A NaI-based cryogenic scintillating calorimeter: status and results of the COSINUS project

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Abstract. The COSINUS (Cryogenic Observatory for SIgnals seen in Next-generation Underground Searches) project aims to provide a model independent cross-check of the long-standing DAMA/LIBRA claim on the observation of dark matter, by using the same target material (NaI) with a different experimental approach. The use of sodium iodide (NaI) crystals, operated at cryogenic temperature as scintillating calorimeters, provides both a low energy threshold for nuclear recoil events as expected from dark matter particle interactions, and the possibility to perform particle discrimination. Indeed, the dual read-out of phonon and light allows to perform signal-to-background discrimination on an event-by-event basis, a unique feature in comparison to other NaI-based dark matter searches. In this paper we will discuss in detail the COSINUS detector concept and we will present the performances of our first prototypes together with the results of the first measurements.

1. Introduction

Although the evidence for the existence of Dark Matter (DM) is nowadays well-established on the basis of several astrophysical measurements [1], its nature still remains unknown. Among several DM theories, the Weakly Interacting Massive Particles (WIMPs) are one of the most promising DM candidates. WIMPs, with a mass in the (GeV-TeV)$/c^2$ range, are expected to interact with ordinary matter with cross sections similar or smaller than the weak processes.

Direct DM search techniques are currently based on the detection of WIMPs scattering off the target nuclei and, since the expected recoil energies are well below 100 keV, an ultra-low background and highly sensitive detection apparatus is needed. At present several experimental efforts are ongoing all over the word using a variety of experimental approaches exploiting single or dual channel read-out based on the detection of scintillation light, phonon and/or charge signals induced by particles interacting in the detector target.

The analysis of present DM experiments is based on the detection of an excess of events over the expected background or on the detection of an annual modulation of the event rate...
Figure 1. Projected sensitivity for a NaI-based experiment using COSINUS detector technology (solid blue band, 1 σ confidence level for spin-independent elastic dark matter nucleus scattering. Recent results from experiments using silicon and germanium targets are drawn in green, results from CRESST-II (CaWO₄) are depicted in red and exclusion limits using liquid noble gases in magenta. Limits drawn in cyan correspond to bubble chamber technology and experiments with CsI target. The light blue shaded regions correspond to the interpretation of the DAMA/LIBRA (NaI(Tl)) modulation signal by Savage et al. [2]. The benchmark point (blue cross) indicates the mass and cross-section chosen for the simulated WIMP contribution presented in section III of [3]. Gray-shaded regions in parameter space will be affected by coherent neutrino nucleus scattering on NaI mainly originating from solar neutrinos [4]. Figure from [3], references therein.

caused by the seasonal variation of the Earth’s velocity with respect to the dark matter halo [5]. While in the former approach the number of expected recoil events depends on the DM model assumptions, as the mass of dark matter particle, the interacting cross-section and the detector properties, a pure modulation signal can be considered model-independent.

Nonetheless, in the experimental panorama of the DM direct search the situation is strongly controversial: the DAMA/LIBRA collaboration reports a statistically robust modulation signal (>9σ) over 14 annual cycles [6] using a detector based on 250 kg of highly radiopure sodium iodide (NaI(Tl)) crystals operated at room temperature in the underground site of the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. In the standard elastic scattering scenario, the DAMA/LIBRA result is not consistent with the null results of other direct search experiments (see Figure 1). Further studies are therefore needed to understand the origin of the modulation signal observed by the DAMA/LIBRA experiment and, in particular, the target dependence of the result; several R&D projects and experiments with alkali halide as target are currently running or in construction [7, 8, 9]. Among them, the COSINUS project [3] aims to develop a NaI-based detector operated at cryogenic temperature, thus exploiting both the scintillation light signal of NaI crystals and the phonon signal in a cryogenic detector. The dual channel read-out allows to perform particle identification, thus resulting in an effective suppression of the dominant β/γ background.

2. NaI-based cryogenic scintillating calorimeter

In the DM sector, the use of cryogenic scintillating calorimeters is successfully implemented in the CRESST experiment [10] while it is used by LUCIFER/CUPID³-0 [11] for the search for neutrinoless double-beta decay.

A particle interacting in a cryogenic scintillating calorimeter produces two coincident signals:
the major part of the deposited energy is converted into phonons (heat signal) while a small fraction (O(few percent)) goes into the production of scintillation light. The heat signal is therefore exploited to precisely measure the energy deposited in the target crystal and is almost independent from the particle type. The amount of scintillation light, instead, strongly depends on the particle type and can be used to perform particle identification, thus allowing the suppression of the dominant $\beta/\gamma$ background with respect to nuclear recoil signal events. The light to phonon ratio, the so-called light yield (LY), is characteristic for each type of event: in particular $\beta$ and $\gamma$ particles produce the most light and get assigned a LY = 1 by definition, while $\alpha$-particles and neutrons show a lower LY quantified by the so-called quenching factor (QF).

Figure 2 shows the concept of a COSINUS detector module: a NaI target crystal is coupled via an interface (typically silicon oil) to a crystal (e.g. CdWO$_4$) carrying the Transition Edge temperature Sensor (TES) which reads the phonon signal. The target is inserted in a beaker-shaped light detector made from high-purity silicon. The light detector is equipped with a second TES reading the heat rise of the beaker caused by the absorption of scintillation photons. The whole detector module is operated at few milli-Kelvin. The need for the use of the CdWO$_4$ carrier crystal, is due to the hygroscopic nature and the low melting point of the NaI crystal making it difficult to evaporate the TES directly onto the NaI surface. By covering a large fraction of the NaI crystal surface, the beaker-shaped light detector exhibits a very high light yield while simultaneously serving as an active veto for external backgrounds and radioactive decays close to the surfaces of the NaI crystal and its surrounding material.

Figure 3 shows the result of simulated data for an exposure of 100 kg days (with the assumption detailed in [3]) in the light yield - energy plane: black, blue and green bands correspond to electron, Na and I recoils respectively. Black dots indicate events originating from a flat background contribution of 1 c/(keV kg d) and a $^{40}$K contamination with an activity of 600 $\mu$Bq while red dots indicate Na and I scattered off by a hypothetical WIMP with a mass of 10 GeV/c$^2$ and a cross section of $2 \times 10^{-4}$ pb (following the DAMA interpretation of Savage et al. [2]). Magenta boxes indicate the regions which may contribute to the DAMA/LIBRA energy range of positive modulation detection corresponding to 2-6 keV$_{ee}$ (where ee = electron equivalent).
3. Status and results of the COSINUS project

The first COSINUS detector prototype was realized using an undoped/pure NaI crystal with dimensions of 30x30x20 mm$^3$ and a weight of 66 g. The NaI is attached through a very thin layer of silicon oil to a carrier crystal made of CdWO$_4$ (diameter = 39.2mm, thickness = 1.6mm) equipped with a TES made by a thin film (200 nm) of superconducting tungsten (W-TES) produced at the Max-Planck-Institute for Physics in Munich. The cryogenic light detector consists of a sapphire wafer (diameter = 40mm, thickness $\approx$460 $\mu$m) equipped with a TES optimized for light measurement. To increase the absorption efficiency of the blue scintillation light a 1-$\mu$m-thick layer of silicon is epitaxially grown onto the sapphire disc (SOS = Silicon On Sapphire). The whole setup is surrounded by a reflective foil [12].

The measurement was carried out in the test facility of the Max-Planck-Institute for Physics located in the underground site of LNGS, consisting of a dilution refrigerator allowing detector operation at temperatures as low as 7 mK. The TESs were read out with commercial dc-SQUID electronics (Applied Physics Systems company). The hardware-triggered signals were recorded in a 328 ms window at a sampling rate of 25 kHz. Both detectors were always read out simultaneously, independent of which one triggered. The detectors were irradiated with $\gamma$-rays from an $^{41}$Am source with an energy of 59,541 keV. After applying quality cuts to reject unstable detector operation, pile-up and bad pulse-shape events, a final exposure of 0.46 kg days was collected [12].

Figure 4 shows the events surviving quality cuts in the light-energy plane. A linear relation between light output and the energy deposited in the NaI crystal is clearly visible. Magenta solid lines confine the central 80% of the $\beta/\gamma$-band. Accounting for the QFs given in [14], red and green bands correspond to recoils off Na and I respectively, while the almost horizontal event population at very small light energies originates from particle events taking place in the CdWO$_4$ carrier crystal. The black dashed line indicates the hardware trigger threshold of the phonon detector at 10 keV, essentially limited by the high pile-up rate observed. The energy resolution at the $\sim$60 keV calibration line is found to be 5.0 keV showing a significant improvement towards lower energies. By comparing the amplitude of a scintillation light pulse induced from a 59,541 keV x-ray in the NaI, originating from the $^{241}$Am calibration source, to a direct hit of the light
detector from a $^{55}$Fe X-ray calibration source, we find that 3.7% of the energy deposited in the NaI crystal is measured as light [12].

In the second detector prototype realized, the beaker-shaped light detector, foreseen for the final detector design (Figure 2), was implemented. The prototype was tested in the same facility used for the first prototype and, after applying the quality cuts, a total exposure of 1.32 kg days was collected. The result is shown in 5: black solid lines indicate a fit of the $\beta/\gamma$-band to the data with 80% bands. The mean line of the band is well modeled by a simple linear function, the width of the band includes contributions from the baseline resolutions of phonon and light detector, a Poisson-statistics term accounting for the quantization of the scintillation light photons and a empiric term scaling with light energy (e.g. potential position dependencies). Moreover, three characteristic structures are clearly evident: the line at $\sim 60$ keV originating from gammas from the $^{241}$Am source, the so-called escape peaks from I at $\sim 30$ keV and a line at around 3 keV caused by $^{40}$K Auger electrons. Na (blue) and I (green) recoil bands are calculated using the QFs of [14]. The magenta band is populated by events originating in the carrier crystal and showing a different pulse-shape than events in the NaI absorber [13].

The phonon detector was operated with a hardware trigger threshold of $(8.26\pm0.02(\text{stat.}))$ keV, still significantly above the COSINUS design goal of 1 keV. A baseline resolution for the phonon detector of 1.01 keV was achieved increasing to 4.5 keV at the $^{241}$Am-peak at about 60 keV. With the second prototype an absolute light yield of 13.1 %, corresponding to an average of $\sim 40$ photons/keV (given a mean scintillation photon energy of 3.3 eV), was obtained. This value is roughly three times higher than that obtained with the first prototype and has been achieved thanks to the geometry of the beaker-shaped light detector [13].

Both in the measurement of the first and second COSINUS prototypes, we found that NaI exhibits a different pulse shape compared to other materials ($\text{Al}_2\text{O}_3$, $\text{CaWO}_4$, $\text{ZnWO}_4$, $\text{CdWO}_4$, $\text{CaF}$, and $\text{TeO}_2$) and, thus, cannot be convincingly described by the model for cryogenic particle detectors of [15]. We performed a pulse shape analysis by averaging O(100) events of the same energy deposition. We fit the averaged pulse both with the two-component model described in [15] and with a three-component fit. In the latter case, to the standard thermal and non-thermal components described in [15], we added a second thermal component. The results are shown in Figure 6 and 7 respectively: the residuals of both fits clearly show that the additional third component significantly improves the fit result and almost perfectly describes the measured pulse, while the two-component fit does not [12, 13]. As a result of this analysis we can conclude that
the peculiarity of NaI is a long decay time of the pulse. As the decay time exceed the maximally available record window of the present DAQ we will switch to a dead-time free DAQ in the future, thus allowing to record the full tail which is a immensely useful tool to understand the origin of this third pulse component.

4. Conclusions and perspectives

The COSINUS R&D project aims at developing a NaI-based detector to solve the long-standing tension of the DAMA/LIBRA result in the panorama of direct DM searches. By using the same target material of the DAMA experiment, the target dependencies can be ruled out. Moreover, the use of a cryogenic apparatus and of a dual channel read-out, will allow to perform a signal to background discrimination on an event-by-event basis unique to NaI DM searches.

The first prototype developed by the COSINUS collaboration was the first successful measurement of a NaI crystal operated as cryogenic scintillating calorimeter measuring simultaneously the phonon and light signal from a particle interaction. The implementation of the second prototype has been the proof-of-principle measurement of the final detector design. We measured 13.1% (∼40 photons/keV) of the energy deposited in the NaI as scintillation light thus exceeding the original COSINUS design goal (4%) by more than a factor of three and proving that undoped NaI exhibits an outstandingly high light output at low temperatures. Moreover we observed a peculiar phonon pulse-shape previously not seen in numerous other materials.

At present, we are carrying out the optimization of the performances of a new detector prototype in a dedicated low-background cryostat in the underground Hall C at LNGS while the realization of further prototypes, by using high-purity both doped and undoped crystals, is foreseen. These tests together with the planned neutron test beam at the Tandem accelerator at TUM/LMU in Munich, to directly measure for the first time the QFs of a NaI crystal operated at cryogenic temperatures, will open the way for the realization of the COSINUS DM detector.

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References

[1] Olive K A et al. (Particle Data Group) 2014 Chin. Phys. C38 090001
[2] Savage C, Gelmini G, Gondolo P and Freese K 2009 JCAP 0904 010 (Preprint 0808.3607)
[3] Angloher G et al. 2016 Eur. Phys. J. C76 441 (Preprint 1603.02214)
[4] Gütlein A et al. 2015 Astropart. Phys. 69 44–49 (Preprint 1408.2357)
[5] Drukier A K, Freese K and Spergel D N 1986 Phys. Rev. D33 3495–3508
[6] Bernabei R et al. 2013 Eur. Phys. J. C73 2648 (Preprint 1308.5109)
[7] Thompson W G (COSINE-100) 2017 Current status and projected sensitivity of COSINE-100 TAUP 2017 (Preprint 1711.01488)
[8] Amare J et al. 2017 The ANAIS-112 experiment at the Canfranc Underground Laboratory TAUP 2017 (Preprint 1710.03837)
[9] Tomei C (SABRE) 2017 Nucl. Instrum. Meth. A845 418–420
[10] Angloher G et al. (CRESST) 2016 Eur. Phys. J. C76 25 (Preprint 1509.01515)
[11] Artusa D R et al. 2017 Phys. Lett. B767 321–329 (Preprint 1610.03513)
[12] Angloher G et al. (COSINUS) 2017 JINST 12 P11007 (Preprint 1705.11028)
[13] Reindl F et al. (COSINUS) 2017 (Preprint 1711.01482)
[14] Tretyak V I 2010 Astropart. Phys. 33 40–53 (Preprint 0911.3041)
[15] Pröbst F 1995 Journal of Low Temperature Physics 100 69–104 ISSN 1573-7357