$\frac{dE}{dx} = -\sigma \rho v^2 \tag{1}$$

where σ is the nuclearite cross section, and ρ the density of the medium. The cross section has the typical atomic value $\sigma = \pi \times 10^{-16}$ cm^2 for nuclearite masses $M \leq 8.4 \times 10^{14}$ GeV, and $\pi(3M/4\pi\rho_N)^{2/3}$ for larger masses. Assuming that outside the atmosphere the velocity of a nuclearite is $\beta = 10^{-3}$, in order to cross the Earth its mass should be larger than about 10^{22} GeV [5]. As we expect that the nuclearite flux in the cosmic rays decreases with increasing mass (as for heavy nuclei), we concentrate for this analysis only on downgoing nuclearites.

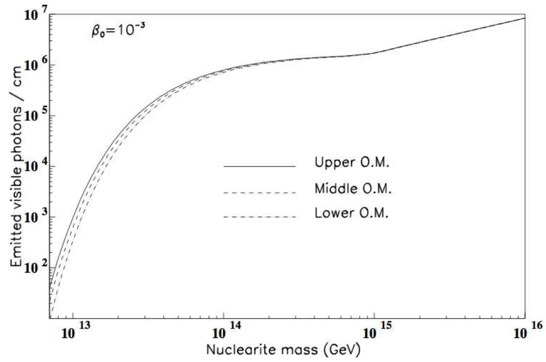

Figure 1: Light yield from a vertically down-going nuclearite at the level of the upper, middle and lower ANTARES storeys.

2.2 Principle of nuclearite detection in ANTARES

The energy release through elastic collisions (Eq. 1) results in the over-heating of the nuclearite track in matter. In the case of water, it is estimated that a fraction $\eta \simeq 3 \times 10^{-5}$ of the energy loss is dissipated as visible black body radiation emitted by the expanding cylindrical shock wave [5]. The number of visible photons emitted per unit path length may be estimated as:

$$\frac{dN_\gamma}{dx} = \eta \frac{dE/dx}{\langle E_\gamma \rangle} \tag{2}$$

where $\langle E_\gamma \rangle \simeq \pi$ eV is the average energy of visible photons.

As a simple exemplification Fig. 1 shows the light yield at the ANTARES depth assuming a vertically down-going nuclearite, with the initial velocity (above the Earth atmosphere) $\beta = 10^{-3}$, as a function of its mass. The curves correspond (from up to down) to the light yield at the level of the upper, middle and respectively lower ANTARES storeys. Nuclearites with masses larger than few 10^{13} GeV produce enough light to be detectable with the ANTARES telescope. A complete Monte Carlo simulation describing the light production along nuclearite paths, considering initial isotropic arrival direction from the upper hemisphere and distances from the detector axis expanding to 5 absorbtion lengths in water was developed and used in the analysis described bellow.

3 Nuclearite search strategy in ANTARES

The basic information in ANTARES is the "hit", the time and charge (amplitude) information of a photon detected by a PMT. If the charge is over a pre-defined threshold, the hit is called "L0" hit and buffered. A local coincidence ("L1" hit) is defined as two L0 hits in the same storey within 20 ns, or a single hit with large amplitude (3 photoelectrons (pe) or more, collected by a single PMT). The "directional trigger" (DT) requires at least 5 L1 casually connected hits anywhere in the detector, within a 2.2 μs window. A second trigger, implemented in a later phase, is the "cluster trigger" (CT). It is based on the "T3" cluster, a combination of two L1 hits in adjacent or next-to-adjacent storeys, and requires two of such clusters in a 2.2 μs window. All PMT pulses in a 2.2 μs time window are conserved in a buffer. If a trigger occurs, all hits with charges above a given threshold are saved for the actual time window, together with the previous buffered information. If, in the next time window another trigger fires, the data are merged together, so the minimum duration of an event "snapshot" is 4.4 μs.

The data recorded in 2007 and 2008 were obtained during ANTARES completion, so they refer to various detector configurations. The variations in bioluminescence imposed also different L0 threshold values. In order to maximize the analysis efficiency, the ANTARES approach is to start with a "blind analysis". This consists in defining the search strategy using Monte Carlo simulations, and validating them on a small fraction (15%) of the available data.

The search for nuclearites in ANTARES is based on the fact that the duration of a nuclearite event should be much longer (about 1 ms) than in the case of a muon. Furthermore, the luminosity produced by the passage of a nuclearite is expected to be orders of magnitude larger than from muons. The isotropic light emitted along the heated path should induce a long succession of fake muon signals, so we can use the same triggers as those implemented for relativistic ionizing particles. Monte Carlo simulations have been performed for different nuclearite masses, in all ANTARES configurations during 2007 and 2008. The background level was extracted from real runs. The simulated events were processed using the DT and CT (for the time period in which they were active) triggers. Triggers select only the hits compatible with the passage of a muon, so nuclearite events may expand on multiple adjacent snapshots. Downwards going muons are the main source of background for nuclearite searches, so we investigated the snapshot duration dt for both simulated muons and nuclearites, defined as the time difference between the last and the first L1 hits that produce a trigger. Muons were simulated using the MUPAGE code [7]. Fig. 2 shows a comparison between the distributions of snapshot durations for simulated nuclearites and muons. This result corresponds to a 5 line ANTARES configuration, DT trigger and a 3 pe L0 threshold. The vertical line (at a snapshot duration of 3250 ns) represents the optimized cut for this configuration. All configurations were analyzed in a similar way, and optimal cuts (ranging between 2500 and 4750 ns) were defined as to minimize the upper flux limits obtainable if no signal is found. In the following we refer to those first level selection, based only on the snapshot duration, as "C1" cuts. We tested the C1 cuts on 15% of real data, selected to reproduce the proportion of different experimental configurations.

For the few events passing the C1 cut, the evolution in time of the event charge barycenter was studied. As the light

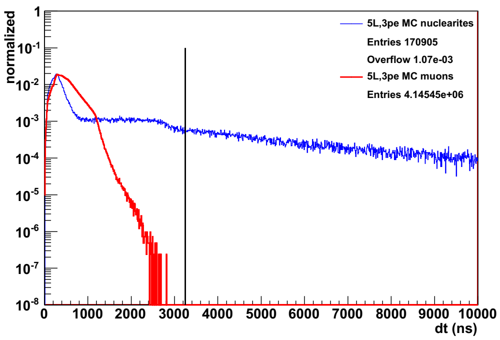

Figure 2: Snapshot duration distributions for simulated nuclearites and muons, broader and narrower curves respectively. The distributions are normalized to unity, and were obtained for a 5 line ANTARES configuration, DT only and a 3 pe threshold. The vertical line marks the optimal C1 cut for this configuration.

emitted by nuclearites is isotropic, the charge barycenter offers an estimation of the position of the source at a certain moment. All events were consistent with static light sources, so they were interpreted as bioluminescence bursts. Characteristic to those events is that they were all single-snapshot events. In order to reduce the bioluminescence background, we introduced a second level cut C2, to be applied only to single-snapshot events, requiring an event duration twice the C1 cut value. With this second cut, no event in the 15% data sample survived.

The efficiencies of the cuts for different nuclearite masses were computed and are presented in Table 1. They are defined as the fraction of the nuclearite events detectable after filtering the data.

In terms of nuclearite mass, the threshold of our search (defined as the minimum mass of a nuclearite entering the Earth atmosphere with $\beta = 10^{-3}$) is about 3×10^{13} GeV. This is in agreement with the results presented in Fig. 1.

4 Results

After unblinding, we performed the analysis of the experimental data collected during the 2007 and 2008 runs. The analysis followed the pre-defined strategy: data are filtered applying the corresponding C1 cuts, or the C2 cuts for the single-snapshot events. No residual contamination was found from downward going atmospheric muons after this selection.

Very few events survived our cuts, but they are not compatible with the hypothesis of slowly downgoing particles; they might be safely interpreted as due to bioluminescence. Their topology was investigated using the event charge barycenter versus time correlation. This approach is equivalent to a fast but less accurate geometrical reconstruction of the event. Consequently, we could compute a 90% confidence level upper limit for a flux of downward going nuclearites, from the ANTARES 2007 and 2008 data. Our result is presented in Fig. 3, compared with the MACRO limit [8], as updated in [9], and with the SLIM limit [10]. All limits in Fig. 3 are obtained in the same hypothesis: nuclearites are supposed to enter the Earth atmosphere with a velocity of 300 km/s, and refer only to downgoing nuclearites. In order to traverse the Earth, such slow moving objects should have masses larger than some 10^{22} GeV [5].

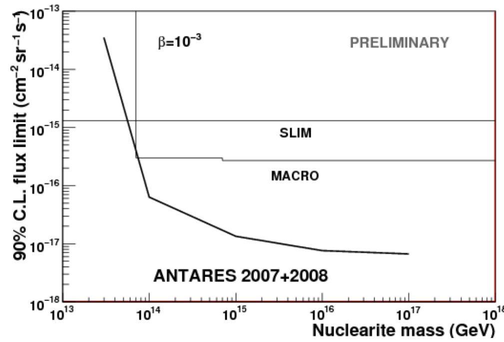

Figure 3: The ANTARES 90% CL upper limit for a flux of downgoing nuclearites, obtained from the 2007 and 2008 data. The final limits reported by MACRO and SLIM are also shown.

We recall that MACRO was an underground detector operated in the National Gran Sasso Laboratories of INFN, and SLIM was a passive detector operated at high altitude, at the Chacaltaya Cosmic Ray Laboratory.

The shape of our limit reflects the narrowing around the vertical direction of our solid angle acceptance as the nuclearite mass becomes smaller. The ANTARES preliminary limit improves significantly the MACRO result in all the common mass range; the SLIM limit remains better for nuclearite masses lower than about 5×10^{-3} GeV.

5 Conclusions

We have presented the strategy to search for downward going nuclearites as well as the preliminary results obtained from the 2007 - 2008 data analysis with the ANTARES neutrino telescope. The results discussed were obtained after unblinding the data corresponding to the detector configurations during the 2007 and 2008 data tacking. No candidate event survived all criteria; the 90% C.L. ANTARES upper flux limit improves significantly the MACRO result [8, 9]. In the lowest mass region, the SLIM limit [10] still remains the most stringent published result.

The same analysis procedure will be applied for the ANTARES data recorded after the completion of the detector (2009 and later on).

Detector configuration	3×10^{13} GeV eff. (%)	10^{14} GeV eff. (%)	10^{15} GeV eff. (%)	10^{16} GeV eff. (%)	10^{17} GeV eff. (%)
5L, DT,10 pe	-	5.4	65.6	80.1	88.6
5L, DT, 3 pe	-	15.9	73.0	82.0	87.2
10L, DT, 10 pe	-	5.0	66.5	83.2	86.2
10L, DT, 3 pe	-	18.8	75.5	80.2	91.4
10L, DT, CT, 3 pe	3.0	70.3	83.8	84.0	92.6
9L, DT, CT, 3 pe	4.6	70.0	83.2	83.7	93.5
9L, DT, CT, 10 pe	1.7	67.7	82.8	83.9	93.9
12L, DT, CT, 10 pe	5.4	68.5	82.4	82.6	94.0
12L, DT, CT, 3 pe	2.1	70.4	83.0	83.4	92.5

Table 1: Efficiency of our analysis for different nuclearite mass values and various ANTARES configurations, used in 2007 and 2008.

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