Newtorites in bar detectors of gravitational wave

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Abstract. The detection of particles with only gravitational interactions (Newtorites) in gravitational bar detectors was studied in 1984 by Bernard, De Rujula and Lautrup. The negative results of dark matter searches suggest to look to exotic possibilities like Newtorites. The limits obtained with the Nautilus bar detector will be presented and the possible improvements will be discussed. Since the gravitational coupling is very weak, the possible limits are very far from what is needed for dark matter, but for large masses are the best limits obtained on the Earth. An update of limits for *MACRO* particles will be given.

1. Introduction

Many experiments have searched for supersymmetric WIMP dark matter (DM), with null results. This may suggest to look for more exotic possibilities. In this paper we will extend our previous exotic particle search with gravitational wave (gw) cryogenic bar detectors [1] to the detection of particles having DM with only gravitational interactions. Newtorites were proposed in 1984 by Bernard, De Rujula and Lautrup [2]. In this case the excitation of a bar detector is due directly to the newtonian force and the signals are very small because the newtonian force is extremely weak. We will focus on the Nautilus and Explorer detectors that our group operated for decades. We will describe the analysis procedure and the selection criteria to identify candidate events. Then, starting from the energy distributions of the candidates events we will present upper limits to Newtorites. The same data can be used to give upper limits on a generic particle with strong interaction ($MACRO$) as suggested in [3].

The sensitivity to Newtorites of interferometric gw wave detectors will be also briefly discussed.

2. The Nautilus and Explorer Data

The gravitational wave gw detector Nautilus[4] is located in Frascati (Italy) National Laboratories of INFN. Nautilus started operations around 1998. The current run started in 2003. The detector Explorer, similar to Nautilus, was located in CERN (Geneva-CH). 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 to reduce the seismic and acoustic noise and cooled to about 2 K by means of a superfluid helium bath. The (gw) excites the odd longitudinal modes of the cylindrical bar.

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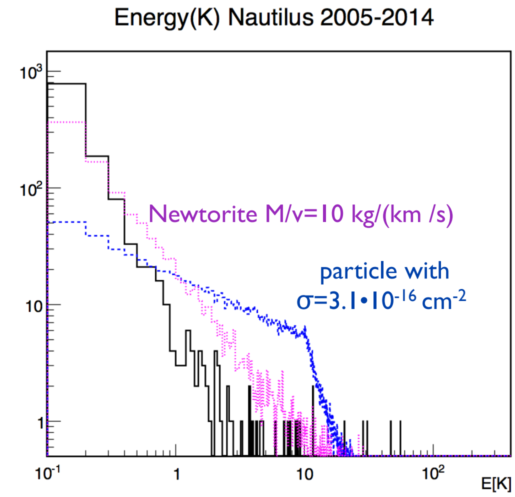

Figure 1. Nautilus 2005-2014. Event energy distribution measured in Kelvin units (continuous line) compared with a Montecarlo for a particle having cross section $\sigma = 3.1 \cdot 10^{-16} cm^2$ and $\beta = 10^{-3}$ (dashed, blue online) and with the Newtorite Montecarlo for M/v=10 kg s/km (dots, magenta online). Montecarlo events are normalized in order to have the same number of events as the real data.

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 and recorded on disk with an ADC sampled at 5kHz. Both detectors are equipped with cosmic ray telescopes to veto excitations due to large showers.

The data are processed off-line, applying adaptive frequency domain filters optimized for short delta-like signals. In order to select clean events we have applied several cuts to the data. The most important cuts are based on: the noise (average of the output in 10 minutes periods), the gain of the electronic chain, the SQUID locking working point, the seismic monitors, the event shape. We have removed also periods with an high event rates and runs having live-time less than 10h. The efficiency of those cuts is verified continuously using the extensive air showers detected by the cosmic ray detector.

We have used only the Nautilus data to give Newtorite upper limits. We have used the full data set, including Explorer, to give upper limits to $MACRO$ particles. The total live-time of the Nautilus data set is 1846 days. The energy distribution of the 931 Nautilus events surviving the cuts and having E$\geq$0.1 K is shown in Fig. 1, together with the result of a Montecarlo simulation of a particle having cross section $\sigma = 3\ 10^{-16}$cm^{-2} and $\beta = 10^{-3}$ and the result of a Montecarlo simulation of a Newtorite having M/v=10 kg s / km (see later).

3. Newtorite signal

Due to the long range nature of the newtonian force, Newtorite signals could occur even if the particle does not cross the bar. In the case of a point like particle moving with a constant velocity v along a straight trajectory coming from infinity and going to infinity, the vibrational amplitude of the nth-vibrational mode is given by[2]:

$$A_n = -\frac{2GM}{Vv} \int_V \frac{\mathbf{u_n} \cdot (\mathbf{x_T} - \mathbf{x_T^0})}{(x_T - x_T^0)^2} d^3\mathbf{x} \tag{1}$$

Here G is the gravitational constant, M the mass of the bewtorite, $\mathbf{x_T}$ are the transverse coordinates of a volume element of the detector relative to a fixed point $\mathbf{x_T^0}$, arbitrarily chosen along the particle track ; $\mathbf{u_n}$ is the spatial part of the nth normal-mode oscillation normalized to the volume V of the bar. For a thin bar with radius r and length L ($r \ll L$) $\mathbf{u_n}$ can be approximately written, using cylindrical coordinates. as:

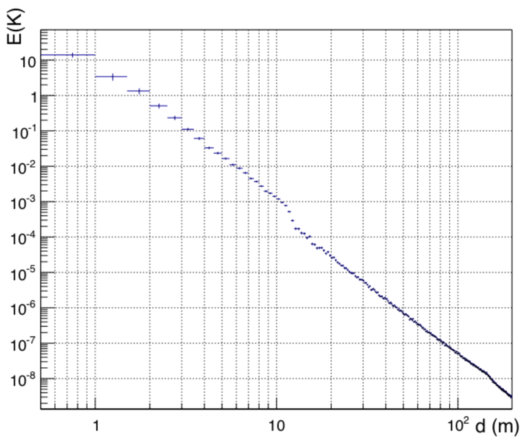

Figure 2. Average from different directions of the signals due to a M/v=10 kg s / km Newtorite vs. distance from the bar center. The signal for different values of M/v (see eq.(4)), scales as $(M/v)^2$

$$u_n^r = \sqrt{2}\sigma_P \pi (r/L) sin(n\pi z/L)$$
$$u_n^z = \sqrt{2} cos(n\pi z/L) \tag{2}$$

Here σ_P is the aluminium Poisson module. The energy variation in the bar is obtained by:

$$\Delta E_n = \frac{1}{2k_B}\rho A_n^2 V \qquad [\mathrm{K}] \tag{3}$$

Here k_B is the Boltzman constant. In this paper we are only interested in the first longitudinal mode n=1, and we assume that the velocity v of the particle is large enough that most of the signal is contained in a few ms. This requirement is due to the δ-like filter used to extract the antenna events. Different filters could in principle detect longer signals. The signal is a fairly complicated function of the Newtorite's trajectory and has been computed in [2] in the particular case of orthogonal trajectory in the middle of the bar, and for $r/L \to 0$. In this case we can put $u_1^r = 0$ and we obtain:

$$\Delta E \sim 30\pi r^2 \frac{\rho G^2}{k_B L}(\frac{M}{v})^2 \qquad [\mathrm{K}] \tag{4}$$

Numerically we have for Nautilus $\Delta E \sim 2.4(M/v)^2$ K with M expressed in kg and v in km/s.

In the general case the signal has been computed by numerical integration of eq.1 inserted in a Montecarlo to simulate random directions. The result of one of those calculations as a function of the distance of the trajectory from the bar center and for M/v=10 kg s/km is shown in Fig 2. From this figure we can see that, at large distance d, the signal energy scales as 1/d^4, as expected from eq.1. The signal falls below the energy threshold used in this analysis (see the next paragraphs) for d larger than $\sim$ 3 m for M/v=10 kg s/km. For M/v=100 kg s/km this threshold occurs at $d \gtrsim$ 10 m.

As a consequence, it is more important to select data with very low noise than to increase the livetime. In Tab. 1 we show the limits obtained using the Nautilus 2011 only. The limits with the full Nautilus data are typically a factor 2 higher.

4. Newtorite and MACRO limits and possible improvements

To compute the limits on the maximum allowed number of events we have used the so called *optimum interval method* to find an upper limit for a one-dimensionally distributed signal in the

M/v $kg\ km^{-1}\ s$	acceptance $(m^2 sr)$	events upper limit	flux upper limit $(cm^{-2}s^{-1}sr^{-1})$
1	33.4	37	$4.5 \cdot 10^{-12}$
2	85.3	23	$1.1 \cdot 10^{-12}$
5	209	22	$4.3 \cdot 10^{-13}$
10	426	22	$2.1 \cdot 10^{-13}$
20	888	22	$1.0 \cdot 10^{-13}$
40	1652	22	$5.5 \cdot 10^{-14}$
60	2398	21	$3.5 \cdot 10^{-14}$

Table 1. Nautilus 2011. Newtorite acceptances and upper limits. Livetime=278.8 days, 160 events $\geq$ 0.1K

presence of an unknown background [5]. The expected signal is computed by Montecarlo. In the Montecarlo, particles are extracted on a cylindrical surface much larger than the antenna bar. The Montecarlo therefore computes the acceptance in the case of simulated events that release at least 0.1 K and survive the analysis cuts.

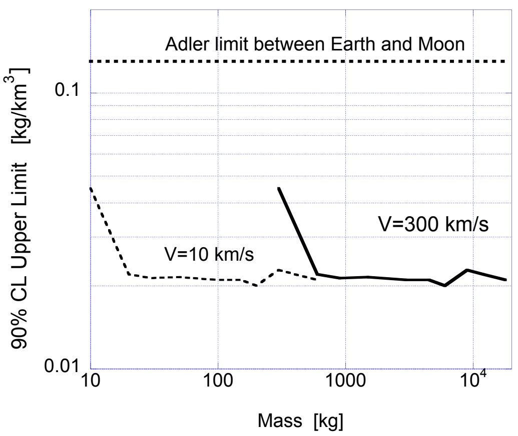

Figure 3. Newtorites density upper limits for v=10 and v=300 km/s vs the Newtorite mass. The limits are obtained from the Nautilus 2011 data set. As the mass increases the limit reaches a plateau. Adler [6] obtains a direct upper limit of the mass of Earth-bound dark matter lying between the radius of the moon orbit and the geodetic satellite orbit

The limits are shown in Tab. 1 together with the acceptance. The Nautilus 2011 data set is the one with the lowest noise and gives Newtoriteslimits a factor 2 better than the full Nautilus data set; the full data set, including Explorer, is used in the limits for the $MACRO$ particles. The limits are also shown in fig.3 for two values of the velocity v =10 and 300 km/s. Our limit, although very far from the DM expected density ($5 \cdot 10^{-13}\ kg/km^3$), could be of some interest due to the lack of other experimental limits derived from the direct detection of DM particles that only interact gravitationally and on the Earth.

There are several limits obtained studying the motion of celestial body in the solar system. For example Adler [6] obtains a direct upper limit of the mass of Earth-bound dark matter lying between the radius of the moon orbit and the geodetic satellite orbit. The value obtained is 0.13 kg/km^3, larger than our limit shown in fig.3. Considering larger volumes Pitjev [7] has found a limit for possible DM inside the Earth-Sun orbits of the order of $1.4 \cdot 10^{-7} kg/km^3$.

Our direct limit on Newtorites could be improved by orders of magnitude using two or more nearby bar antennas in coincidence. The performances for Newtorites of two antenna in coincidence have been studied by a Montecarlo simulation that uses as input the Nautilus 2011 data set (therefore assuming the same performances of Nautilus 2011). In the Montecarlo we assumed two antennas, positioned 1.5 m apart, with uncorrelated noise. Larger distances, up to tens of meters, can still produce a detectable signal, depending on the value of M/v. The result of this study is that a gain of about 300 seems to be possible in 10 years of operations with noise similar to that of Nautilus 2011. This gain is not enough to reach the Pitjev bound. To reach this bound it is necessary to increase the number of antennas and to reduce their noise. We recall that the current antenna noise is limited by technology and is far from the intrinsic quantum limit of this kind of device $\Delta E = \hbar\omega_0 = 6\ 10^{-31}$ joules. So a large R&D effort would be necessary to approach this limit.

The possibility to detect Newtorites in the gw interferometric detector has been discussed by V. Frolov in a talk at the GWDAW 2014 conference in Takayama (Japan). The detection is based on the measurement of an acceleration on the mirrors. The best acceleration sensitivity in the aLigo interferometer optimized at low frequency is around $10^{-15} m\ s^{-2}\ Hz^{-1/2}$ at 20Hz to be compared to $10^{-18} m\ s^{-2}\ Hz^{-1/2}$ for a Newtorite mass of ∼1kg at a distance of 7 km. Study are in progress to evaluate the signal to noise ratio using signal templates. Much better prospects are for the planned ET interferometer having a better sensitivity and the possibility of coincidences between the three interferometers.

Finally it's important to note that interesting limits can be obtained with the gw bar data for other exotic particles, like the $MACRO$ particles. An allowed region for the $MACRO$ dark matter can be obtained in the plane cross section vs. mass, by excluding the region with upper limit on the flux smaller than the dark matter flux, following the approach of Ref [3]. Fig.4 shows the excluded region. It is interesting to observe that studies of cosmological galaxy and cluster halos suggest a value $\sigma/M = 0.1\ cm^2$/g. For the comparison with constraints using other techniques see ref. [3].

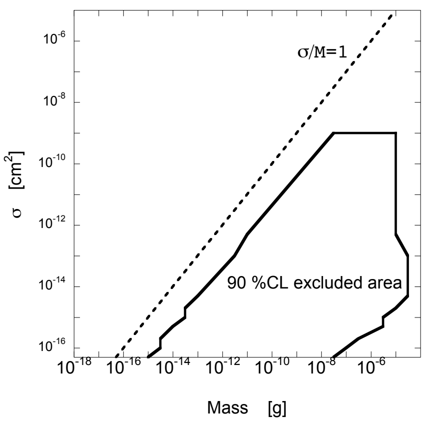

Figure 4. $MACRO$ particles 90 % CL excluded regions in the plane cross section - mass, computed for $\beta = 10^{-3}$ particles. The line σ/M=1 is drawn for reference.

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