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Dark Matter detection with the COSINUS experiment

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Summary. — Using a NaI target is essential to test the long-standing DAMA/LIBRA claim of the detection of a Dark Matter (DM) signal in a model-independent way. COSINUS is developing the first cryogenic scintillating calorimeter based on a NaI absorber. This technique provides an event-by-event particle identification strategy based on a dual-channel readout (heat and light). An excellent energy resolution and a low threshold are essential for a direct detection DM experiment. In this regard, Transition Edge Sensors (TESs) are an established technology that has already proven its potential in other leading cryogenic DM experiments (like CRESST-III). However, the hygroscopicity of NaI prevents the deposition of the TES sensor directly onto its surface, which would guarantee optimal thermal coupling. For this reason, COSINUS adopted an alternative design for the heat channel readout, called remoTES, which is currently in the R&D phase and has already shown promising results (in terms of energy threshold and resolution) when tested on various absorbers (Si, TeO_2).

1. – Introduction

The DAMA/LIBRA experiment performs its search for dark matter by using 250 kg of highly radio-pure NaI(Tl) crystals operated as scintillators (at room temperature) coupled to photomultiplier tubes in the underground environment of the Laboratori Nazionali del Gran Sasso (LNGS). The experiment observes an annual modulation signal that matches what one would expect from the Earth's movement in the DM halo (both period and phase) with robust statistical significance ($13.7\,\sigma$ C.L. over a total of 22 annual cycles for a total exposure of 2.86 t·yr in the (2–6) keV energy interval [1]). This result is in tension with the exclusion limits traced by other direct detection experiments using different target materials [2]. However, since the interaction mechanism of a hypothetical DM particle and ordinary (baryonic) matter is unknown, a direct comparison between experiments using different targets is challenging: the interaction has to be modeled and depends on properties of the target material (mass number, nuclear form factors, etc.) [2]. Reproducibility is a primary principle of the scientific method, and it is one of the strictest tests that any scientific result has to pass before being accepted as a new contribution to knowledge. COSINUS is a next-generation direct-detection DM experiment that will perform a model-independent cross-check of the DAMA/LIBRA results by using the same target material (NaI) [3, 4]. Other current and next-generation experiments (*e.g.*, COSINE [5], SABRE [6], ANAIS [7], PICO-LON [8]) adopt the same strategy and use NaI targets. However, COSINUS is the only experiment based on cryogenic calorimeters and the only one that will implement a particle discrimination strategy, allowing it to discriminate γ/β events from nuclear recoils.

Indeed, it is currently unclear if the positive modulation signal observed by DAMA/LIBRA is due to particles scattering off the electrons or the nuclei. At the same time, β/γ events constitute the dominant background (*e.g.*, from the unavoidable ^{40}K contaminations in NaI crystals). Furthermore, even if we assume that the signal comes from nuclear recoils, lacking any particle identification strategy, DAMA/LIBRA cannot tell apart I recoils from Na ones. Consequently, the discovery claim translates into two different regions in the parameter space, depending on which is the recoiling nucleus (Na or I). COSINUS addresses all these problems by operating NaI as a scintillating cryogenic calorimeter. The detector will be capable of performing particle discrimination of Na recoils, I recoils, and β/γ interactions on an event-by-event basis. The progress of the R&D activities is reported in [9-11].

2. – Detector design and remoTES

Scintillating cryogenic calorimeters have excellent energy resolutions and low energy thresholds compared to traditional ionization detectors or scintillators. The COSINUS single module has two main elements: an absorber and a light detector (LD). The former is a NaI crystal that acts as the active detector volume and the DM target at the same time. The LD consists of a silicon beaker surrounding the NaI, designed to absorb the scintillation photons emitted by the crystal. Both are equipped with a highly sensitive temperature sensor. By keeping the system at $\sim$10 mK it is possible to measure the temperature increase of the absorber due to a single particle interaction, which is proportional to the deposited energy (heat channel). Similarly, the scintillation photons emitted by NaI are absorbed in the LD, allowing it to measure the energy converted into light. Since different types of particles cause the emission of different amounts of light by the NaI, combining the heat and the light signals provides an effective particle discrimination tool. To measure small temperature variations of the NaI absorber and the silicon beaker it is crucial to choose a high-performance sensor (sensitive to tiny temperature variations $\mathcal{O}(\mu\mathrm{K})$) and achieve good thermal coupling between the sensor and the detector. This is especially true for NaI, as its Debye temperature is low ($\Theta_D \simeq 163.2\,\mathrm{K}$), which translates into small temperature increases per unit of deposited energy, potentially worsening the resolution and threshold. To reduce these effects, COSINUS will use TESs, which are superconductive thin films (usually made of tungsten) operated near its transition temperature T$_c$, where the resistance has a strong temperature dependence. Thus they can convert tiny temperature increases ($\mathcal{O}(\mu\mathrm{K})$) in measurable resistance variations ($\mathcal{O}(\mathrm{m}\Omega)$) induced by small energy depositions ($\mathcal{O}(\mathrm{keV})$). The excellent sensitivity of TESs has been widely demonstrated by experiments such as CRESST-III, which posed the strongest constraints on the low-mass region of the DM parameters space, from 0.16 to 1.8 GeV/c^2 [12]. In CRESST-III, these optimal performances are largely due to the sensitivity to non-thermal phonons, obtained by fabricating the TES directly onto the absorber. NaI crystals are hygroscopic and cannot undergo the same

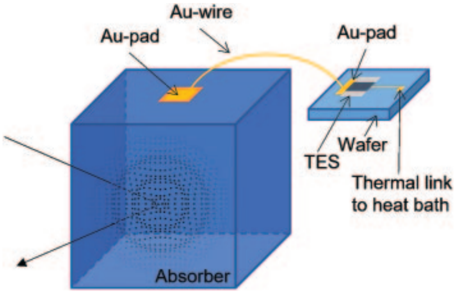

Fig. 1. – Schematic view of a remoTES design. The wafer where the TES is fabricated (right) is separated from the absorber crystal (left), which is equipped with a gold pad linked directly to the TES via a gold bonding wire. Figure reprinted from [13].

TES fabrication process (which involves electron-beam evaporation, sputtering, chemical etching, and photolithography) [13]. This forces COSINUS to find an alternative design for the coupling of the TES sensor with the NaI absorber. Although other approaches can be thought [10], recently the COSINUS collaboration started to test a new design, originally proposed in [14] and called remoTES, which shows very promising results [13]. In this design, shown in fig. 1, the TES is fabricated onto a separate wafer; the absorber crystal is then equipped with a gold pad that transmits the heat signal to the TES onto the carrier through a thin gold wire. This design guarantees higher reproducibility and better radiopurity standards. Moreover, it allows reducing handling the crystal, thus minimizing the occasions to degrade it due to exposure to humid air.

The LD consists of an encapsulated silicon beaker surrounding the NaI crystal. Providing an almost 4π coverage, the LD maximizes the light collection and works also as an active veto for surface events due to nuclear recoils and α particles. The TES sensor is fabricated directly onto the silicon beaker.

3. – Results and performances

The remoTES design introduces new elements to the detector configuration, each with its own thermal capacity and conductivity. This adds new time constants to the signal formation and influences the pulse shape, potentially harming the energy resolution and threshold. On the other hand, data showing a stronger electron-phonon coupling in Au than in W [14] can be found in the literature. As the following measurements prove, these competing effects in these preliminary tests seem to show a net positive impact of the remoTES design on detector performance.

Silicon (Si) and tellurium dioxide (TeO_2) are common absorber materials used in cryogenic calorimeters. Thus, they can be used to validate the remoTES design: Si is a useful benchmark as it is very well studied in low-temperature applications, while TeO_2 has similar solid-state properties to NaI, so its performances with the remoTES can be representative of the ones expected for a NaI-based detector. In ref. [13], the COSINUS collaboration has tested a Si absorber of $20 \times 10 \times 5\,\mathrm{mm}^3$ (2.33 g) equipped with a remoTES constituted by an Au-pad (3 mm diameter, 200 nm thickness) deposited by Magnetron-sputtering, a $17\,\mu$m thick Au bonding wire, and a W-film TES deposited onto an Al_2O_3 wafer ($10 \times 10 \times 0.4\,\mathrm{mm}^3$). The connection between the wire and the Au-pad on the Si was realized using a silver-loaded epoxy ($\sim 25\,\mu$g). In [13] the authors also studied the performances of a TeO_2 crystal of $20 \times 10 \times 2\,\mathrm{mm}^3$ (2.27 g) equipped with a remoTES constituted by a 400 nm thick Au-foil glued onto the absorber surface by using epoxy resin, a $17\,\mu$m thick Au bonding wire, and a W-film TES deposited on an Al_2O_3 wafer ($10 \times 10 \times 0.4\,\mathrm{mm}^3$). In both measurements, the TES consisted of a 100 nm-thick tungsten film of an area of $220 \times 300\,\mu\mathrm{m}^2$ and two aluminum pads for biasing of the sensor. The area of the W-film not overlapping with the pads is $70 \times 300\,\mu\mathrm{m}^2$. An uncollimated ^{55}Fe calibration source was placed under the absorbers for calibration purposes. When needed, it was possible to reject events relative to interactions in the gold pad or the TES wafers through pulse shape discrimination. The spectra of both Si and TeO_2 detectors feature a clear calibration peak at 5.89 keV due to ^{55}Fe. Given this calibration, and assuming Gaussian fluctuations in the noise, it is possible to estimate the (baseline) energy resolutions. The measured values (in σ) were (87.8 ± 5.6) eV for the Si absorber and (193.5 ± 3.1) eV for the TeO_2 absorber [13]. Assuming an energy threshold equal to five times the baseline resolution, these detectors perfectly meet the requirements needed for a direct detection DM experiment. Assuming a similar behavior for a NaI crystal, these results prove the effectiveness of the remoTES for the COSINUS scientific goals.

4. – Conclusion

Operating NaI as a scintillating cryogenic calorimeter poses some challenges due to the peculiarities of this material. One of the main obstacles is the difficulty of depositing a TES directly onto the crystal surface, which is the standard heat channel readout in other successful DM cryogenic experiments. COSINUS adopted an alternative design, called remoTES, which solves the problem by avoiding direct deposition onto the crystal surface. The first tests conducted on Si and TeO_2 absorbers show very promising results in terms of energy threshold and resolutions.

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