Search for low-mass dark matter with the CRESST-III experiment

Holger Kluck

on behalf of the CRESST collaboration

UCLA Dark Matter 2018 symposium
February 21-23, 2018
Outline

• CRESST basics: How the experiment works

• Searching for low-mass DM with CRESST-III
CRESST basics
Search for low-mass dark matter with the CRESST experiment

The CRESST collaboration
The CRESST experiment

- Target: CaWO$_4$ @ O(10mK)
- Signature: recoiling nucleus induced by scattering off dark matter particle
The CRESST experiment

- **Target:** CaWO$_4$
- **Signature:** recoiling nucleus
- **Phonon signal:** measurement of recoil energy

\[ \Delta E/C = \Delta T \]

1keV $\sim$ 1µK
The CRESST experiment

- Target: CaWO$_4$
- Signature: recoiling nucleus
- Phonon signal: energy
- Read-out by a TES (transition edge sensor)
The CRESST experiment

- Target: CaWO$_4$
- Signature: recoiling nucleus
- Phonon signal: energy
- Read-out by a TES
- Scintillation light signal: separated detector inside a reflective & scintillating housing, particle dependent
The CRESST experiment

- Target: CaWO$_4$
- Signature: recoiling nucleus
- Phonon signal: energy
- Read-out by a TES
- Scintillation light signal: particle dependent

→ Particle identification
Search for low-mass dark matter with the CRESST experiment

The CRESST experiment

![Graph showing light yield versus energy for different elements: W (tungsten), Ca (calcium), O (oxygen), and α (alpha particles). The graph is normalized to 1 by calibration and indicates quenched light for nuclear recoils.]

- Light yield = light signal/phonon signal
- Energy / keV
- Normalized to 1 by calibration
- Quenched light for nuclear recoils

February 23, 2018
Search for low-mass dark matter with the CRESST experiment

The CRESST experiment

Discrimination between
- electron recoils, i.e. dominant radioactive background
- nuclear recoils, i.e. potential DM signal

Light yield = light signal/phonon signal

Energy / keV
Searching for low-mass DM with CRESST-III
Results of CRESST-II phase 2

[Figure showing dark matter particle mass and cross section]
Search for low-mass dark matter with the CRESST experiment

Results of CRESST-II phase 2


- TUM40: successfully reduced intrinsic background

Coherent Neutrino Scattering on CaWO$_4$

February 23, 2018
Results of CRESST-II phase 2

- TUM40: successfully reduced intrinsic background
- Ongoing modelling of em. background with Geant4
Search for low-mass dark matter with the CRESST experiment

Results of CRESST-II phase 2


- TUM40: successfully reduced intrinsic background
- Low-mass search → low threshold
  Lise: 307eV

aka 'Lise'

Coherent Neutrino Scattering on CaWO₄

Dark Matter Particle Mass (GeV/c²) vs. Dark Matter Particle-Nucleon Cross Section (pb)
Search for low-mass dark matter with the CRESST experiment

Results of CRESST-II phase 2

- TUM40: successfully reduced intrinsic background
- Low-mass search $\rightarrow$ low threshold Lise: 307eV
- $\rightarrow$ combine both in CRESST-III

[Image: Graph showing dark matter particle mass vs. cross section, with TUM40's reduced intrinsic background highlighted.]
Optimized detector design

Detector design optimized for low-mass dark matter:

- cuboid crystal with strongly reduced dimension: \((20 \times 20 \times 10)\) mm\(^3\) and \(\approx 24\) g
- goal: detection threshold of 100 eV
- self-grown crystal with low total background of \(\approx 3\) keV\(^{-1}\)kg\(^{-1}\)d\(^{-1}\) in [1,40] keV
- veto against surface related background: fully scintillating housing + instrumented sticks (“iSticks”)
Status of CRESST-III phase 1

- May 2016: 10 CRESST-III modules installed
- Oct 2016: extensive $\gamma$-calibration
- Since Nov 2016: data taking (80% blinded, 20% training set)
- ~April 2017: extensive n-calibration
- July 2017: first results @TAUP2017
Threshold

- New DAQ in CRESST-III: continuous sampling of pulse traces
- Set threshold based on noise distribution after optimum filter

Amplitude distribution of a typical empty base line pulse trace

Analytical description of amplitude distribution

22.6 eV

26.1 eV
First results from CRESST-III phase 1

![Graph showing threshold values for different detectors (A, B, D, E, J). The design goal is indicated with a dashed line.]
Detector A high threshold analysis:

**Analysis threshold:** 100 eV

Data taking period: 2016-10-31/2017-07-05

Detector mass: 24 g

Total exposure: 2.39 kg d
Detector A: neutron calibration
Search for low-mass dark matter with the CRESST experiment

Detector A: physics data

[arXiv:1711.07692]
Detector A: energy spectrum

Average background $[1,40]$ keV: $\sim 3.5$ kg$^{-1}$ keV$^{-1}$ d$^{-1}$
$\Rightarrow$ same as in TUM40
Search for low-mass dark matter with the CRESST experiment

Detector A: energy spectrum

$^{179}\text{Ta} + e^- \rightarrow ^{179}\text{Hf} + \nu_e$ ($T_{1/2}=1.8\text{yr}$)

M-shell 2.6 keV

L-shell 11.3 keV

[arXiv:1711.07692]
Detector A: acceptance region

- 50% O recoils below 99.5% W recoils above

[arXiv:1711.07692]
Search for low-mass dark matter with the CRESST experiment

Detector A: accepted events

Counts

[arXiv:1711.07692]

Energy [keV]

All Events

Events in ROI
Assume all accepted events are dark-matter caused
→ Use Yellin’s optimum interval method to set an exclusion limit
Search for low-mass dark matter with the CRESST experiment

Detector A: exclusion limit

Dark Matter Particle-Nucleon Cross Section (pb) vs. Dark Matter Particle Mass (GeV/c^2)

[arXiv:1711.07692]
Search for low-mass dark matter with the CRESST experiment

Detector A: exclusion limit

',Detector A' (CRESST-III 2017)

Total exposure: 2.39 kg d
Threshold: …… 100 eV

'Lise' (CRESST-II 2016)

Total exposure: 52.2 kg d
Threshold: …… 307.3 eV

[arXiv:1711.07692]
Search for low-mass dark matter with the CRESST experiment

Detector A: exclusion limit

Factor 10 improvement at 500 MeV/c²

[arXiv:1711.07692]
Detector A: exclusion limit

Experimental range extended down to 350 MeV/c²
Detector A: limitations

Detector A: 2.39 kg d
TAUP 2017

CRESST-III phase 1: projection for 50 kg d

[arXiv:1711.07692]
Search for low-mass dark matter with the CRESST experiment

Detector A: limitations

Non-flat background at threshold
Summary

• **First** results of CRESST-III phase 1: detector A
  – 100eV-analysis
  – x10 improvement @ 500 MeV/c²
  – extend range down to 350 MeV/c²

• but that is **not the end**:
  – continue data taking → better understanding of backgrounds
  – 3 more detectors with threshold $\ll 100\text{eV}$
  – 3 times lower optimum threshold for detector A

→ **New frontiers: new potentials & new challenges!**
Above ground limit
Additional slides
The CRESST experiment

Located in Italy, under the Gran Sasso mountain, at the LNGS @ ~3600mwe

μ's  \( \sim 3 \cdot 10^{-8} \text{ s}^{-1} \text{ cm}^{-2} \)

γ's  \( \sim 7 \cdot 10^{-1} \text{ s}^{-1} \text{ cm}^{-2} \)

n's  \( \sim 4 \cdot 10^{-6} \text{ s}^{-1} \text{ cm}^{-2} \)

Active μ veto

γ shield: 20cm Pb

14cm Cu against background from Pb

n shield: 45cm PE + inner PE

Cryostat
CRESST-III: detectors

- G-LD: no transition
- I-all: no transitions
- B- one iStick: heater broken cannot be operated
- C and D - iStick system: working, but introduces strong noise on phonon channel

6/50 TES not working (including the 5 of detector I)
- The wiring is >10 years old
- A TES is a sensitive but challenging device
Search for low-mass dark matter with the CRESST experiment

100 eV-pulses
Optimum filter

Pulse-height evaluation with optimum filter:

The Gatti-Manfredi filter maximize the ratio between the amplitude of the treated pulse and the noise RMS

Resolution typically improved by factor 2 to 3
Detector A: selections & efficiencies

Remove pulses where a correct determination of the amplitude is not guaranteed. Designed on non blind data (20% of physics data randomly selected) not included in the final exposure.

- Data quality events which cannot properly be analyzed
- Pulse shape e.g. events in iSticks, pileup
- Coincidences here: only with muon veto and iSticks

73.6% @ threshold
DAQ
Search for low-mass dark matter with the CRESST experiment

DAQ

Standard (high threshold) dark matter analysis

Classic DAQ

Pulses
Empty baselines

Template
Fit/ Energy determination
Cuts

Spectrum
Efficiency

Continuos DAQ

Data

Transfer function
Threshold analysis

Threshold
Trigger efficiency

Pulses
Empty baselines

Threshold analysis and low threshold dark matter analysis
Holder-related backgrounds

- Target is held by $\text{CaWO}_4$ sticks
Holder-related backgrounds

- Target is held by CaWO$_4$ sticks
- Event in stick: surface background, relaxation, …
Holder-related backgrounds

- Target is held by CaWO$_4$ sticks
- Event in stick: surface background, relaxation, …
- Signal in instrumented stick (iStick)
Holder-related backgrounds

- Target is held by CaWO$_4$ sticks
- Event in stick: surface background, relaxation, …
- Signal in instrumented stick (iStick)
- Degraded signal in target
Holder-related backgrounds

- Target is held by CaWO$_4$ sticks
- Event in stick: surface background, relaxation, …
- Signal in instrumented stick (iStick)
- Degraded signal in target

$\Rightarrow$ iStick/target is a powerful tool to reject holder-related backgrounds
‘TUM40’ radiopurity

- CaWO$_4$ crystal production at TU Munich
- TUM40: radiopurity improved by factor 2-10

Commercial crystal TUM40

$^{179}$Ta L1(EC) $^{227}$Ac $^{210}$Pb

~3.5 counts/kg.d keV on average
Going beyond ‘TUM40’ radiopurity

- Cleaning procedure e.g. by re-crystallization, chemical purification of raw materials
- Recently: First steps in chemical purification of CaCO$_3$ powder.

*work by H.H. Trinh Thi, A. Münster, A. Erb*
Going beyond ‘TUM40’ radiopurity

- Cleaning procedure e.g. by re-crystallization, chemical purification of raw materials
- Recently: First steps in chemical purification of CaCO$_3$ powder. (work by H.H. Trinh Thi, A. Münster, A. Erb)
- Measured contamination decreased by …
  - factor 2-7 for Th
  - factor 15-35 for U
Search for low-mass dark matter with the CRESST experiment

Outlook to CRESST-III phase 2

Phase 2: 1000 kg.d
- 100 modules x 2 yr
- Reduce background by a factor of ~100

Coherent Neutrino Scattering on CaWO₄

[arXiv:1503.08065]
Dark photon limits

[Graph showing the relationship between kinetic mixing $\kappa$ and dark photon mass $m_\gamma$ with various experimental constraints from DAMIC, XENON10, XENON100, and CRESST-II Phase 2. The graph highlights limits on dark photon interactions based on observations from different experiments and theoretical predictions.]

---

Search for low-mass dark matter with the CRESST experiment

February 23, 2018

Search for low-mass dark matter with the CRESST experiment

U/Th background modelling

Sideband measurement: $\alpha$-activity, e.g.

$^{220}\text{Rn}$

Piecewise equilibrium between $\alpha/\beta$ emitter

Scale each simulated $\beta$ spectrum individually
EURECA

- Coordinated effort for a joint next generation DM search
- ~100 members from 23 institutes, including CRESST + EDELWEISS
- Cooperation with SuperCDMS on …
  - exp. site: study possibilities to install future EURECA detectors at SNOLAB
  - common tower infrastructure
  - electronic development
  - background simulation: geometries of potential EURECA detectors fully implemented in SuperCDMS’ Geant4 code “SuperSIM”