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The ASTAROTH Project: enhanced low-energy sensitivity to Dark Matter annual modulation

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Abstract. ASTAROTH is a novel R&D project which aims at improving the physics reach of future direct dark matter detection experiments based on NaI(Tl) scintillating crystals. There is a strong need to test the long standing DAMA positive observation of an annual modulation that could be due to Dark Matter (DM), with the same target material and in a model independent way. ASTAROTH aim is the enhancement of the sensitivity to the annual modulation signal, compared with present technology, by lowering the detection energy threshold in order to observe sub-keV recoils for the first time. This can be achieved by reading the scintillation light from the NaI(Tl) crystals with arrays of Silicon PhotoMultipliers (SiPM), and placing the detectors in a cryogenic environment. SiPMs feature lower dark noise than Photomultiplier Tubes (PMTs) at $T < 150$ K and allow for higher light collection. The cooling medium is liquid Argon, as it is an excellent scintillator that can be instrumented to act as a veto against several backgrounds.

Here we present the status of the ASTAROTH project, introducing the innovative design of the detector chamber that will be used for the demonstration of the technology. Then, we will show the preliminary results of our first ever measurements performed on a single NaI(Tl) crystal read out by one SiPM array in a cryogenic set-up cooled with liquid nitrogen.

1. Introduction: Dark Matter annual modulation

The search and understanding of Dark Matter represents one of the most interesting challenges of contemporary astro-particle physics, still escaping physicists grasp. The lone claim of DM observation obtained so far by the DAMA experiment [1] has yet to be confirmed. Since over 20 years, at the underground Gran Sasso National Laboratory (LNGS, IT) DAMA has been observing an annual modulation of the interaction rate with their target array of NaI(Tl) crystals. Despite the claim that this modulation is due to DM interaction, a model-independent verification of the result has not been possible so far. Attempts to explain the DAMA observation in terms of Earth-bound background phenomena have always come short so far; as well, no other experiment around the world ever yielded a positive observation. Data comparison is difficult and model-dependent, since the detectors are either based on a different technique and/or target

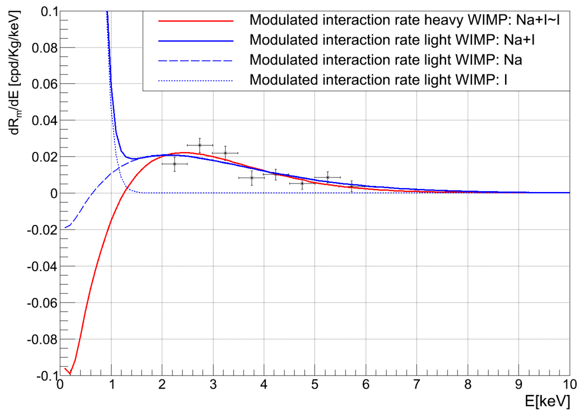


Figure 1: Modulation amplitude in the simple case of Weakly Interacting Massive Particles (WIMPs [9]) spin-independent elastic scattering off NaI nuclei, for two combinations of WIMP parameters (m, σ) favoured by DAMA Phase-I results (black dots - including Phase-II results worsens the fit, but it does not change the overall shape [10]). Heavy/light WIMP refer to masses of $\sim$80 GeV/$\sim$10 GeV, respectively.

material [2, 3, 4], or they lack the necessary sensitivity. It is therefore mandatory to deploy a next-generation NaI(Tl) detector with sensitivity comparable with or higher than DAMA, to test its claim in a model-independent way and add information about DM nature.

2. Current technological status

The sensitivity of experiments based on NaI(Tl) crystals depends strongly on the detection energy threshold and the achievable background rate. The most recent phase of DAMA (DAMA/LIBRA phase-II) achieved a background rate of 0.72 counts/day/kg/keV in the modulation energy Region of Interest (ROI): [1,6] keV. Dominating backgrounds in this ROI mainly come from radioactivity of trace contaminants in the crystals, namely U and Th chain elements, ^{87}Rb, but most importantly ^{40}K, ^{210}Pb out of equilibrium and ^{3}H. Running experiments like ANAIS and COSINE only managed so far to reach background lower limits that are 4-5 times higher than DAMA [5, 6]. The SABRE experiment [7] did recently publish results from a single crystal acquisition, reporting a background rate in the ROI of 1.2 counts/day/kg/keV [8]. However, extensive production of high-performance crystals is still to be demonstrated.

All running experiments can achieve a low-energy threshold of 1 keV. However, a large amount of new information on DM, including larger amplitude and a possible phase flip, could lie below the 1 keV limit. This is illustrated in Fig. 1. Though excluded by several experiment, the simple model in the example clearly shows the gain in achieving sub-keV interaction sensitivity.

The design of running experiments invariably features large-mass parallelelipedal crystals (5-10 kg each), with the two end faces coupled to PMTs and the lateral surface wrapped in reflecting foils (e.g. Teflon). This design, even with high Quantum Efficiency (QE) ($\sim$ 35%) PMTs, limits light collection in the range [7,15] phe/keV [11, 12, 13, 14]. This poorly compares with the emission of $\sim$ 42 γ/keV expected from a properly Tl-doped NaI scintillator at room temperature. PMT dark noise also affects the low energy part of the spectrum, worsening pulse shape analysis efficiency in separating noise from actual scintillation events in the crystal. Overall, PMT use will probably hinder future attempts to further reduce the energy threshold.

3. The strategy for an enhanced physics reach

ASTAROTH aims at overcoming the described limitations by adopting Silicon PhotoMultipliers (SiPM) for the read-out of scintillation light from smaller NaI(Tl) crystals. SiPMs average Photon Detection Efficiency (PDE) at NaI(Tl) wavelengths (420 nm) is around 55%, far higher than the QE of best commercially available PMTs. As well, they are compact, low-radioactivity devices, when compared to PMTs, and feature lower dark noise below 150 K temperature.

Given these properties, ASTAROTH initial proposal is to employ $5\times5\times5$ cm^3 cubic crystals, read on all faces by SiPMs, avoiding the use of reflectors. Optical photon transport studies show that such design can boost light detection efficiency up to 50%, depending on SiPMs PDE. SiPMs low dark noise at low temperature implies that the foreseen detector will be operated in a cryogenic environment. A natural choice is to immerse the crystals in a Liquid Argon (LAr) bath at 87 K. Argon is a highly efficient scintillator (λ = 128 nm), and it can be read out as well, with SiPMs or PMTs, thus serving as veto detector for enhanced background rejection.

The overall ASTAROTH strategy is to *encapsulate* crystals in fully transparent, synthetic quartz containers filled with dry neon atmosphere, allowing straightforward manipulation and protection from humidity (NaI is highly hygroscopic). The containers are nested in a copper cage which features anchoring points for detector support and SiPM array installation, as shown in Fig. 3 Left. Crystals are cooled down in a controlled way and operated in a wide range of temperatures, 87-150 K. The natural low limit (liquid Argon boiling point), is set by SiPM dark noise not decreasing further below this temperature. Similarly, in some SiPMs dark noise becomes comparable to that of PMTs at $\sim$150 K [15], thus negating the aforementioned advantages. Exploring the full range is needed as the trend of NaI(Tl) properties in cold is not well predictable. Few measurements in literature yield different results on Light Yield and Nuclear Quenching Factor, which seem to be quite dependent on the specific crystal, set-up and interacting particles. Therefore, it is important to characterise the integrated system (crystal + SiPMs) in the full range of temperatures, to find the best operational point.

A preliminary simulation of the full design was applied to a "physics-scale" detector, featuring eight larger, $10\times10\times10$ cm^3 crystals (around 30 kg mass). Early results show that, assuming 0.19 events/kg/day/keV in a ROI of [0.2,6] keV, three years of data taking would lead to fully probe the DAMA allowed regions in the DM (m, σ) parameter space.

4. Detector demonstrator

In order to prove our strategy, we developed a custom cryogenic chamber, which should ensure crystal survival during all phases of a cooling cycle and provide stable read-out of the output signals. This translates into the following thermal requirements: (i) time gradient on the crystal limited to $<$ 20 K/h; (ii) spatial gradients (over crystal dimensions) $<$ 1 K; (iii) temperature stability in time, during data taking, within 0.1 K. The design is optimized to allow changing and fixing at will the operation temperature, in order to find best working point for the crystals.

The demonstrator is a dual-wall, vacuum-insulated radio-pure copper chamber, featuring a specially designed Stainless Steel (SS) thermal bridge between its two walls (Fig. 2). The chamber is immersed in a LAr bath providing cooling power by conduction through the SS bridge and bringing the whole set-up to 87 K. Low pressure Helium gas filling the main volume serves as heat transfer medium and provides the necessary thermal inertia. A heater with tunable power is embedded in a flex Kapton support and glued on the inner copper wall: this is used to raise and fix the temperature at will up to 150 K. The overall detector design was fully simulated with a Finite Element Analysis (FEA) in two steps. First, a static thermal simulation takes as inputs the LAr cooling power and heater power. The resulting equilibrium temperature in the whole inner volume is extracted, demonstrating a $<$0.01 K uniformity, well within our requirements. Secondly, a mechanical simulation is performed, with the temperature maps obtained in the first stage as input. Simulations pinpointed the most stressed areas (the region around the thermal bridge) and were used to iterate on the design.

5. ASTAROTH components characterization

The demonstrator detector will be delivered by end 2021. In the meantime, data taking campaigns were performed, in order to study independently the crystal and SiPM behaviour as a function of temperature, and later perform a first cooling cycle of the integrated system.

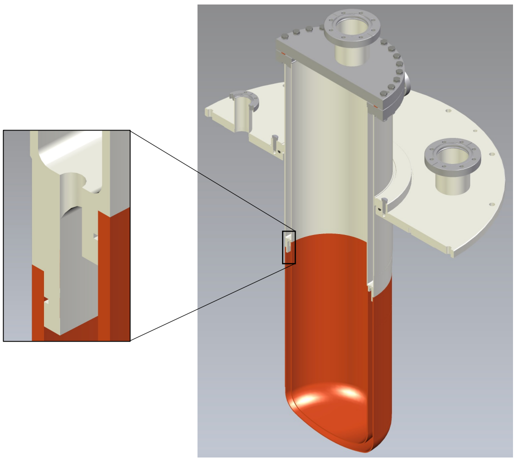


Figure 2: Section of the demonstrator design, with detail of thermal bridge. The chamber is designed to host two 5×5×5 cm^3 crystals, that will be supported by a custom-designed thermally insulating structure (in glass fibre for the demonstrator) hanging from the top closing flange.

5.1. Crystal characterization at LNGS

The characterization of a NaI(Tl) crystal was performed at LNGS. In order to remove all possible sources of uncertainty not scintillator-related, a non-encapsulated NaI(Tl) cubic crystal, 2"-side, was employed. The crystal was wrapped in Teflon tape and cooled under vacuum with a cold-head. A single face was read-out, with a 1" PMT kept outside the cryo-environment, to rule out its own temperature-related effects. We collected waveforms and spectra in a wide range of temperatures (77 $\rightarrow$ 300 K), with and without a ^{137}Cs source placed on top of the cryo-cooler. Data analysis is in progress and it has to take into account the fact that the crystal scintillation time-profile appears to change significantly with temperature, as the decay-time constant τ varies from ∼250 ns (300 K) to around 1.5-2.0 μs (77 K). This makes it challenging to correctly obtain a consistent light yield measurement at all temperatures: for this reason a new test run is being planned, in order to account for this effect. During the new run, we will also investigate the very long signal tails at low temperature, which could affect pile-up.

5.2. SiPM characterization at Politecnico di Milano

Within ASTAROTH, we plan to test different SiPM technologies and read-out solutions, mainly with devices from Fondazione Bruno Kessler (FBK) and Hamamatsu (HPK).

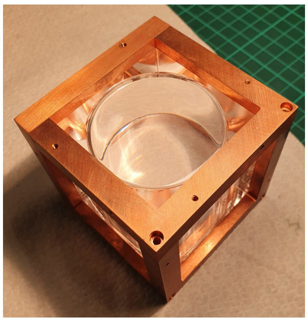
The first tested device is a 1" HPK array, S13361-3050 series with 64, 3x3mm sensors[1]. It was characterized at Politecnico di Milano in a dedicated vacuum setup, equipped with a two-stages cold-head (Leybold RGD 510). A custom cold amplifier reads out either the full active area, by summing the individual channels, or each SiPM individually. Measurements of the single phe response and gain histograms were performed with a dedicated HPK PLP-10 laser head (405 nm), over a temperature range of 70-140 K. Preliminary analysis shows that, while the array break-down voltage changes with temperature (as expected), the trend of *gain vs overvoltage* (VoV) is stable over the inspected temperature range. These data can be used to calibrate those collected with the integrated system, described next.

5.3. Full system tests at LASA laboratory

A first cooling cycle of the full system, featuring one cylindrical 5 × 5 cm ($H \times \varnothing$) crystal[2] and the mentioned 1" HPK SiPM array, was performed at LASA (*Laboratorio Acceleratori e Superconduttività Applicata*) laboratory. The crystal, wrapped in Lumirror™, was equipped with

[1] Four more arrays (2× two-inch FBK; 2× two-inch HPK) will be received in 2021-2022.

[2] As the technology to produce leak-tight, sharp cubic quartz containers is still being perfected, these early tests are carried out with a cylindrical encapsulated crystal.



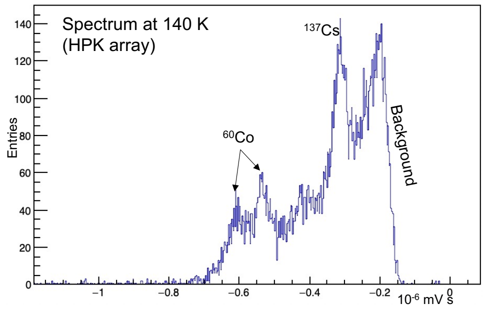


Figure 3: Left: cylindrical crystal 5 × 5 cm ($H \times \varnothing$) used in 2021 for integrated test at LASA, with its copper cage. Right: spectrum obtained at 140 K with said crystal and S13361-3050, 1" HPK array at LASA integrated test.

the array, multiple temperature sensors, and then placed inside a SS single-wall chamber. The chamber, filled with dry He, was inserted in a containment dewar and then cooled by being exposed to cold N_2 gas from a *mixer*, i.e. a circuit mixing liquid and warm gas to produce a gas mixture at a tunable temperature. We collected data in the 110-150 K range, 110 K being the lower limit reachable with this set-up. The crystal was exposed to γ-sources ^{137}Cs (662 keV) and ^{60}Co (1.17 & 1.33 MeV), placed outside the dewar. Peaks from the sources are clearly visible in the spectra, as shown in Fig. 3 Right, demonstrating the success of this first cooling test.

6. Conclusions

The ASTAROTH project aims at lowering the energy threshold down to the sub-keV region for direct dark matter (DM) detection via annual modulation. To achieve this goal, we devised a sound strategy based on crystal readout with SiPMs in a cryogenic environment, that will ensure overcoming the present technological limitations. We are building a demonstrator detector, which will house 1-2 encapsulated 5×5×5 cm^3 NaI(Tl) cubic crystals operated at a controlled and tunable temperature. In the meantime, we are performing independent characterization of NaI(Tl) crystals and of different SiPM technologies at cryogenic temperature. The data collected during this first series of tests will flow into the preparation of the first run in cold with our demonstrator detector, which will take place in 2022.

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