Direct Dark Matter Search with the CRESST-III Experiment

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Direct Dark Matter Search with CRESST

CRESST-I ($\text{Al}_2\text{O}_3$)

Heat

EDELWEISS, SuperCDMS (Ge)
CDMS-II (Si, Ge)

elastic DM particle-nucleus scattering

CRESST-II,III ($\text{CaWO}_4$)

Ionization
CoGeNT (Ge)
DarkSide (Ar)

Scintillation
LUX, XENON (Xe)
DAMA (NaI)
DEAP (Ar)
Cryogenic Rare Event Search with Superconducting Thermometers located at the Laboratori Nazionali del Gran Sasso (LNGS)

- target material: $\text{CaWO}_4$ single crystals
Working Principle of CRESST

Cryogenic Rare Event Search with Superconducting Thermometers located at the Laboratori Nazionali del Gran Sasso (LNGS)

- target material: CaWO$_4$ single crystals
- particle interaction
  - → heat (phonon) signal
  - read-out with thermometer
  - → light signal
  - read-out with light absorber + thermometer
Working Principle of CRESST

Cryogenic Rare Event Search with Superconducting Thermometers located at the Laboratori Nazionali del Gran Sasso (LNGS)

- target material: CaWO$_4$ single crystals
- particle interaction
  - $\rightarrow$ heat (phonon) signal
    read-out with thermometer
  - $\rightarrow$ light signal
    read-out with light absorber + thermometer
- reflective and scintillating housing
  - $\rightarrow$ maximize light collection
  - $\rightarrow$ veto surface events
Background Discrimination

energy deposition

> 90%  
phonon signal:  
precise energy measurement

< 10%  
light signal:  
dependent on type of interacting particle
Background Discrimination

Energy deposition:

- > 90%
- < 10%

**Phonon signal:**
- Precise energy measurement

**Light signal:**
- Depending on type of interacting particle

→ Active background discrimination on event-by-event basis:

\[
\text{Light Yield} = \frac{E_L}{E_{Ph}}
\]
Results of CRESST-II Phase 2 (2013-2015)

CRESST-II 2015:
1 detector – crystal mass $\sim 300 \text{ g}$ – exposure 52 kg days – threshold $\sim 300 \text{ eV}$

EUR PHYS J C Volume 76, Number 1 (2016)
Goal for CRESST-III

Goal:
increase performance via decreasing phonon detector threshold to $\sim 100$ eV

EUR PHYS J C Volume 76, Number 1 (2016)
CRESST-III Phase 1: Detector Modules

- crystal mass and dimensions: $\sim 24$ g, $(20 \times 20 \times 10)$ mm$^3$
- holding with CaWO$_4$ sticks
  $\rightarrow$ fully scintillating housing
- instrumented sticks (iSticks) for holding main crystal
  $\rightarrow$ veto for events happening in sticks

![Diagram of detector modules](image)
CRESST-III Phase 1: Installed Detectors

- 10 small detector modules installed
- Majority of CaWO$_4$ crystals produced at Technical University of Munich (TUM)

→ Data taking started in summer 2016
CRESST-III Phase 1: Thresholds

Detector module A

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware threshold</td>
<td>48 eV</td>
</tr>
<tr>
<td>Data taking period</td>
<td>31/10/16 - 05/07/17</td>
</tr>
<tr>
<td>Non-blind data set (dynamically growing)</td>
<td>20%</td>
</tr>
<tr>
<td>Total measuring time (blind)</td>
<td>2540 h</td>
</tr>
<tr>
<td>Total exposure after cuts</td>
<td>2.21 kg days</td>
</tr>
</tbody>
</table>

→ Analysis threshold for a ‘high-threshold analysis’: 100 eV

A. Münster (TUM)
CRESST-III Phase 1: Thresholds

detector module A

data taking period | 31/10/16 - 05/07/17
non-blind data set (dynamically growing) | 20 %
total measuring time (blind) | 2540 h
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→ analysis threshold for a 'high-threshold analysis': 100 eV
CRESST-III Phase 1: Detector Module A

exposure: 2.2 kg days

acceptance region: 100 eV $<$ Energy $<$ 40 keV

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CRESST-III Phase 1: Detector Module A

exposure: 2.2 kg days

acceptance region: 100 eV < Energy < 40 keV
CRESST-III Phase 1: Detector Module A

- **conservative assumption**: all accepted events are DM recoils
- **exclusion limit**: Yellin’s optimum interval method
→ improvement by one order of magnitude at 0.5 GeV/c²
→ reach of direct DM search experiments extended to 0.35 GeV/c²
Detector Module A: Exclusion Limit

\[ \text{improvement by one order of magnitude at 0.5 GeV/c}^2 \]
\[ \rightarrow \text{reach of direct DM search experiments extended to 0.35 GeV/c}^2 \]
CRESST-III Phase 2

Goal: improve radiopurity by a factor of 100

All steps of CaWO$_4$ crystal production take place at the TUM!

CaCO$_3$ $\rightarrow$ WO$_3$ $\rightarrow$ CaWO$_4$ crystal ingot $\rightarrow$ cut & polished crystal

$m \sim 800$ g  
h $\sim 130$ mm  
$\varnothing \sim 45$ mm
CRESST-III Phase 2

Goal: improve radiopurity by a factor of 100

All steps of CaWO$_4$ crystal production take place at the TUM!

- WO$_3$ → CaWO$_4$ → crystal ingot cut & polished crystal

- improve radiopurity via
  - chemical purification applied to dissolved raw materials → promising results
  - recrystallization as Czochralski crystal growth is cleaning process
Gram-Scale Calorimeters: Further Reduction of Threshold

- $\text{Al}_2\text{O}_3$ crystal ($m = 0.5$ g) operated above ground without shielding
- achieved threshold: 19.7 eV

→ sensitivity to a new range of MeV-scale DM
Conclusion

■ **CRESST-II Phase 2 (2013 - 2015)**
  - leading sensitivity for DM particle masses below $\sim 1.7\text{ GeV/c}^2$

■ **CRESST-III Phase 1 (since 2016)**
  - detector design optimized to search for DM particles below $\sim 1\text{ GeV/c}^2$
  - threshold goal of 100 eV achieved for 4 detectors
  - first DM analysis with partial data set of 1 detector (2.2 kg days)
    $\rightarrow$ one order of magnitude improvement at 0.5 GeV/c$^2$
    $\rightarrow$ sensitivity extended down to 0.35 GeV/c$^2$

■ **CRESST-III Phase 2**
  - goal: improve radiopurity
  - promising results achieved by purification of the raw materials for CaWO$_4$ crystal production
Thank you for your attention!
The CRESST Experiment: Setup

- cryostat
- muon veto
- radon box
- Pb
- Cu
- PE
- cold finger
- detector carousel
Transition Edge Sensor (TES)

\[ \Delta T \]

\[ \Delta R \]

Temperature [mK]

Resistance [mΩ]

10

\[ \Delta T \]

Temperature [mK]
Production of CaWO₄ Powder

**raw materials:** selected CaCO₃, WO₃ powders

**Solid State Reaction**

\[
\text{CaCO}_3 + \text{WO}_3 \rightarrow \text{CaWO}_4 + \text{CO}_2 \uparrow
\]

Al₂O₃ crucible – dedicated furnace – (1100 - 1200) °C – 2 repetitions

**Precipitation Reaction**

\[
\text{Ca(NO}_3)_2 + (\text{NH}_4)_2\text{WO}_4 \rightarrow \text{CaWO}_4 \downarrow + 2 \text{NH}_4\text{NO}_3
\]

CaCO₃ and WO₃ dissolved in HNO₃ and NH₃ – quartz ware – dropping into NH₃ host solution
Purification of Raw Materials

**liquid-liquid extraction**
- Extractant: trioctylphosphine oxide (TOPO)

**coprecipitation**
- Precipitate: CaWO₄
Crystal Growth via Czochralski Method

- melt CaWO₄ powder in Rh crucible of Czochralski furnace
- lower seed crystal into CaWO₄ melt
- draw in z direction under rotation
  ⇒ Formation of a cylindrically shaped crystal with crystallographic orientation of seed crystal
Fully Scintillating Housing: Veto of Surface Backgrounds

![Graph showing light yield vs. energy with Foil Events tagged by pulse shape.](arXiv:1410.1753)
CRESST-III Phase 1: Neutron Calibration
CRESST-III Phase 1: 100 eV Pulse

Detector Module A: Hardware Trigger Efficiency

\[ \chi^2 / \text{ndf} = 49.446 / 25 \]
\[ E_{\text{thr}} = (48.3 \pm 0.6) \text{ eV} \]
\[ \sigma = (10.8 \pm 0.7) \text{ eV} \]
\[ P = (0.0373 \pm 0.0134) \]
Detector Module A: Software Trigger Efficiency

typical baseline trace

Analytical description of amplitude distribution in empty baselines
Detector Module A: Software Trigger Efficiency

optimum filter (Gatti-Manfredi filter)

→ maximizes the ratio between pulse amplitude and noise RMS

allow 1 count/(kg day) of noise distribution after optimum filter
- Maximum gap method: Consider largest gap (0 events observed)
- Optimum interval method: Consider largest interval with certain number of events observed