remoTES: A new design for the cryogenic NaI detectors of the COSINUS experiment

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Abstract

The increasing statistical significance of the DAMA/LIBRA annual modulation signal is a cause for tension in the field of dark matter direct detection. The COSINUS experiment aims at a model-independent cross-check of the DAMA/LIBRA signal claim, using NaI crystals operated as cryogenic scintillating calorimeters at millikelvin temperatures. Such a setup enables measurement of phonon and scintillation light signals via Transition Edge Sensors (TESs) and allows particle discrimination on an event-by-event basis. The non-standard properties of NaI cause an obstacle when attaching a TES directly onto the surface of the crystal. This can be overcome with the "remoTES" design, where the TES is attached to an external wafer crystal. We present the results from a first successful operation of NaI and other crystals as cryogenic calorimeters with the remoTES design.

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1 Introduction

Astronomical and cosmological observations imply that 26 % of the universe's mass content is composed of non-luminous and non-baryonic dark matter (DM) [1]. The nature of DM is still unknown and yields one of the major open questions in modern physics. Various new fundamental particles and extensions to the Standard Model have been proposed as DM candidates [2,3], among those, weakly interacting massive particles (WIMPs) are favored by the DM direct detection community [4].

Despite immense experimental effort, no convincing DM signal has been observed until today and the DM hypothesis has been ruled out for most excess signals seen by experiments such as XENON [5] or CRESST [6]. However, there is one long-standing signal claim remaining, namely by the DAMA/LIBRA experiment [7,8]. DAMA's claim is based on the hypothesis that the DM rate should be subject to an annual modulation due to Earth's motion within the Milky Way. In the last 25 years, DAMA/LIBRA has continuously observed such a modulation with period and phase in-line with the DM hypothesis. By today, the statistical significance of the signal has reached over 13σ in the 1-6 keVee energy range. However, the region of the parameter space corresponding to the DAMA signal under the standard scenario assumptions has been ruled out by the null results of various other experiments [9]. In order to perform a model-independent investigation of the DAMA/LIBRA signal, it is mandatory to utilize the same target material, sodium iodide (NaI) [9, 10]. Alongside other planned and active experiments - such as SABRE [11], COSINE [12] and ANAIS [13] - the COSINUS (Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches) experiment aims at such a model-independent test of the DAMA/LIBRA signal claim [14].

In contrast to its competitors, COSINUS will operate NaI crystals as cryogenic scintillating calorimeters, cooled down to milli-Kelvin temperatures and read out by Transition Edge Sensors (TESs). With this detector setup, each particle interaction in the detector material leads to both a phonon/heat and a light signal. While the particle-independent phonon signal gives a measure of the total deposited energy in the crystal, the scintillation signal is subject to light-quenching and allows for particle discrimination. The COSINUS setup thus enables separation of nuclear recoils (possible DM signal) from the electron/gamma-background (e/γ) on an event-by-event basis.

To absorb and measure the scintillation light, the NaI crystals will be placed in a beaker-shaped silicon detector equipped with a tungsten TES (W-TES) thermometer as developed and refined by the CRESST collaboration [15]. For measurement of the heat signal, direct fabrication of the TES thermometer onto the absorber crystal would ensure excellent transmission of the non-thermal phonons to the W-film. Unfortunately, this production procedure is not possible for NaI as the crystals are soft, hygroscopic, and have a low melting point. The COSINUS collaboration thus developed the so-called *remoTES*, where the TES is instead placed on a remote wafer crystal that is connected to the absorber. This detector design is described in detail in section 2. Several R&D measurements have been performed with *remoTES* detectors and different absorber materials, the results of which are summarized in section 3. Finally, in section 4 we conclude and give an outlook on future work planned regarding setup and detector design of COSINUS.

2 *remoTES* detector design

The idea behind the *remoTES* detector was first proposed by M. Pyle et al. [16] as a simple and reproducible alternative to the direct fabrication of TESs onto absorber crystals. The COSINUS implementation of the *remoTES* detector is schematically depicted in Figure 1, showing both

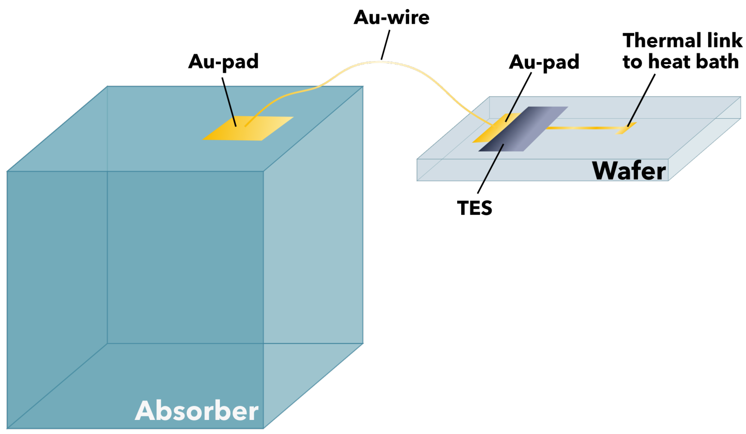


Figure 1: Schematics of a *remoTES* phonon detector. The TES is directly fabricated onto the wafer crystal (light blue, right), which is connected via a combination of gold pads and gold bonding wire to the absorber crystal (darker blue, left).

the absorber and wafer crystal [17]. The fabrication-intensive W-TES is attached to the wafer-like separate crystal and connected to the heat bath via a gold thermal link. The absorber crystal itself is connected to the TES via a system of gold pads and gold bonding wire(s). Any signal created by thermal and athermal phonons in the absorber crystal is then transmitted to the TES via electron-phonon coupling in the gold pad. Although the heat capacity of the gold pad and wire bond is diminishing the overall created signal, the factor ten higher electron-phonon coupling in gold compared to tungsten [16,18] is expected to compensate for this loss. Moreover, the *remoTES* design avoids signal loss due to acoustic mismatch between different materials, as would occur in the so-called *composite design* which has been previously suggested and probed by the COSINUS collaboration [19].

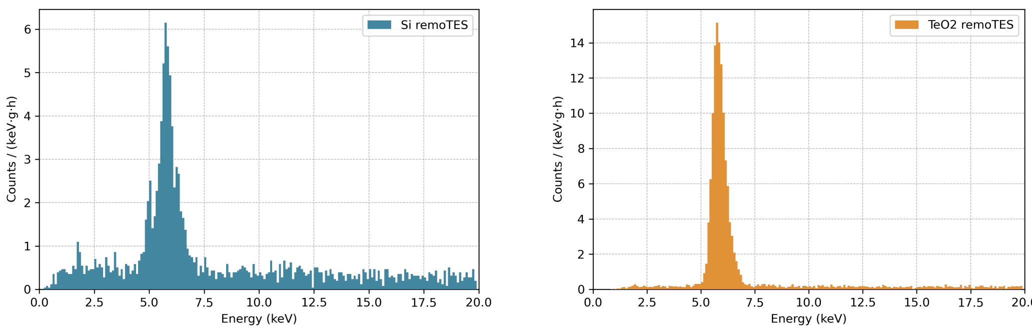
While the application of the W-TES to the wafer crystal (Al_2O_3 in all prototypes) is sa standardized procedure, the specifics of the remaining *remoTES* design vary between different prototypes. In this work we present the construction details and results of three different prototypes, featuring silicon (Si, 2.33g), tellurium dioxide (α- TeO_2, 2.27g), and sodium iodide (NaI, 3.67g) absorber crystals. The process of attaching the gold pad to the absorber crystal can be adapted to the physical and chemical properties of the crystal. The same is true for the method of attaching the gold wire to the pad on the absorber, as standard wedge- or ball-bonding may not be possible for soft and fragile absorber crystals. The details of the *remoTES* design for each of the three prototype absorbers are summarised in Table 1.

3 Results from prototype measurements

The two measurements with Si and TeO_2 absorber crystals were performed at an above-ground wet dilution refrigerator of the CRESST group at the Max-Planck Institute for Physics in Munich. The most recent measurement of a NaI *remoTES*, reported here, was instead performed at the CRESST test cryostat located at the INFN Gran Sasso Underground Laboratory (LNGS). Specifics of the setup and the analysis chain for the above-ground runs can be found in [17]. For the NaI underground run, where the *remoTES* was operated in a module together with a beaker-shaped Si light detector, the analysis chain is comparable. In all runs at least two types of particle pulse event classes could be observed, one for hits in the absorber crystal and one for hits in the wafer crystal. More detail on these event classes and the discrimination process can be found again in Ref. [17].

Table 1: Specifics and baseline resolutions of the three prototype *remoTES* detectors used in the presented measurements.

Absorber material	**Au-pad properties**	**Au-wire properties**	**Baseline resolution (eV)**
Si 20x10x5 mm^3	• 3mm diameter, • 200 nm thickness, • Magnetron-sputtering,	• glued to absorber Au-pad with silver-loaded epoxy, • 17 μm thick wire,	87.8 ± 5.6 eV,
TeO_2 20x10x2 mm^3	• 400 nm thick foil, • glued onto absorber with two-component epoxy resin,	• wedge bonded to absorber Au-pad, • 17 μm thick wire,	193.5 ± 3.1 eV,
NaI 10x10x10 mm^3	• 1 μm thick foil, • glued onto absorber with two-component epoxy resin,	• wedge bonded to absorber Au-pad, • 17 μm thick wire,	373 ± 16.3 eV.



(a) (b)

Figure 2: Energy spectra of two *remoTES* detectors exposed to a ^{55}Fe source: (a) Si and (b) TeO2 absorber.

In all runs ^{57}Co and ^{55}Fe sources were used for the energy calibration. The X-rays of 5.89 keV (K_α) and 6.49 keV (K_β)) produced by the ^{55}Fe-source can be seen in the spectra for the Si and TeO_2 measurements shown in Figure 2. For a measurement with the NaI absorber, which included a neutron source (AmBe), we show the combined result of light and *remoTES* phonon signal in a so-called light yield plot. The 2D histogram in Figure 3 shows the total recoil energy as measured by the *remoTES* on the x-axis and the light yield $LY = \frac{\text{light signal}}{\text{phonon signal}}$ on the y-axis. In this presentation of the data, light quenching takes full effect and one can discriminate the e/γ events, at a light yield of one, from the quenched nuclear recoil events. The events visible between the two bands at energies higher than 50 keV can be attributed to inelastic recoils off iodine nuclei, whereas the dense population of events around 6 keV consists of X-ray events produced by the ^{55}Fe source.

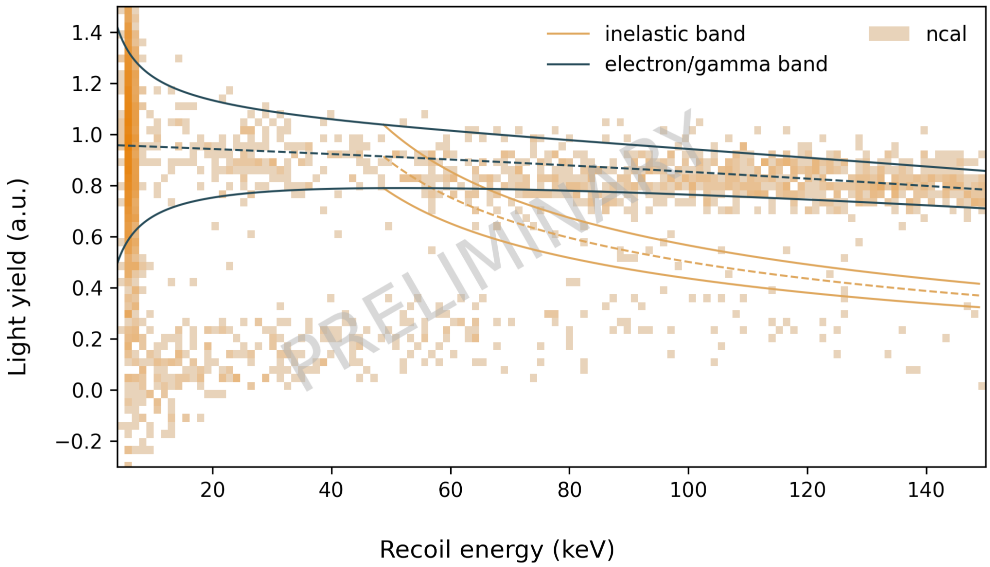


Figure 3: 2D histogram of phonon signal versus light yield for a NaI *remoTES* measurement with a neutron source (AmBe). The e/γ at a light yield of one is clearly separated from the nuclear recoil events at lower light yields.

For all measurements, the baseline resolution is determined following the well-established procedure described in [17] and can be found in Table 1. The threshold of the detectors can be estimated as five times the baseline resolution.

4 Conclusion and outlook

Through various prototype measurements, we have shown, that the *remoTES* detector design gives an easy-to-fabricate alternative to the direct deposition of TESs onto absorber materials. The successful operation of a *remoTES* with a NaI absorber crystal, enabling particle discrimination, was an important milestone for the COSINUS experiment. With an achieved baseline resolution of under 400 eV, corresponding to a true recoil energy threshold of <2 keV, the detector prototypes are closing in on the final design goal of a 1 keV threshold. While work is ongoing within the collaboration to refine the design of the detector modules (*remoTES* plus Si beaker light detector), the construction of the experimental setup is currently taking place in Hall B of LNGS. The first phase of data taking with the COSINUS experiment is planned to start in autumn 2023, and the first DM results are expected by the end of 2024.

References

[1] N. Aghanim et al., *Planck 2018 results*, Astron. Astrophys. **641**, A6 (2020), doi:10.1051/0004-6361/201833910.

[2] M. Cirelli, N. Fornengo and A. Strumia, *Minimal dark matter*, Nucl. Phys. B **753**, 178 (2006), doi:10.1016/j.nuclphysb.2006.07.012.

[3] G. Arcadi et al., *The waning of the WIMP? A review of models, searches, and constraints*, Eur. Phys. J. C **78**, 203 (2018), doi:10.1140/epjc/s10052-018-5662-y.

[4] B. W. Lee and S. Weinberg, *Cosmological lower bound on heavy-neutrino masses*, Phys. Rev. Lett. **39**, 165 (1977), doi:10.1103/PhysRevLett.39.165.

[5] E. Aprile, *Search for new physics in electronic recoil data from XENONnT*, Phys. Rev. Lett. **129**, 161805 (2022), doi:10.1103/PhysRevLett.129.161805.

[6] G. Angloher, *Latest observations on the low energy excess in CRESST-III*, (arXiv preprint) doi:10.48550/arXiv.2207.09375.

[7] R. Bernabei et al., *Final model independent result of DAMA/LIBRA-phase1*, Eur. Phys. J. C **73**, 2648 (2013), doi:10.1140/epjc/s10052-013-2648-7.

[8] R. Bernabei et al., *First model independent results from DAMA/LIBRA-phase2*, Nucl. Phys. At. Energy **19**, 307 (2018), doi:10.15407/jnpae2018.04.307.

[9] J. Billard et al., *Direct detection of dark matter—APPEC committee report*, Rep. Prog. Phys. **85**, 056201 (2022), doi:10.1088/1361-6633/ac5754.

[10] F. Kahlhoefer, F. Reindl, K. Schäffner, K. Schmidt-Hoberg and S. Wild, *Model-independent comparison of annual modulation and total rate with direct detection experiments*, J. Cosmol. Astropart. Phys. **2018**, 074 (2018), doi:10.1088/1475-7516/2018/05/074.

[11] M. Antonello et al., *The SABRE project and the SABRE proof-of-principle*, Eur. Phys. J. C **79**, 363 (2019), doi:10.1140/epjc/s10052-019-6860-y.

[12] G. Adhikari et al., *Strong constraints from COSINE-100 on the DAMA dark matter results using the same sodium iodide target*, Sci. Adv. **7**, eabk2699 (2021), doi:10.1126/sciadv.abk2699.

[13] J. Amaré et al., *Annual modulation results from three-year exposure of ANAIS-112*, Phys. Rev. D **103**, 102005 (2021), doi:10.1103/PhysRevD.103.102005.

[14] G. Angloher et al., *The COSINUS project: Perspectives of a* NaI *scintillating calorimeter for dark matter search*, Eur. Phys. J. C **76**, 441 (2016), doi:10.1140/epjc/s10052-016-4278-3.

[15] A. H. Abdelhameed, *First results from the CRESST-III low-mass dark matter program*, Phys. Rev. D **100**, 102002 (2019), doi:10.1103/PhysRevD.100.102002.

[16] M. Pyle, E. Figueroa-Feliciano and B. Sadoulet, *Optimized designs for very low temperature massive calorimeters*, (arXiv preprint) doi:10.48550/arXiv.1503.01200.

[17] G. Angloher et al., *First measurements of remotes cryogenic calorimeters: Easy-to-fabricate particle detectors for a wide choice of target materials*, Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **1045**, 167532 (2023), doi:10.1016/j.nima.2022.167532.

[18] W. A. Little, *The transport of heat between dissimilar solids at low temperatures*, Can. J. Phys. **37**, 334 (1959), doi:10.1139/p59-037.

[19] K. Schäffner et al., *A* NaI*-based cryogenic scintillating calorimeter: Results from a COSINUS prototype detector*, J. Low Temp. Phys. **193**, 1174 (2018), doi:10.1007/s10909-018-1967-3.