Quark nuggets search using 2350 Kg gravitational waves aluminum bar detectors

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Abstract:
The gravitational wave resonant detectors can be used as detectors of quark nuggets, like nuclearites (nuclear matter with a strange quark). This search has been carried out using data from two 2350 Kg, 2 K cooled, aluminum bar detectors: NAUTILUS, located in Frascati (Italy), and EXPLORER, that was located in CERN Geneva (CH). Both antennas are equipped with cosmic ray shower detectors: signals in the bar due to showers are continuously detected and used to characterize the antenna performances. The bar excitation mechanism is based on the so called thermo-acoustic effect , studied on dedicated experiments that use particle beams. This mechanism predicts that vibrations of bars are induced by the heat deposited in the bar from the particle. The geometrical acceptance of the bar detectors is 19.5 m^2 sr, that is smaller than that of other detectors used for similar searches. However, the detection mechanism is completely different and is more straightforward than in other detectors. We will show the results of ten years of data from NAUTILUS (2003-2012) and 7 years from EXPLORER (2003-2009). The experimental limits we obtain are of interest because, for nuclearites of mass less than 10^{-4} grams, we find a flux smaller than that one predicted considering nuclearites as dark matter candidates.

Keywords: Nuclearites, Gravitational,Bar,Detectors

1 Introduction

Cosmic ray showers can excite mechanical vibrations in a metallic cylinder at its resonance frequencies and can provide an accidental background for experiments searching gravitational waves (*gw*): this possibility was suggested many years ago and a first search, ending with a null result, was carried out with room temperature Weber type resonant bar detectors [1].

Later on, the cryogenic resonant *gw* detector NAUTILUS [2] was equipped with a streamer tube extensive air shower detector [2] and the interaction of cosmic ray with the antenna was studied in detail. This apparatus allowed the first detection of cosmic ray signals in a *gw* antenna, that took place in 1998, when NAUTILUS was operating at a temperature T = 0.14 K [3], i.e. below the superconducting (s) transition critical temperature $T_c \simeq 0.9$ K. During this run many events of very large amplitude were detected[4]. This unexpected result suggested in 2002 the construction of a cosmic ray detector for the EXPLORER detector and a measurement with a dedicated apparatus to study the response of an aluminum bar at low temperatures [5]. The experiment was also motivated by the need of a better definition of the thermo-physical parameters of the alloy Al5056, used in the bar detector, at low temperatures.

A detailed study of this effect is indeed useful to study the performance of *gw* bar detectors for exotic particles [6] like nuclearites, and to understand the noise due to cosmic rays in interferometric *gw* detectors [7]. In this paper we will report on an update of the results obtained on nuclearites in ref. [6] with an increase on the exposure of about a factor 30.

Recently the possibility to have compact ultradense quark nuggets objects has been stressed again, see for example reference [8]. Probably the negative dark matter searches in LHC and in direct and indirect experiments pushed in this direction. Nuclearites are an example of compact objects that could be constituent of the dark matter; the results described in this paper are therefore of more general interest. More informations on the nuclearites detection are in another paper at this conference [9].

2 The NAUTILUS and EXPLORER *gw* bar detectors

The *gw* detector NAUTILUS[10] is located in Frascati (Italy) National Laboratories of INFN, at about 200 meters above sea level. NAUTILUS started operations around 1998. The current run started in 2003.

The detector EXPLORER [11] was located in CERN (Geneva-CH) at about 430 meters above sea level. The EXPLORER run ended in June 2010.

Both detectors use the same principles of operation. EXPLORER and NAUTILUS consist of a large aluminum alloy cylinder (3 m long, 0.6 m diameter) suspended in vacuum by a cable around its central section and cooled to about 2 K by means of a superfluid helium bath. The (*gw*) excites the odd longitudinal modes of the cylindrical bar, which is cooled to cryogenic temperatures to reduce the thermal noise and is isolated from seismic and acoustic disturbances. To record the vibrations of the bar first longitudinal mode, an auxiliary mechanical resonator tuned to the same frequency is bolted on one bar end face. This resonator is part of a capacitive electro-mechanical transducer that produces an electrical a.c. current that is proportional to the displacement between the secondary resonator and the bar end face. Such current is then amplified by means of a dcSQUID superconductive device. NAUTILUS is also equipped with a dilution refrigerator that enables operations at 0.1 K, further reducing the thermal noise. In the period considered, however, the refrigerator was not operational, in order to maximize the detector duty cycle.

Both detectors are equipped with cosmic ray telescopes, to veto excitations due to large showers. The two telescopes rely on different technologies (scintillators for Explorer, streamer tubes for NAUTILUS) but both provide a monitor of comparable effectiveness and a continuous check of the antenna sensitivity.

The output of the SQUID amplifier is conditioned by band pass filtering and by an anti-aliasing low-pass filter, then sampled at 5 kHz and stored on disk. Sampling is triggered by a GPS disciplined rubidium oscillator, also providing the time stamp for the acquired data. The data are processed off-line, applying adaptive, frequency domain filters. We first whiten the data, i.e. remove the effect of the detector transfer function. A filter matched to delta (or very short) excitations is then applied to this stream. The filter is designed and optimized for delta-like signals, but it works equally well for a wider class of short bursts, like e.g. damped sinusoids with decay time less than 5 msec. The noise characteristics estimate is updated averaging the output over 10 minutes periods. Traditionally the noise is expressed as energy in Kelvin units. The typical noise of data considered in this paper is between 1 and 5 mK.

At present, while the large interferometers VIRGO and LIGO are undergoing massive overhauls to upgrade their sensitivity, there are still two resonant detectors, NAUTILUS and a similar detector AURIGA, that continue to operate in astro-watch mode, i.e. as sentinels recording data that could be analyzed in conjunction with a significant astrophysical trigger, such as the explosion of a nearby supernova, or any astronomical event thought to be a possible source of *gw*.

3 The thermo-acoustic model

The interaction of energetic charged particles with a normal mode of an extended elastic cylinder has been extensively studied over the years, both on the theoretical and on the experimental aspecta.

The first experiments aiming to detect mechanical oscillations in metallic targets due to impinging elementary particles were carried out by Beron and Hofstander as early as in 1969 [12]. A few years later, Strini et al. [13] carried out an experiment with a small metallic cylinder and measured the cylinder oscillations. The authors compared the data against the thermo acoustic model in which the longitudinal vibrations are originated from the local thermal expansion caused by the warming up due to the energy lost by the particles crossing the material. In particular, the vibration amplitude is directly proportional to the ratio of two thermophysical parameters of the material, namely the thermal expansion coefficient and the specific heat at constant volume. The ratio of these two quantities appears in the definition of the Grüneisen parameter γ. It turns out that while the two thermophysical parameters vary with temperature, γ practically does not, provided the temperature is above the material superconducting (s) state critical temperature.

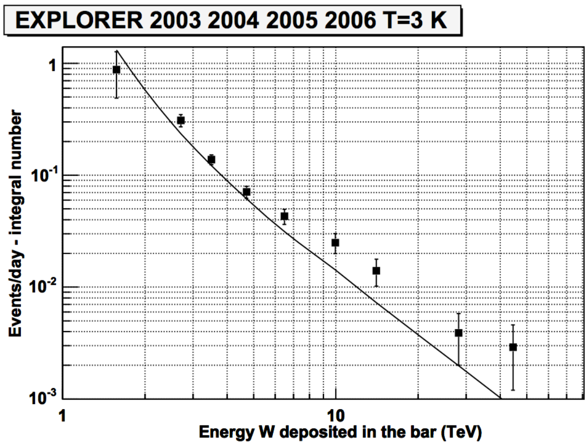

Fig. 1: Integral distribution of extensive air showers in Explorer, the line shows the prediction based on the thermo acoustic model [18]. The largest event has 360 TeV. (670 K in Kelvin units)

Detailed calculations, successively refined by several authors [14, 15, 16] agree in predicting, for the excitation energy E of the fundamental vibrational mode of an aluminum cylindrical bar, the following equation:

$$E = \frac{4}{9\pi}\frac{\gamma^2}{\rho L v^2}(\frac{dW}{dx})^2 \times \\ \times [sin(\frac{\pi z_o}{L})\frac{sin[(\pi l_o cos(\theta_o)/2L]}{\pi R cos(\theta_o)/L}]^2 \quad (1)$$

where L is the bar length, R the bar radius, l_o the length of the particle track inside the bar, z_o the distance of the track mid point from one end of the bar, θ_o the angle between the particle track and the axis of the bar, $\frac{dW}{dx}$ the energy loss of the particle in the bar, ρ the density, v the longitudinal sound velocity in the material. This relation is valid for the normal-conducting (n) state material and some authors (see ref. [14, 15]) have extended the model to a super-conducting (s) resonator, according to a scenario in which the vibration amplitude is due to two pressure sources, one due to $s-n$ transitions in small regions centered around the interacting particle tracks and the other due to thermal effects in these regions now in the n state.

It is important to note, at this point, that a *gw* bar antenna, used as particle detector, has characteristics very different from the usual particle detectors which are sensitive to ionization losses: indeed an acoustic resonator can be seen as a zero threshold calorimeter, sensitive to a vast range of energy loss processes. The usual *gw* software filter works well up to a time scale of the order of the order of 5 msec, corresponding to a $\beta = 4 \times 10^{-6}$ for a 60 cm particle track. So the antenna is sensitive to very slow tracks: this is another very important difference with to the usual particle detectors.

As anticipated in the introduction, the first detection of signals in a detector output due to cosmic ray events, took place in 1998 with NAUTILUS at $T = 0.14$ K [3], i.e. below the s transition temperature $T_c \simeq 0.9K$. and many events of unexpectedly large amplitude were detected. This result suggested an anomaly either in the model or in the cosmic ray interactions[4]. However the observation

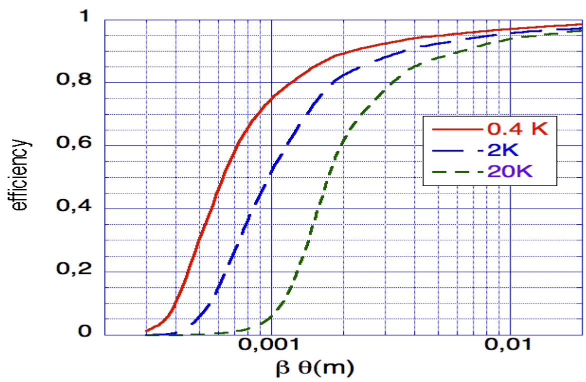

Fig. 2: Efficiency respect to the geometrical acceptance as functions of $\beta\theta(M)$ for 3 different thresholds of energy detection (in Kelvin).

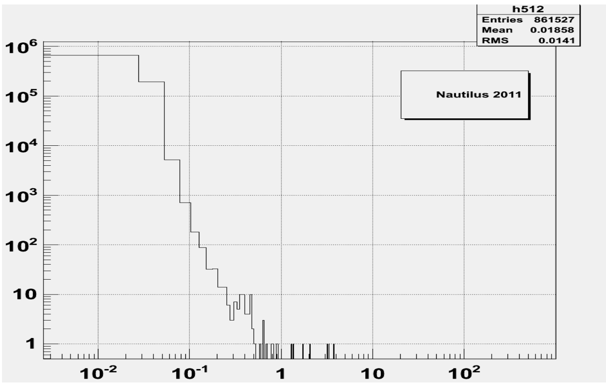

Fig. 3: Energy distribution (in Kelvin units), of the "best" run year 2011 of NAUTILUS. The energy of the biggest event is 3.7 K. This event is a cosmic ray (Extensive Air Shower).)

was not confirmed in the 2001 run with NAUTILUS at $T = 1.5$ K [17] and therefore we made the hypothesis that the unexpected behavior was due to the superconducting state of the material. An extended paper on this argument has been published [18] and the results of a dedicated experiment on an electron particle beam confirmed this result [5]. Now we have a good agreement both in rate and amplitude of the extensive ray shower detected in NAUTILUS and EXPLORER as shown in Fig.1, with the expectation based on cosmic ray physics and the thermo acoustic model. Therefore we are confident that we have a full understanding of the *gw* bar detectors used as particle detector.

4 Nuclearite search in NAUTILUS and EXPLORER

According to [19, 20] nuclearites are considered to be large strange quark nuggets, with overall neutrality ensured by an electron cloud which surrounds the nuclearite core, forming a sort of atom. Nuclearites with galactic velocities are protected by their surrounding electrons against direct interactions with the atoms they might hit.

As a consequence, the principal energy-loss mechanism for a nuclearite passing through matter is atomic collision. For a massive nuclearite the energy-loss rate is[19]:

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

where ρ is the density of the traversed medium, v the nuclearite velocity and A is its effective cross-sectional area. The effective area can be obtained by the nuclearite density ρ_N. For a small nuclearite of mass less than 1.5 *ng*, the cross-section area A is controlled by its electronic atmosphere which is never smaller than 10^{-8} cm:

$$A = \begin{cases} \pi \cdot 10^{-16}\,\mathrm{cm}^2 & for\ M < 1.5ng \\ \pi\left(\dfrac{3M}{4\pi\rho_N}\right)^{2/3} & for\ M > 1.5ng \end{cases} \tag{3}$$

where $\rho_N = 3.5 \cdot 10^{14}\, g/cm^3$ and M is the nuclearite mass.

According to Eq. 2, nuclearites having galactic velocity and mass heavier than 10^{-14} g penetrate the atmosphere, while those heavier than 0.1 g pass freely though an Earth diameter. Equation 2 breaks down in a solid at velocity smaller than the sound velocity in the medium; in aluminum this correspond at $\beta = 2 * 10^{-5}$; for subsonic velocity the energy loss becomes a constant and the nuclearite is rather quickly brought to rest.

Inserting Eq. 2 in Eq. 1 we obtain the energy in the fundamental mode of a cylindrical bar, that is the energy detected in gravitational *gw* bar detectors. Using the thermo acoustic parameters at T=2K [5] we have for a vertical nuclearite of mass M and velocity $c\beta$ in the middle of the NAUTILUS (or EXPLORER) bar:

$$\Delta E[Kelvin] = 10.7\left(\frac{\beta\theta(M)}{10^{-3}}\right)^4 \tag{4}$$

where ΔE is the energy variation of of bar fundamental mode measured in Kelvin and $\theta(M) = (M/1.5\ ngr.)^{1/3}$ if M$>$ 1.5 ngr. otherwise $\theta(M) = 1$

The maximum geometrical acceptance for a nuclearite isotropic distribution is given by $2\pi S_{tot} = 19.54\ m^2 sr^{-1}$, where S_{tot} is the bar surface. The effect of the track path length and angle has been computed for an isotropic distribution by a Montecarlo. The results as function of $\beta\theta(M)$ and for different ΔE thresholds are in Fig.2.

For this search we have used the standard filter matched to delta. In order to reduce noise we have applied several "standard" cut to the data. The most important are: the gain of the electronic chain, the SQUID locking working point, the noise outside the useful bandwidth of the detector, the seismic monitors. In addition we have put a cut on the run length, requiring at least 10h and a cut on the noise of the filtered data. The noise cut is $T_{eff} < 5\ mk$ for EXPLORER and $T_{eff} < 2.5\ mK$ for NAUTILUS. The total live-time with those cuts is 2089.9 days for NAUTILUS and 1831.4 days for EXPLORER.

The nuclearite flux upper limits have been computed starting from the energy distributions. Since the antenna noise is not-gaussian and changes with the run conditions we have identified the data stretches with the smallest noise, dividing data in years. The best data-set is the Nautilus run in 2011. Therefore the 90%C.L. flux limit has been computed using the Nautilus 2011 run, live-time=305.9 days for small amplitude signals $\beta\theta(m) \leq 0.002$. Otherwise for $\beta\theta(m) > 0.002$ we have used the full data set with a total live-time=3921.3 days. The results are in Fig. 4. For $\beta\theta(m) > 0.01$ where the background is negligible the flux upper limit is dominated only by the live-time. Note that in this search events in coincidence with the cosmic ray

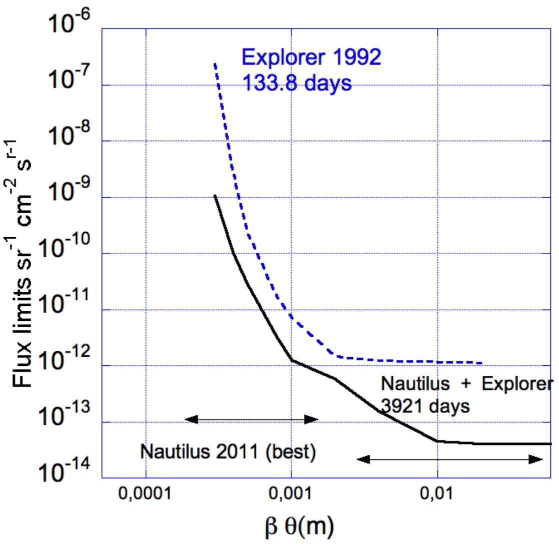

Fig. 4: 90% C.L. isotropic flux upper limits compared to previous results (Explorer) [6]. For nuclearites that can not penetrate the Earth there is a factor 2 in the flux limit.

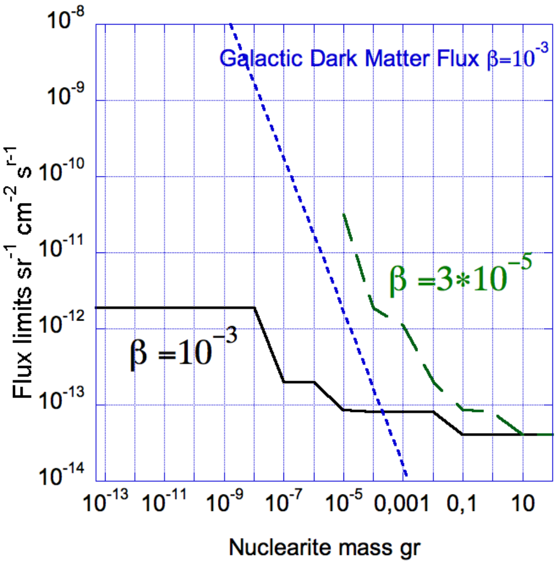

Fig. 5: Flux upper limits for $\beta = 10^{-3}$ and $\beta = 3 \cdot 10^{-5}$ (Earth escape velocity) vs mass.

detector are not removed. This is because fast nuclearites could produce light in the Explorer scintillators (due to black body emission[19]) and could be confused with a cosmic ray event.

Finally Figure 5 shows the upper limits vs f the nuclearite mass and for $\beta = 10^{-3}$ typical of the galactic dark matter. For mass$\leq 10^{-4}$ and mass $\geq 5 \cdot 10^{-14}$ gr. (threshold due to the atmosphere) this limit is significantly smaller than the flux of galactic dark matter. Earth is transparent for nuclearite of mass ≥ 0.1 gr., this produces a factor 2 reduction in the flux limit. Figure 5 also shows the limits for $\beta = 3 \cdot 10^{-5}$, the Earth escape velocity. Those limits are derived from Fig 4, computing the appropriate $\beta\theta(M)$.

Other experiments above sea level using track etch detectors have obtained lower limits. The SLIM limit[22] for $\beta = 10^{-3}$ is $1.3 \cdot 10^{-15} cm^{-2} s^{-1} sr^{-1}$. and the OHYA[23] limit is $3.2 \cdot 10^{-16} cm^{-2} s^{-1} sr^{-1}$. There is no quantitative theory describing the track etch mechanism. Track etch detectors have been calibrated with slow charged ions, assuming energy lost by Coulomb elastic collisions. In principle this process is different from the energy loss of Eq.2.

5 Conclusions

The energy loss predicted for compact ultradense quark nuggets DM particles varies in different models, but the main energy loss mechanism is similar to one of nuclearites given by Eq. 2. With *gw* bar detectors we directly measure in a calorimetric way this energy. This technique has been verified on a particle beam and is used to continuously monitor the antenna performance using the extensive air showers in the cosmic rays. Therefore our results on nuclearites are more general and could be applied to other compact objects[8].

Our data analysis is still in progress: in particular we are looking for additional signatures to separate genuine delta like events from the noise and we are trying different optimizations of the the data quality cuts. The efficiencies of those cuts can be measured using cosmic rays.

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