The CRESST-III low-mass WIMP detector

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Abstract. The next generation direct dark matter experiment CRESST-III has a high potential to significantly increase the sensitivity to low-mass WIMPs ($m_\chi \lesssim 10\,\text{GeV}/c^2$). We present the new CRESST detector module: it consists of a 24 g CaWO$_4$ crystal operated as a phonon detector and a 20x20 mm^2 silicon-on-sapphire light detector. The phonon energy threshold is lowered to $\sim$100 eV and a light detector resolution of typically 5 eV is achieved. A fully-scintillating inner detector housing is realised which efficiently rejects events from surface-alpha decays. The CaWO$_4$ sticks holding the target crystal are also operated as calorimeters to discriminate all possible artefacts related to the support structure. A projection for the sensitivity to spin-independent WIMP-nucleon scattering is given for the first phase of CRESST-III which will start beginning of 2016.

1. The state-of-the art: Direct Dark Matter Search with CRESST-II

The direct dark matter search experiment CRESST-II (Cryogenic Rare Event Search with Superconducting Thermometers) uses scintillating CaWO$_4$ crystals as target material for dark matter particles [1]. The modular detectors of about 300 g each are based on a two-channel readout: 1) The target crystal itself is operated as a cryogenic bolometer at mK temperatures to measure the total energy deposited by a particle interactions. This (often called) phonon channel is equipped by transition edge sensors (TES) which are realized as thin W-films. 2) An independent light detector (silicon-on-sapphire disc with TES) measures the scintillation light output induced by particles in the CaWO$_4$ crystal. This technique provides a background discrimination since the light output of different types of particle interactions differs due to light quenching [1, 2]. In
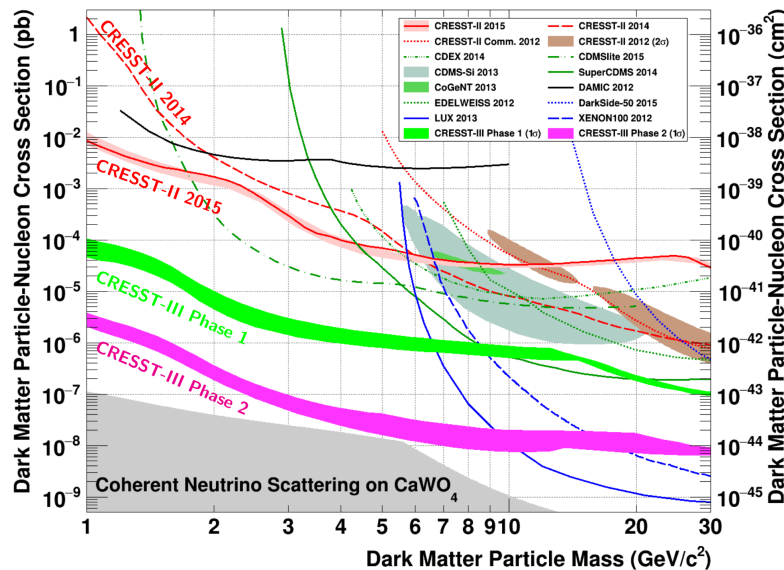
Figure 1. Spin-independent dark matter particle-nucleon cross section versus the dark matter particle mass: recent results from direct dark matter searches [10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. The results of CRESST-II Phase 2 [5, 6] (dashed and full red lines) and the projections (1-σ bands) for CRESST-III are indicated (in green and pink) [20].

particular, the dominant beta/gamma events can be distinguished from possible WIMP-induced nuclear-recoil events. The latter can, to a certain extent, even be identified as O, Ca and W recoils [3].

CRESST-II Phase 2 started in July 2013 with a total target mass of $\sim 5\,\mathrm{kg}$ using 18 detector modules of four different detector types [4]. So far, two datasets of this measurement campaign have been analysed and the obtained results were recently published [5, 6]. Several significant improvements with respect to previous phases of CRESST have been achieved: Using a new detector design, previously observed backgrounds from surface-alpha decays are rejected with high efficiency [5, 7]. In addition, $CaWO_4$ crystals from in-house production at the Technische Universität München [8] were operated in the CRESST-II setup for the first time. Thereby, the intrinsic background level could be reduced significantly to an average beta/gamma rate of $3.44\,/[\mathrm{kg\,keV\,day}]$ in the region-of-interest (1-40 keV) [9] which is about an order of magnitude better than for previously available $CaWO_4$ crystals. An energy threshold as low as $\sim 300\,\mathrm{eV}$ and a resolution of $\sigma_{ph}{=}(0.090{\pm}0.010)\,\mathrm{keV}$ (at 2.60 keV) are reached with these $CaWO_4$ phonon detectors [6]. For the silicon-on-sapphire light absorbers (diameter: 40 mm, thickness: 500 μm) typically a resolution of $\sigma_l \gtrsim 5\,\mathrm{eV}$ is achieved.
All events observed in the region-of-interest for dark matter search are compatible with known backgrounds. There are no indications for an excess signal. Therefore, the most conservative approach was chosen and limits on the spin-independent WIMP-nucleon scattering cross section were derived (see Fig. 1) [5]. The data explore new regions of parameter space for dark matter particle masses below $2\,\mathrm{GeV/c^2}$ and disfavour a dark matter interpretation of the CRESST-II results [1].

2. Low-mass WIMP search with CRESST-III
The CRESST-II data demonstrated, that a low energy threshold is crucial for the sensitivity to low mass dark matter particles: since the expected exponential dark matter particle-recoil

spectra extend to energies of $\mathcal{O}(1\,\text{keV})$ only, for dark matter particle masses of $\mathcal{O}(1\,\text{GeV}/c^2)$ [21], a low energy threshold is crucial for the sensitivity to low-mass WIMPs. For the next phase of the experiment, CRESST-III, which will be dedicated to low-mass dark matter search ($\sim 1\,\text{GeV}/c^2$), we aim for an energy threshold of 100 eV. This will be achieved by a straight-forward approach: the size of the $CaWO_4$ crystals is scaled down by a factor of 10 which corresponds to a target mass of 24 g. Considering basic phonon physics [22] this should improve the signal-to-noise ratio by a similar factor. Hence, the design goal should be easily achievable and, indeed, first measurements with a prototype module suggest that thresholds below 100 eV are in reach. Projections for the sensitivity have been calculated based on the following assumptions: an energy threshold of 100 eV using the 24 g crystals; moderate improvements concerning the light channels (details see [20]) and the CRESST-II background level. In Fig. 1 the projected sensitivity for CRESST-III phase 1, which can be achieved with an exposure of 50 kg-days is shown (yellow band) [20]. For the second phase of CRESST-III crystals of improved quality are necessary. Our goal is to achieve an (intrinsic) background level, which is 100 times lower than at present. To reach this goal, the dedicated crystal-growth facility at the Technische Universität München [8] will be of high importance. Fig. 1 (blue band) shows the projected sensitivity of such a setup reachable with an exposure of 1000 kg-days [20].

3. The CRESST-III detector module
In this section, the main components of the new CRESST-III detector module are briefly introduced.

Transition-edge-sensor (TES):   As mentioned in section 2, smaller crystals ($m = 24$ g, V=20x20x10 mm^3) will be used for CRESST-III. This design allows to operate the detector in a calorimetric mode, i.e. the TES can be designed such that incoming phonon flux is integrated in the sensor [22]. This can be realized by a thin W film ($A = 4\,\text{mm}^2$, $d = 200\,\text{nm}$) and a relatively weak thermal coupling to the heat bath (via a thin Au stripe and a Au wire bond). An additional advantage of that design is the applicability of so-called phonon collectors. Relatively large Al films ($A = 4\,\text{mm}^2$) are attached to the W film, which provide a significantly increased phonon collection area without the penalty of a higher heat capacity. We expect an increase in the signal-to-noise ratio by a factor of 10 compared to previously used 300 g detectors in CRESST-II. Hence, the desired threshold of 100 eV should be feasible; first measurements with a prototype module indicate that sub-100 eV thresholds are in reach.

The $CaWO_4$ target crystal: For CRESST-II, crystals have been provided by the Technische Universität München [8]. These show the lowest intrinsic background level ever observed with $CaWO_4$. At energies below 40 keV an average rate of 3.44 [kg keV day] is observed, which corresponds to an improvement by a factor of 3-10 compared to previously available (commercial) crystals. For CRESST-III only TUM-grown crystals will be installed. Using the dedicated growth facility, a Czochralski furnace, there are clear ideas to further improve the intrinsic radiopurity of the $CaWO_4$ crystals: multiple-crystallization and a chemical purification of the raw materials are promising techniques which are currently under investigation.

Surface-alpha event rejection: Surface-alpha contaminations in the inner detector housing, in particular ^{210}Po decays, are a harmful background for dark matter search. The resulting recoils of heavy nuclei (e.g. ^{206}Pb) in the target crystal have low light outputs comparable to that of W recoils and can thus mimic dark matter particle recoils. This challenge can be met with a fully scintillating inner detector housing [7]. This is achieved by $CaWO_4$ sticks which hold the target crystal (3 per detector) and a polymeric foil surrounding the detector (see Fig. 2). Since the
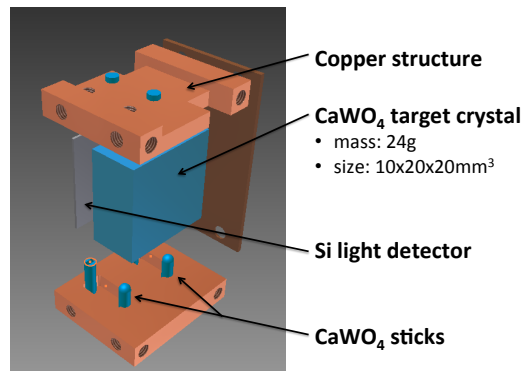
Figure 2. Principle scheme of the new detector holder for CRESST-III.

alpha particles of MeV energies corresponding to such a decay produce additional light in this scintillating layer, the ^{206}Pb recoils no longer show up as nuclear recoils but have light outputs comparable to electron recoils. This provides a discrimination of this event class and already in CRESST-II [7] an efficient veto against all kinds of surface-alpha events could be achieved.

The Silicon-on-Sapphire (SOS) Light Detector: Accordingly to the phonon detector, the size of the SOS light detector can be reduced by a factor of $\sim \pi$ to 20x20 mm^2 (thickness 400 μm). Using the well-established and optimized calorimetric TES of CRESST-II and accounting for the reduction in volume, thresholds of $\mathcal{O}(5\,\text{eV})$ are in reach. SOS absorbs $\sim 85\%$ of scintillation photons at λ=420 nm (maximum emission of CaWO$_4$) compared to $\sim 60\%$ for pure silicon. Similarly to the main crystal, the light detector is clamped by CaWO$_4$ sticks (part of the active veto against surface backgrounds, see Fig. 2).

The instrumented detector holder: The material holding the detectors (in this case, the CaWO$_4$ sticks) acts itself as a particle detector. Due to the interface stick-target crystal, part of the phonon signal induced in the CaWO$_4$ stick is transmitted to the CaWO$_4$ target crystal (about 1-5%) and detected as a (degraded) signal in the TES. At lowest energies, such events can mimic low-energy dark matter particle induced recoils. Most of the events in the CaWO$_4$ sticks are electron recoils with corresponding scintillation light. However, nuclear recoils, in particular surface-alpha events on the stick surfaces (with a reduced scintillation light output), might mimic dark matter induced recoils in the target crystal. Possible stress relaxations (not observed so far) induced by clamping the target crystal might induce phonon-only events in the crystal at lowest energies. To fully reject these backgrounds, a new system is implemented. The CaWO$_4$ sticks that hold the target crystal will be equipped with TES and operated as calorimeters. The sensor which is similar to the TES used for the light detector is evaporated on a Si wafer and glued onto the sticks (see Fig. 3). The ratio between the signal detected in the stick TES and the simultaneously detected degraded signal in the TES of the target crystal can be used for an efficient discrimination of events originating from the sticks. In this way events related to the detector holder can efficiently be rejected.

4. Outlook
Motivated by the CRESST-II results [5][6], a new detector module for CRESST-III dedicated to low-mass dark matter search has been developed. Two detector prototypes have been successfully tested and the production of 10 modules is currently ongoing. The mounting at
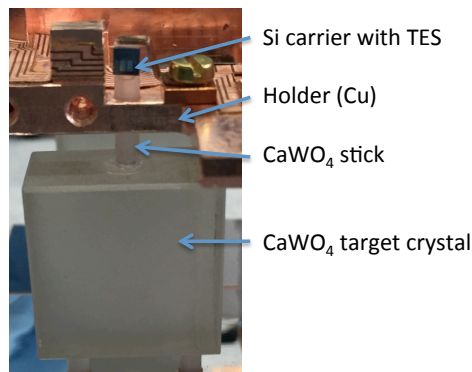
Figure 3. Picture of the new CRESST-III detector module with a zoom into one CaWO$_4$ stick equipped with a TES (on a glued Si carrier). With these instrumented sticks, different kinds of backgrounds related to the detector holder can be rejected (see text).

LNGS in Italy is scheduled for early 2016 and first results form the first phase of CRESST-III are expected one year thereafter.

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