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COSINUS:TES-instrumented NaI Crystals for Direct Dark Matter Search

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Abstract
In the last years, the COSINUS (Cryogenic Observatory for SIgnals seen in Next generation Underground Searches) experiment has made significant progress both in the construction of its facility and in pursuing its physics goals: At Laboratori Nazionali del Gran Sasso (LNGS) in Italy, an underground facility was constructed, which will house experimental detectors for dark matter direct detection in a dry dilution cryostat. Construction of the main structures at the COSINUS site is finished, including the control building, the cryostat access level, and the water tank which will serve as a Cherenkov muon veto around the cryostat. With a nuclear recoil threshold of 4 keV, the latest COSINUS detector prototype approaches the design goal of 1 keV, and particle discrimination on event-by-event basis has been demonstrated. This contribution gives a brief overview on the status of COSINUS.

Keywords Direct search for dark matter · Annual modulations · Transition edge sensors · Cryogenic detectors · NaI detectors

1 Introduction

To this date, the signal reported by the DAMA/LIBRA collaboration remains a topic of discussion in the field of direct dark matter (DM) search. DAMA/LIBRA operates NaI crystals as scintillators at room temperature in the LNGS underground laboratory, and measures an annually modulated rate of particle interactions over time. The modulation phase and period correspond to the prediction for a classical

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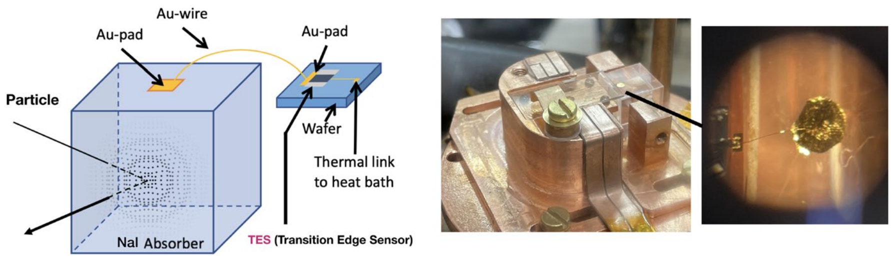

Fig. 1 Left: Schematic view of a NaI crystal read out via remoTES [5]. Particle interactions in the absorber cause the creation of phonons, which propagate through the crystal and eventually couple to the Au pad. The TES is mounted on a wafer, and coupled to the Au pad with an Au wire. Right: Image of a COSINUS detector prototype without the surrounding Si beaker light detector. The NaI crystal is located on the right side, and the area around the Au pad with the connection to the TES on the Al_2O_3 wafer is enlarged for better visibility

WIMP (Weakly Interacting Massive Particle) candidate [1]. This signal could not be confirmed by other direct DM experiments, which provide strong constraints on the mass and cross section of yet-unknown and only weakly interacting particles [2]. However, most of these experiments employ different target materials, and only in recent years experiments with NaI-targets such as COSINE [3] and ANAIS [4] have emerged. The latter use a similar approach as DAMA/LIBRA, i.e., they are single-channel experiments and measure scintillation light. The energy of nuclear recoil events is quenched with respect to e^-/γ interactions; therefore, the nuclear recoil energy has to be inferred from the measured scintillation light energy using a quenching factor (QF) in this approach. In contrast to this, COSINUS employs NaI crystals as cryogenic bolometers, where a transition edge sensor (TES) is used to collect phonons from the absorber crystal and thus measures a temperature signal which accounts for ~90% of the nuclear recoil energy. A Si beaker surrounding the crystal collects the scintillation light from particle interactions and provides a second readout channel. With this concept, e^-/γ interactions can be discriminated from nuclear recoils, and the recoil energy can be calculated using the combination of the two channels. The effect of the QF on the signal interpretation is greatly reduced.

2 Detector Design

COSINUS detectors follow the remoTES design outlined in [5] and first proposed in [6]. The TES is fabricated on a separate wafer, and connected to a Au pad on the NaI absorber crystal via a Au bond. As this approach does not require direct fabrication of the sensor onto the crystal, it allows using hygroscopic materials such as NaI as bolometric targets. The wafer material (typically Al_2O_3) is chosen such that collection of scintillation light from the absorber is inefficient. Additionally, prototypes are tested where a direct line of sight from the wafer to the absorber is avoided in the mounting. Figure 1 illustrates the basic detector design schematically. The characteristics of the TES, such as its size and the dimensions and properties of the Au connection, are subject to a series of R &D measurements. Different TES configurations are tested with Si absorber crystals [5] [7], as Si is non-hygroscopic and thus easier to handle, allowing for faster prototype preparation. The connection of the TES to the absorber, e.g., the type of Au layer on the crystal (foil or sputtered), is optimized with NaI prototypes.

3 Prototype Results

In two recent measurements, the working principle of COSINUS detectors has been demonstrated: A prototype operated at the Max Planck Institute of Physics in December 2021 displayed a nuclear recoil energy resolution of 2.0 keV and was operated with a threshold of 20 keV [8]. In a subsequent measurement in 2022, an improved prototype was operated in the CRESST underground test facility at LNGS, which featured a resolution of 440 eV and an analysis threshold of 4 keV [9], closer to the COSINUS design goal of 1 keV. Both detector modules employ a 3.7 g cubic NaI crystal.

Figure 2 shows the results from the improved prototype, which are described in detail in [9]. The neutron calibration dataset is displayed, where an external AmBe neutron source was used to produce nuclear recoils in the absorber crystal. Additionally, a (module-)internal ^{55}Fe source was present to allow for calibration of the two detector channels. The light yield, i.e., the ratio between light and phonon channel energy is shown as a function of the energy measured in the phonon channel. A parametrization of the nuclear recoil bands (cf. [10]) was extracted from this measurement, and used with the background-only dataset in [9] to obtain constraints on the DM-nucleon spin-independent elastic scattering cross section as a function of assumed dark matter particle mass. With a few days of runtime, the total exposure

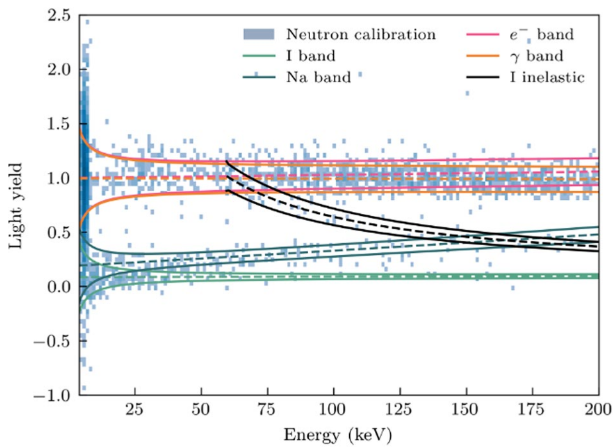

Fig. 2 Light yield for events measured with a COSINUS detector prototype as a function of the energy measured in the phonon channel. An AmBe neutron source was used in the measurement to induce nuclear recoils. A parametric description of the LY bands and the corresponding energy spectra of the different event classes was fitted to the data, and e /γ and nuclear recoil bands are clearly separated. Figure from [9]

for this measurement was only 11.6 g·d, about five hundred thousand times smaller than that of, e.g., COSINE-100 [3]. For the final COSINUS detector design, NaI crystals of about 30 g will be used, and in the first measuring phase with the full setup, 100 kg·d of exposure will be collected. With 20 detector modules, this corresponds to 6 months of data taking.

In the “default” scenario of WIMP-like DM particles from an isothermal halo [11], a signal compatible with DAMA/LIBRA has already been excluded by many other direct DM search experiments. However, it should be noted that COSINUS will provide a model-independent cross check, as its detectors feature particle identification; and thus, a rare event search for nuclear recoils is performed instead of a modulation experiment without background discrimination [12].

4 COSINUS Facility

Fig. 3 shows the cryogenic facility of COSINUS in the LNGS underground laboratory. It is located next to the XENON experiment, and consists of a control building with three levels and the water tank with a cryostat access level on its top. The water tank surrounds the dry well (a steel tube) in which the COSINUS dry dilution cryostat will be operated. The cryostat itself is surrounded by ultra-pure NOSV Cu shielding. In order to mount detectors, it can be lifted out and accessed from the top level, which has already been classified as an ISO7 cleanroom environment. The control building hosts the gas handling interface of the cryostat, controls of the water circulation system, and a small office space. Photomultipliers will be mounted inside the water tank in order to create a Cherenkov muon veto layer around the cryostat. The water in the tank will be periodically cycled and cleaned. COSINUS will feature a closed-loop dilution refrigerator with pulse tube pre-cooling, produced by

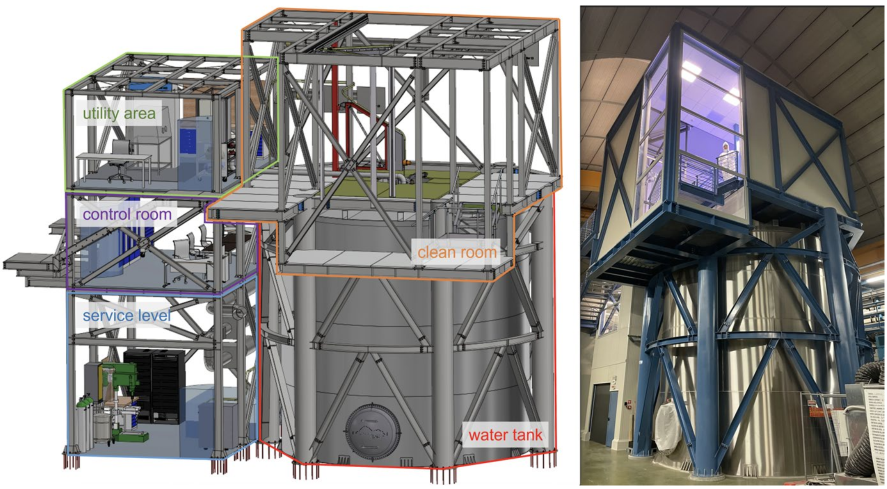

Fig. 3 COSINUS facility located at LNGS. Left: Schematic view with control building and water tank. Right: On-site picture taken in August 2023

Cryoconcept [13]. To avoid vibrations from the pre-cooling system propagating to the detectors, the pulse tube will be mechanically decoupled from the cryostat itself via the use of two separate steel frames. In addition, mechanical decoupling at the detector stage will be implemented. The electrical infrastructure and cryostat lifting system have been installed and aligned successfully; while, the cryostat itself was delivered at the end of 2023, allowing for commissioning of the facility in the beginning of 2024 and the subsequent first measuring phase of COSINUS.

5 QF Measurement

In single-channel NaI experiments such as DAMA/LIBRA, Tl-doped NaI crystals are commonly used in order to enhance the scintillation light output compared to pure NaI. Furthermore, the quenching factors observed for nuclear recoil events in Tl-doped crystals disagree between different studies [14]. Both the influence of the Tl dopant level and the functional dependence of the QF on the recoil energy are unclear. For scintillation light-only NaI experiments, this uncertainty directly propagates to the inferred nuclear recoil energy scale. With high-purity NaI crystals provided by SICCAS, COSINUS has the possibility to study these effects by doping NaI crystals with different defined Tl levels, and measure the QF at cryogenic temperatures in situ using the dual-channel readout of phonon and light signal. Additionally, such crystals can be measured in a neutron beam facility to provide an independent measurement at room temperature. In 2021, five COSINUS crystals doped with 0.1%–0.9% Tl (in powder) were irradiated with a mono-energetic neutron beam at the Triangle Universities National Laboratory (TUNL). Backing detectors at different angles to the beamline were used to detect scattered neutrons, where each angle corresponds to a different nuclear recoil energy between 5 and 30 keV. Additionally, the scintillation light created by the recoil was measured with a PMT attached to the respective NaI(Tl) crystal. Figure 4 shows preliminary results from one of the crystals in this measurement, clearly demonstrating an energy dependence. For comparison, the energy dependent QF description from [9] is also shown. In particular, the resulting QF for Na decreases with recoil energy in both cases, and QFs both at room temperature and from the cryogenic measurement are much lower than the one reported by DAMA/LIBRA in 1997 (0.3). Instead, they are similar to the results from Xu et al. [15], but higher than those reported by Joo et al. [16].

Different calibration methods can have a strong effect on the interpretation of the results from the room temperature measurement, especially if calibration γ lines are far away from the measured nuclear recoil energy region. Therefore data with three different calibration sources (^{241}Am, ^{133}Ba, ^{133}Cs) was recorded by the TUNL group. In Fig. 4, the ^{133}Ba results are shown as an example, as this source provides several γ lines, including a low-energy line at 6 keV. In an upcoming publication, we will compare the resulting QFs for different calibration schemes in detail, and study the systematic uncertainty related to this issue, as well as the effect of different Tl dopant levels in the five crystals.

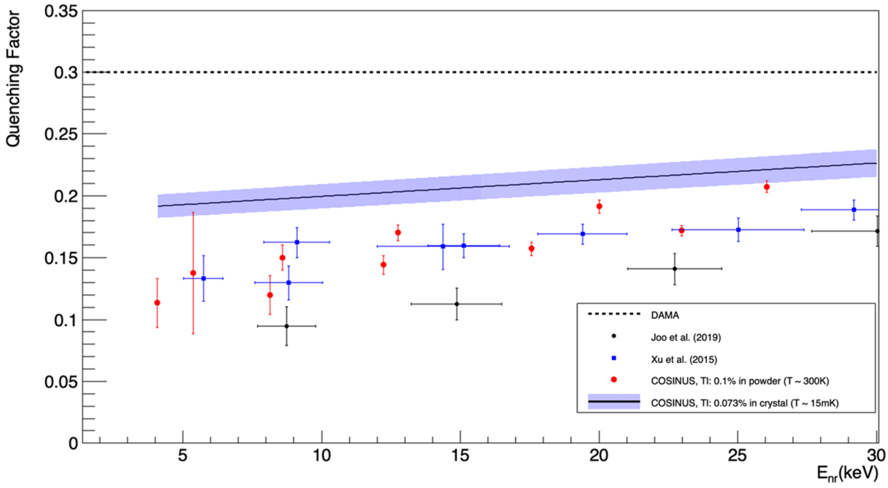

Fig. 4 Na QFs measured with COSINUS NaI(Tl) crystals at room temperature at the TUNL facility (red dots), and at cryogenic temperature ([9], solid black line, with blue shaded uncertainty region). The constant QF assumed by DAMA (dashed black line) and results from [16] and [15] are shown for comparison

6 Conclusion

Construction of the COSINUS facility has progressed rapidly, and will conclude with the delivery of the cryostat at the end of 2023. Commissioning of the experiment will take place early next year, and prototype measurements of detectors have successfully demonstrated that particle discrimination in a cryogenic NaI detector is possible on event-by-event basis. The nuclear recoil energy threshold of 4 keV achieved with the most recent COSINUS prototype is an important milestone on the way to the final detector design. COSINUS detectors allow for a unique study of NaI as detector material, in particular they will provide precise measurements of QF, and enable a definitive cross check of the DAMA/LIBRA modulation signal.

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Declarations

Competing interests The authors declare no competing interests.

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