Transition Edge-Sensor for ALPS: A superconducting microcalorimeter for detecting NIR-photons

Jan Dreyling-Eschweiler, for the ALPS-II collaboration

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Any Light Particle Search (ALPS) at DESY – Light-Shining-through-a-Wall?

ALPS-I: \( \gamma_{\text{in}} \sim 10^{21} \text{1/s} \)

\[ \gamma_{\text{meas}} = (2 \pm 13) \times 10^{-3} \text{1/s} \]


Axion-like particle specs:

- sub-eV mass, weakly interacting with SM
- could explain:
  - TeV transparency (Horns group, UHH)
  - CDM candidate
  - . . .
- \( g_{a\gamma} < \frac{1}{BL} \sqrt{\frac{\gamma_{\text{out}}}{\gamma_{\text{in}} \times \epsilon}} \frac{1}{F(...)} \)
ALPS-II – lower the limit!

\[ ga \gamma < \frac{1}{BL} 4\sqrt{\frac{\gamma_{\text{out}}}{\gamma_{\text{in}} \times \epsilon}} \frac{1}{F(...)} \]

specs of ALPS-I
- laser: 532 nm
- length: 2×5 m

power-ups of ALPS-II
- length: up to 2×100 m
- regeneration cavity
- laser power (1064 nm)

What’s new in ALPS-II: arXiv:1309.3965
Detectors for ALPS-I and ALPS-II

ALPS asks for...

- **Challenge:** detection of low rates (<1/h) single photons (∼1 eV)

- **Requirements:** High efficiency and low (dark) noise

**Si-CCD:**

+ QE >90% (532 nm)
+ DC ∼ 10^{-3}/s
  - 1 h frames at ALPS-I
+ ready to use
  - QE <1.2% (1064 nm)

**TES (from NIST/AIST):**

+ QE >95% (1064 nm)
  - DC <1/s, but no details
+ time/energy res. ∼1μs/0.1 eV
  - sensor availability
  - mK cryogenics

...how does a TES work?
(Superconducting) Transition-Edge Sensor (TES) . . .

...is a calorimeter with...

(a) ![Diagram of a calorimeter setup](image)

(b) ![Diagram of temperature decay](image)

\[ \Delta T = E/C \]

\[ \tau = C/G \]

\[ \tau_{\text{eff}} = \tau/(1 + \alpha/n) \]

(c) ![Diagram of set point and normal superconductive states](image)

\[ \alpha = \frac{T}{R} \frac{dR}{dT} \]

(d) ![Diagram of energy calculation](image)

\[ E = V \int \Delta I dt \]
... negative electro-thermal feedback

P.A.J. De Korte et al., Tes x-ray calorimeter-array for imaging spectroscopy.
Setting up a TES detector for ALPS

Very brief history

- 2011: gaining experience (Trieste, Camerino, Berlin, . . . ) and connecting to small TES-community
- 2012: 30 mK in ALPS-IIa lab, DESY
- 2013: 1064 nm single photons and more . . .

TES detector for ALPS:

- **Sensor:** high-efficient fiber-coupled TES from NIST
- **Read-out:** low-noise SQUIDs from PTB
- **mK-cryogenis:** cryostat from Entropy GmbH
Sensor: TES and SQUID

- **NIST:**
 (chip development over 10 years)

- **TES chip (NIST):**
  - Tungsten (W) film: $T_c \sim 140$ mK
  - sensitive area (volume): $25 \times 25 \ \mu m^2 \ (\times 20 \ \text{nm})$
  - multilayer structure:
    QE $>99 \%$ for 1064 nm

- **Optics:** sleeve to connect single mode fiber (losses $<1 \%$)

- **SQUID chip (PTB) for read-out**
  - Superconducting QUantum Interference Device
  - PTB-Berlin (“Kryosensoren”)
  - noise: $2.5 \ \text{pA}/\sqrt{\text{Hz}}$ (TES noise: $7.0 \ \text{pA}/\sqrt{\text{Hz}}$)

- **module with two channels**
  (scale $\sim 3\text{cm} \times 3\text{cm}$)
Read-out: Converting energy in a voltage output

- $\Delta 1064 \text{ nm} = 1.17 \text{ eV}$
- ↓ absorption
- $\Delta \sim 0.1 \text{ mK}$
- ↓ superconducting transition (TES)
- $\Delta R_{\text{TES}} \sim 1 \Omega$
- ↓ TES electrical circuit
- $\Delta I_{\text{TES}} \sim 70 \text{ nA}$
- ↓ inductive coupling
- $\Delta n\Phi_0$ flux quantum level (SQUID)
- ↓ transformation and amplification
- $\Delta V_{\text{out}} \sim 50 \text{ mV}$
mK-cryogenics: Compact cryostat

- 2nd cryostat from Entropy
- Vacuum dewar (70x33 cm) in a moveable trolley
- Pre-cooling by pulse-tube cooler
  - He4 cycle (20 l at 17.2 bar)
  - water and heavy current
- from 300 K to 2.5 K: in \( \sim 24 \) h
Adiabatic Demagnetization Refrigerator (ADR)

entropy $S$ depends on $T$ and $B$

$\begin{array}{c}
\text{paramagnetic salt pills (spin-system) with 6 T magnet} \\
\rightarrow 2.5 \text{ K to 30 mK: 1-2 h} \\
\rightarrow T_{\text{bath}} = 80 \text{ mK } \pm 25 \mu \text{K (rms) for 24-60 h}
\end{array}$
Ready for signals!?

- Assembling all in the warm and getting cold... wait 24 h
- Check Cryogenics: \( T_{\text{bath}} = 80 \text{ mK} \) or heat switch problems?
- Check SQUID: Quiet environment? Ready for read-out!
- Check TES: Superconductive? Working point!
Signals: 1066.7 nm single photons

1064 nm photon = 1.17 eV event:

- rms < 5 mV
- peak\text{\_average} \approx 50 \text{ mV}
- integral\text{\_average} \approx 120 \text{ nVs}
- rise time \approx 0.2 \mu s
- fall time \approx 4.6 \mu s
- energy resolution: < 8 \%

Peak height = -49.7 mV
Integral average = 119.0 nVs
Rise time \approx 0.15 \mu s
Fall time \approx 4.60 \mu s
2D signal region: integral-peak-plot

Offline: TL -20mV, DT 15μs, sample 1s

- σ = 4.1 ± 0.2 mV
- μ = 52.4 ± 0.2 mV
- ∆E/E = 0.078 ± 0.004

Single photon source:
- ~70 dB attenuated 10μW laser
- Signal rate ≃ 1000/sec
- 1 s sample → 1000 photons
Background with no fiber: TES sees 80 mK

- 14 h measurement
- rate (3σ region): $9.8 \times 10^{-5}$/sec
- no events induced by SQUID
Background with “dark” fiber end at 300 K

- 16 h measurement
- rate (half 3σ region): 42 sec/# → 2.4×10^{-2}/sec
- lighttight ADR
- thermal photons from fiber
Summary and Outlook

Summary

- **ALPS-II**
  - is a light-shining-through-a-wall experiment
  - searching for weakly interacting sub-eV particles
- **TES** is a microcalorimeter
  - with high efficiency for NIR-photons
  - but needs a lot of effort
- 1064 nm signals are well detected, but 300 K background is an issue!

Outlook

- Measure detector efficiency
- Reduce thermal background:
  - Advanced analysis and bandpass filter
- Data of ALPS-IIa in 2014, ALPS-IIc (200 m) in 2017.