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New results on low-mass dark matter from the CRESST-II experiment

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Abstract. The CRESST-II experiment is searching for dark matter particles via their elastic scattering off nuclei in a target material. The CRESST target consists of scintillating $CaWO_4$ crystals which are operated as cryogenic calorimeters at millikelvin temperatures and read out by transition edge sensors. Each interaction in the $CaWO_4$ target crystal produces a phonon signal and also a light signal that is measured by a secondary cryogenic calorimeter. The low energy thresholds of these detectors, combined with the presence of light nuclei in the target material, allow to probe the low-mass region of the parameter space for spin-independent dark matter-nucleon scattering with high sensitivity.
In this contribution results from a blind analysis of one detector module operated in the latest measurement campaign are presented. An unprecedented sensitivity for the light dark matter has been obtained with 52kg live days and a threshold of 307eV for nuclear recoils, extending the reach of direct dark matter searches to the sub-GeV/c^2 region.

1. Introduction

In this era of precision cosmology we know that dark matter constitutes about 85% of the matter in the Universe [1], nonetheless its nature is still unknown. Unraveling this problem is one of the major challenges of modern physics.
Direct dark matter searches exploit a great variety of different detector technologies, all aiming to observe dark matter particles via their elastic scattering off nuclei in their detectors. Cryogenic experiments currently provide the best sensitivity for light dark matter particles, with the CRESST-II experiment advancing to the sub-GeV/c^2 dark matter particle mass regime.
The CRESST target consists of scintillating $CaWO_4$ crystals operated as cryogenic calorimeters at

millikelvin temperatures (*phonon detectors*). Each interaction in $CaWO_4$ produces a phonon signal in the target crystal, yielding a precise energy measurement, and a light signal that is measured by a secondary independent cryogenic calorimeter (*light detector*) allowing for particle identification [2, 3]. A phonon detector and the corresponding light detector form a so-called *detector module*.
Both, phonon and light detectors are read out via tungsten transition edge sensors (TES) and are equipped with a heater to stabilize the temperature in their operating point in the transition between normal and superconducting state. The heater is also used to inject pulses which are needed for the energy calibration and for the determination of the energy threshold.
The experiment is based in the LNGS (Laboratori Nazionali del Gran Sasso) underground laboratory in central Italy. The underground location shields the experiment from cosmic radiation. A complete description of the experimental setup, data acquisition and readout is given in earlier publications [2, 3].

2. CRESST-II phase 2

The second long data-taking period of the CRESST-II experiment, referred to as phase 2, extended from July 2013 to August 2015. In this period 18 detector modules of four different designs were operated, corresponding to a total mass of 5 kg. The dark matter data acquired in the two years of measurement time is accompanied by calibrations with 122 keV γ-rays (^{57}Co-source), high-energy γ-rays (^{232}Th-source) and neutrons (AmBe-source).
In 2014 we reported on first results from phase 2, analyzing the detector module with the best overall performance in terms of background level, trigger threshold and background rejection [4]. This non-blind analysis proved that CRESST-II detectors provide reliable data for recoil energies down to the threshold of 0.6 keV [4]. As a consequence of this observation, we lowered the trigger thresholds of several detectors, achieving the lowest value of 0.3 keV with the module Lise. The results obtained from 52.2 kg days of data taken with the module Lise with its threshold set at 0.3 keV are reported in [5] and will be briefly outlined in the following.

3. Data set and data analysis

Differently from the module used for the 2014 result [4] which is equipped with the upgraded crystal holding scheme employing $CaWO_4$-sticks [6] and a self-grown crystal, the detector module Lise used for the result presented in [5] has a conventional design where metal clamps hold a commercially available crystal. It has to be stressed that the lower threshold of Lise is neither connected to the holding concept, nor to the intrinsic background level of the crystal, but arises from a superior performance of the phonon sensor.
The threshold of the detector is determined directly by injecting low-energy heater pulses with a shape similar to pulses induced by particle interactions and measuring the fraction causing a trigger. The result of this dedicated measurement is illustrated in figure 1.
The methods used for the analysis of the data are thoroughly described and discussed in [4, 5] and references therein. A blind analysis was carried out by first defining a statistically insignificant part of the data set as a training set, on which all methods of data preparation and selection are developed, that are then applied blindly without any change to the final data set. The validity of this approach is exhaustively discussed in [5]. The survival probability of the signal in the data selection is determined by performing the cuts on a set of artificial pulses with discrete energies. The fraction of signals with a certain simulated energy passing each cut yields the respective survival probability. Figure 2 illustrates the cumulative survival probability after each selection criterion.

All events surviving the selection criteria, corresponding to the 52.2 kg days of exposure of the detector Lise, are presented in figure 3 in the light yield - energy plane. The light yield is defined for every event as the ratio of light to phonon signal. Electron recoils have a light yield set to one by calibration (at 122 keV). Nuclear recoils produce less light than electron recoils. The reduction is quantified by the quenching factors for the respective target nuclei, which are precisely known from dedicated independent measurements [7]. In figure 3 the solid blue lines mark the 90 % upper and lower

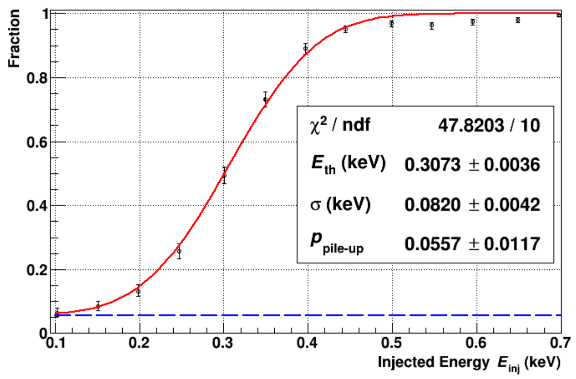

Figure 1. Fraction of heater pulses triggering, injected with discrete energies E_{inj}. The error bars indicate the statistical (binomial) uncertainty at the respective energy. The solid red curve is a fit with the sum of a scaled error function and a constant pile-up probability $p_{pile-up}$ (blue dashed line). The fit yields an energy threshold of $E_{th} = (307.3 \pm 3.6)$ eV and a width of $\sigma = (82.0 \pm 4.2)$ eV.

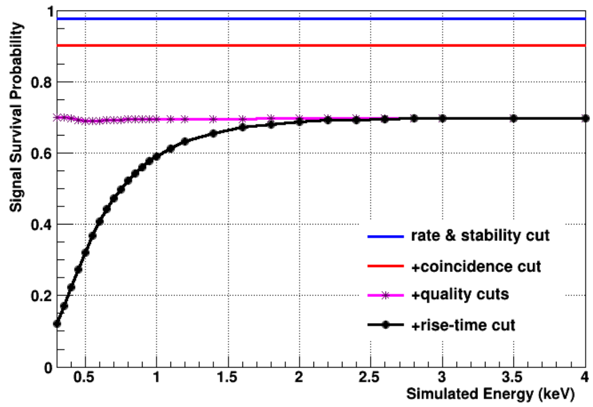

Figure 2. The solid lines represent the signal survival probability after successive application of the selection criteria. The simulated pulses correspond to nuclear recoil events at discrete energies starting from the threshold of 0.3 keV (data points).

boundaries of the e^-/γ-band, with 80 % of electron recoil events expected in between. From this band, with the knowledge of the quenching factors for the different nuclei present in the target material, the nuclear recoil bands for scatterings off tungsten, calcium and oxygen (respectively solid green, not shown and solid red in figure 3) can be analytically calculated.

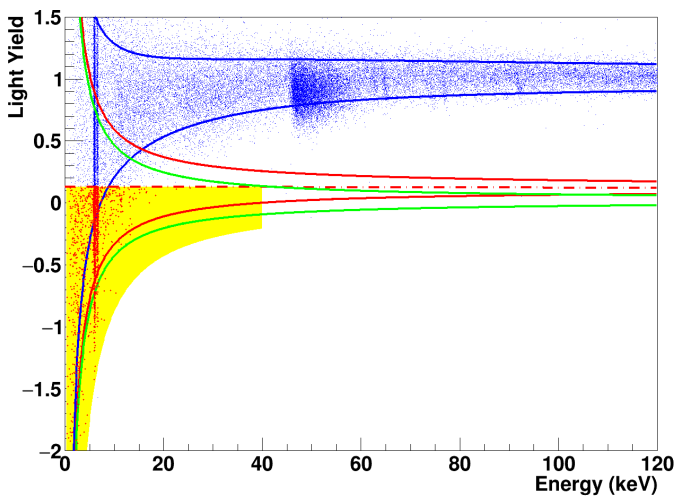

Figure 3. Data taken with the detector module Lise depicted in the light yield - energy plane. The solid lines mark the 90 % upper and lower boundaries of the e^-/γ-band (blue), the band for recoils off oxygen (red) and off tungsten (green). The upper boundary of the acceptance region (yellow area) is set to the middle of the oxygen band (dashed dotted red), the lower one to the 99.5 % lower boundary of the tungsten band. Events therein are additionally highlighted in red.

The e^-/γ-band exhibits two prominent features, a double-peak at ~ 6 keV originating from an

external ^{55}Fe-source and a β-decay spectrum from an intrinsic contamination of the crystal with ^{210}Pb starting at 46.5 keV.
The acceptance region for the dark matter analysis (yellow region in figure 3) extends in energy from the threshold of 307 eV to 40 keV and in light yield the from the 99.5 % lower boundary of the tungsten band to the center of the oxygen band (dashed-dotted red line in figure 3).
For the calculation of the exclusion limit all events inside the acceptance region (highlighted in red) are considered as potential signal events. This assumption is extremely conservative due to the clear large leakage of e^-/γ-events into the acceptance region, which is caused by the limited resolution of the light detector in use in this detector module.

4. Results and discussion

Using the Yellin optimum interval method [8, 9] to calculate an upper limit with 90 % confidence level on the elastic spin-independent interaction cross-section of dark matter particles with nucleons, the exclusion limit resulting from the blind analysis reported in [5] is drawn in solid red in figure 4. For dark matter particle masses higher than ~5 GeV/c^2 this module does not have a competitive sensitivity due to the large number of background events present in the acceptance region. However, for dark matter particles lighter than ~2 GeV/c^2 we explore new regions of the parameter space.

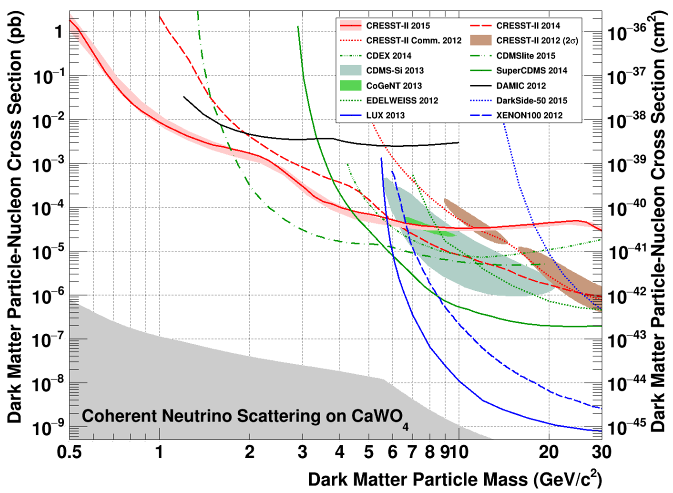

Figure 4. Parameter space for elastic spin-independent dark matter-nucleon scattering. The result from the analysis presented in [5] is drawn in solid red together with the expected sensitivity (1σ confidence level (C.L.)) from a data-driven background-only model (light red band). The remaining red lines correspond to previous CRESST-II limits [4, 10]. The favored parameter space reported by CRESST-II phase 1 [11], CDMS-Si [12] and CoGeNT [13] are drawn as shaded regions. For comparison, exclusion limits (90 % C.L.) of the liquid noble gas experiments [14, 15, 16] are depicted in blue, from germanium and silicon based experiments in green [17, 18, 19, 20, 21]. In the gray area coherent neutrino nucleus scattering, dominantly from solar neutrinos, will be an irreducible background for a $CaWO_4$-based dark matter search experiment [22].

The improvement with respect to the 2014 result [4] (red dashed line) is due to the significantly lower threshold of the detector Lise and to the almost constant background level down to the threshold. The result for the first time extends the reach of direct dark matter searches to dark matter particle masses down to 0.5 GeV/c^2.

5. Outlook

As outlined in [23], the current CRESST approach to obtain a sensitivity gain for low-mass dark matter particles consists in adopting small detector modules with an optimized detector layout.

For the upcoming CRESST-III both, phonon detector and light detector will be substantially reduced in size. The reduction of the crystal volume will allow to achieve lower energy thresholds and to increase the fraction of light reaching the light detectors. The latter, in combination with the enhanced resolution expected in the light detectors as a consequence of the reduced size, will increase the overall discrimination power.

The modules will feature an upgraded holding scheme analogous to the one described in [6] and will mainly be equipped with absorber crystals produced in-house, due to their significantly lower level of intrinsic radioactive contaminations [24, 25].

The results presented in [5] confirm that a low energy threshold represents a crucial requirement for direct dark matter searches aiming to achieve sensitivity to dark matter particles with masses in the 1 GeV/c^2 range and below.

Using next-generation detectors optimized towards the detection of recoil energies as small as 100 eV we expect from the CRESST-III experiment significant progress in the near future in the exploration of the low mass regime.

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