Neganov-Luke Amplified Cryogenic Light-Detectors: Current Status and Future Applications

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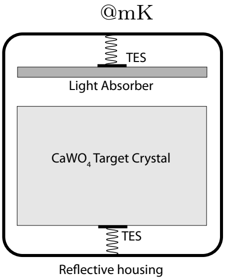
Michael Willers
Excellence Cluster Universe & Physik-Department E15
Technische Universität München

Cryogenic Light Detectors (CRESST & EURECA)

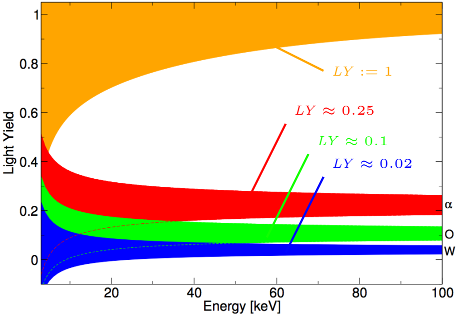
- **Cryogenic light detector:** Semiconductor absorber operated at cryogenic Temperatures ($\mathcal{O}$(mK)), thermal signal read-out with thermometer (**TES**, NTD, MMC)
- Absorber materials: **Si**, Ge, SOS (Silicon on Sapphire)
- Good radiopurity (& active detector), large area

→ Background suppression in rare event search experiments by detecting phonon & light signal!

→ Separation of signal and background evts. via Light Yield

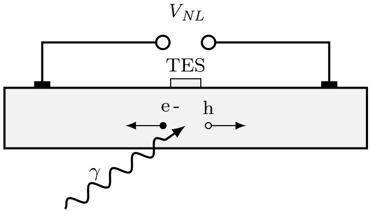


$$LY = \frac{E_{light}}{E_{CaWO_4}}$$



Neganov-Luke Effect

Amplification of thermal signal by drifting electrons & holes in a semiconductor absorber in an applied electric field [1].

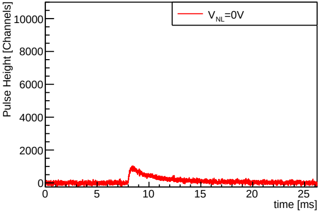


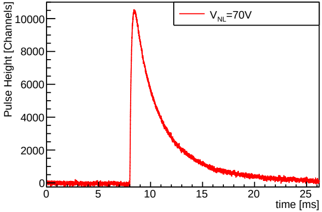
$$E_{tot} = G_{th} \cdot E = \left(1 + \frac{eV_{NL}}{\epsilon}\right) \cdot E$$

$$\epsilon = E_{ph}/\eta$$

(Energy required to create e-h pair)

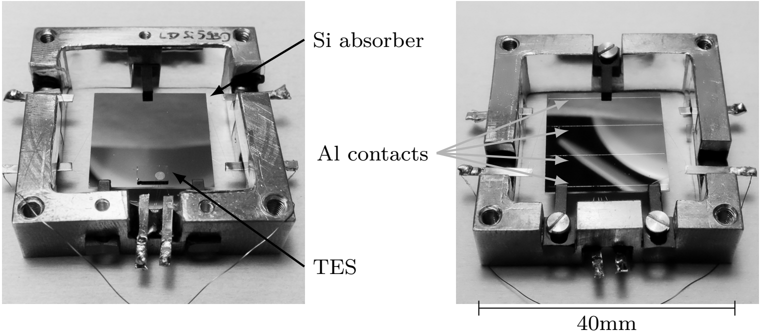
→ Signal amplification **and** improvement in S/N ratio!





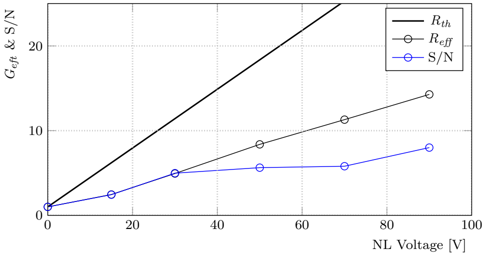
Fabrication

- High-purity p-type Silicon ($\rho > 10\,\mathrm{k\Omega}$) absorber (here: $20 \times 20 \times 0.5\,\mathrm{mm}$).
- Aluminum strips (electrodes) produced via photolithographic lift-off process. (Application of photoresist (PR), baking, UV exposure, developing of PR, deposition of Al, removal of PR & cleaning of substrate)
- Natural oxide layer removed by Ar-etching, Al deposited via EBE or sputtering.
- Substrate + contacts annealed in forming gas.
- TES carrier glued to substrate (EpoTek 301-2).
- TES & Al strips contacted by wire bonding (25μm Al).



Challenges

Amplification (G_{th}) lower than predicted



→ Reduced drift length: charge carriers trapped before reaching electrodes

$$G_{eff} = 1 + \frac{e \cdot V_{NL}}{\epsilon} \cdot \frac{l}{d}$$

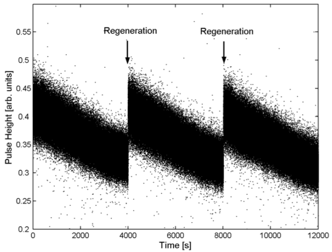
→ Trapping in impurities / defects close to the absorber surface.

→ Achieved amplification varies between devices!

⇒ Possible solution: production process without photolithographic step.
(Structuring with shadow mask currently under investigation)

Challenges

Amplification reduced over time



Initially [2]:
Drift: 20% in $\sim$ 1h
(@ 50keV/s)

$\rightarrow$ Charge carriers trapped (accumulate) near / below aluminum contacts.

$\rightarrow$ effective electric field is reduced:

$$V_{NL} \rightarrow V_{eff,NL}(t)$$

Regular regeneration necessary!
(turn off V_{NL}, flush detector with light, turn on V_{NL})

$\Rightarrow$ **Behavior improved by annealing of substrate / contacts!**
Healing of defects induced during manufacturing.
(Greatly reduced drift / no drift (currently under investigation))

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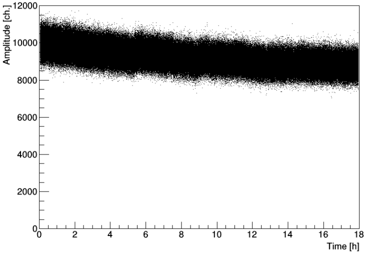
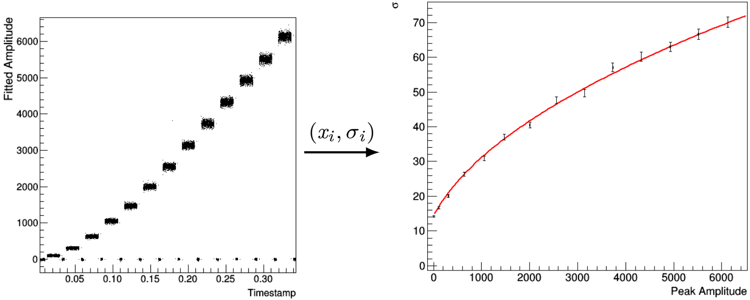


Now:
Drift: 10% in 18h
(@ 50keV/s)

Calibration ($V_{NL} = 0\,\mathrm{V}$)

→ Calibration via "LED Calibration Technique"
(LED mounted outside of cryostat @ room temperature)

- Detector illuminated by light-pulses of variable intensity.
  (λ_{LED} can be chosen to match e.g. scintillation light of crystal.)



- Calibration function (lin. response $x = a \cdot N$ & photon stat. $\sigma_{ph} = a \cdot \sqrt{N}$):

$$\sigma_{tot}^2 = \sigma_{ph}^2 + \sigma_{el}^2 + \sigma_{tr}^2 + \sigma_{pos}^2 + \ldots = \sigma_0^2 + \sigma_{ph}^2 \quad \rightarrow \quad \sigma_{tot} = \sqrt{\sigma_0^2 + a \cdot x}$$

⇒ **Scaling factor a & threshold σ_0 (here: $\sigma_0 \approx 50\,\mathrm{eV}$)**

Calibration (with applied V_{NL})

In ideal case: signal is amplified $x_{NL} = A \cdot x$.

$\rightarrow$ $\sigma_{tot,ideal} = \sqrt{\sigma_0^2 + a \cdot A \cdot x}$

$\Rightarrow$ ideal calibration function does not describe data!

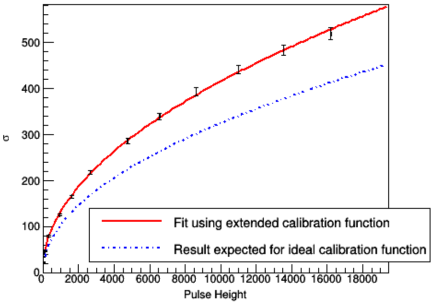
$\Rightarrow$ Extended calibration function [3]:

$$\sigma_{tot} = \sqrt{\sigma_0^2 + \sigma_{NL}^2 + a \cdot A \cdot x + b \cdot x + c \cdot x^2}$$

$\sigma_{cc} = \sqrt{b(V_{NL}) \cdot x} \propto \sqrt{N}$: accounts for incomplete charge collection (trapping)

$\sigma_{rc} = \sqrt{c(V_{NL}) \cdot x^2} \propto N$: accounts for possible recombination of charge carriers.

$\Rightarrow$ Fitting new model to data $\rightarrow$ good agreement! (here: $\sigma_0 + \sigma_{NL} \approx 9\,\mathrm{eV}$)



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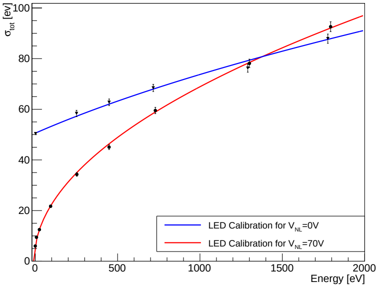


$\rightarrow$ Improvement in resolution below $\sim 1\,\mathrm{keV}$ light energy!

$1\,\mathrm{keV} \approx 70\,\mathrm{keV}\,e^-$ - recoil

$\approx 700\,\mathrm{keV}$ O - recoil

$\approx 3.5\,\mathrm{MeV}$ W - recoil

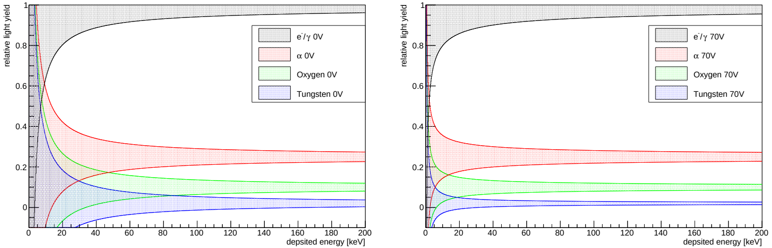
$\Rightarrow$ **Improvement in energy range relevant for DM search.** (Current performance comparable to detectors used in CRESST)

Applications

Improvement of background suppression in $CaWO_4$

→ Improved separation of e^-/γ and nuclear recoils possible.

→ Improved separation of between different nuclear recoils possible.



(calculated 80% LY bands for detector shown on prev. slide)

⇒ Next step: test NL detectors in realistic low-background environment.

Applications

Detectors initially developed for DM search, but other applications possible:

Background suppression in $0\nu\beta\beta$ experiments using TeO_2

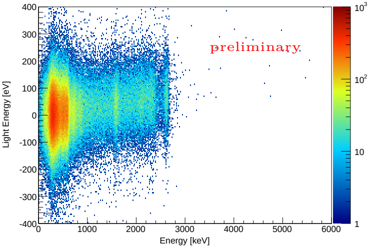
(or other non-scintillating crystals.)

→ Suppression of e^-/γ from α events via Cherenkov light.

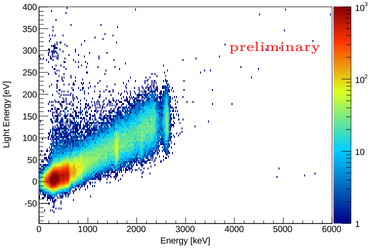
@ $Q_{\beta\beta}(^{130}\mathrm{Te})$ ($= 2.53\,\mathrm{MeV}$): $\approx 450\,\mathrm{eV}$ emitted in Cherenkov light!

Cherenkov threshold: $\sim 50\,\mathrm{keV}$ for e^- and $\sim 400\,\mathrm{MeV}$ for α

$V_{NL} = 0\,V$



$V_{NL} = 70\,V$



Conclusion & Outlook

- Improvement of resolution in energy range relevant for rare event searches.
- Neganov-Luke amplified cryogenic light-detectors have great potential to further improve the background suppression in cryogenic rare event searches. (CRESST, EURECA & possible future $0\nu\beta\beta$ experiments)
- Reduced overall-amplification currently under investigation.
- Great improvements concerning the reduction of G_{eft} over time achieved.

→ further room for improvement → under investigation.

→ Goal: no regeneration necessary!

- New calibration function to described behavior with applied V_{NL}

⇒ Next step: Further investigation of improved production process & annealing.

⇒ Next step: Test NL detectors in realistic low-background environment.

Acknowledgments

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Thank you for your attention!

References

[1] P. N. Luke, "Voltageassisted calorimetric ionization detector," Journal of Applied Physics, vol. 64, p. 6858, 1988.

[2] C. Isaila et al., "Low-temperature light detectors: Neganov–luke amplification and calibration," Physics Letters B, vol. 716, pp. 160–164, 2012.

[3] S. Roth, The Potential of Neganov-Luke Amplified Cryogenic Light Detectors and the Scintillation-Light Quenching Mechanism in CaWO4 Single Crystals in the Context of the Dark Matter Search Experiment CRESST-II. PhD thesis, Technische Universität München, 2013.