Radioactivity induced dark count rate for single near-infrared photon detection with a tungsten transition edge sensor at 80 mK

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Abstract. The intrinsic background count rate of tungsten superconducting transition-edge sensors (TES) is low, and the calorimeters using these sensors can resolve the energy of single photons. These facts make the sensors particularly interesting for the background-limited searches of new processes and particles. In this contribution, the intrinsic background of a tungsten TES has been investigated. After excluding other sources (e.g., cosmic muons, thermal background) to be relevant for the observed background rate of $10^{-4}$ s$^{-1}$ for the detection of photons with a wave length of 1064 nm, we investigate the impact of natural radioactivity. Dedicated measurements using gamma-emitters mounted outside the cryostat have been used to estimate the sensitivity of the TES setup for ionizing radiation. We have found that indeed an increased background can be observed in the presence of the radioactive sources. After selecting events which populate our signal region tuned for single photon detection at near-infrared, roughly 0.5% of the events produced by gamma-rays appear indistinguishable from those due to single photons with 1064 nm wave length. This ratio is consistent with that observed for the residual background detected with the TES at a rate of $10^{-4}$ s$^{-1}$. From this, we conclude that the bulk of the observed background count-rate in the signal region can be explained by natural radioactivity.

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1. Introduction

The development of single-photon and photon-number resolving detectors has been largely driven by the field of quantum information science and metrology (see Fig. 1 in Eisaman et al. (2011)). While in these applications, the requirements of e.g., high count-rate and high efficiency are most important, searches for rare processes benefit from minimized instrumental background. Recently, an experiment has been proposed to search for new light fundamental bosons Bahr et al. (2013) (see the same reference for an in-depth discussion of the underlying physics of axion-photon mixing and the experimental setup). A crucial component of the experiment is a low-background (required dark count rate of $10^{-6} \text{s}^{-1}$) and highly efficient (required overall detection efficiency of 75 %) single-photon detector sensitive at a wave length of 1064 nm. While the required detection efficiency has been demonstrated in previous studies (Lita et al. 2008), the dark count rate of a TES exceeds the requirement: In a previous study of the same sensor as used here (a 25 µm square and 20 nm thick tungsten film) a dark count rate of $10^{-4} \text{s}^{-1}$ had been found (Dreyling-Escheiler et al. 2015).

Here, we investigate the intrinsic dark count rate of a TES in order to clarify the origin of the measured dark count rate. The paper is structured as follows: in the next section, we describe the experimental setup and list the potential origin of dark counts. In Section 3, we give a summary of the measurements carried out followed by Section 4, where the results are interpreted. We conclude on potential approaches to reduce the background further.

2. Experimental setup

The structure of the TES consists of a 20 nm thick layer of W sandwiched in a dielectric stack consisting of 2 nm amorphous Si and 127/132 nm layers of SiNx on top of a 80 nm thick Ag coating. The stack is optimized to reduce the relative reflectance to 0.32 % at $\lambda =1064 \text{ nm}$. The reflectance slowly rises to larger values for $\lambda < 800 \text{ nm}$ and $\lambda > 1500 \text{ nm}$. The active area is a square with 25 µm side length. It resides on a silicon substrate of 275 µm thickness and diameter of 2.5 mm (see Fig. 1 left panel for a photography and a sketch of the assembly mounted on the cold finger). The silicon substrate fits inside a zirconium sleeve which provides a defined connection to a single mode fiber held in a zirconium ferrule. However, in the setup considered here, the sleeve is empty.

The TES is stabilized at its transition temperature of 80 mK via negative thermo-electric feed-back. The TES is read-out via a two-stage squid optimized to operate in typical ambient magnetic field of $10^{-4} \text{T}$ (Drung et al. 2007). The resulting signals are digitized and stored.
using a digital oscilloscope. The TES is mounted inside a cryostat cooled by a two-stage pulse-tube cooler to reach 3 K followed by a two-stage adiabatic demagnetization system. In order to understand the origin of the indistinguishable background events registered in the signal region defined for 1064 nm photons, we have carried out dedicated measurements with radioactive sources mounted outside the cryostat at a distance of \( d_{\text{source}} = (0.2 \pm 0.02) \) m to the detector (see Fig. 1 right panel for a photography of the setup). We used two sources (\(^{60}\)Co with an activity of \( A_{\text{Co}} = 53 \text{ kBq} \) and \(^{22}\)Na with an activity of \( A_{\text{Na}} = 280 \text{ kBq} \)). The sodium source produces a gamma-ray spectrum with a 511 keV annihilation line from the \( \beta^+ \) decay of the \(^{22}\)Na into \(^{22}\)Ne* which emits a 1.275 MeV photon to relax into the ground state. The \(^{60}\)Co nuclei decay via \( \beta^- \) to Ni, populating two excited states which lead to the emission of two photons with 1.17 MeV and 1.3325 MeV. We have simulated the setup with GEANT4 (Allison et al. 2016) and found on average approximately 2 additional Compton scattered electrons with energies above 100 keV that are released inside the aluminum shielding for every gamma-photon impinging from the outside. We have verified this simulation result using a NaI(Tl) based gamma-ray spectrometer mounted inside the aluminum shield while the radioactive source was mounted outside of the shield. We accumulated events with either source individually and with the combination of both sources. The sources faced the detector inside the cryostat. We also took background data without a source. In a different setup, we have determined the response of the TES to an attenuated flux of photons from a laser coupled to a single-mode fiber which guides the light to the TES surface.

3. Data analysis

For each event passing a trigger threshold of 32 mV, the time-line of the output voltage has been recorded in 20 ns steps to cover a total of 20 \( \mu s \). The data are analysed offline to determine the peak voltage (pulse height amplitude: PHA) and the pulse integrale (PI). For calibration purposes, we determine the locus of the events and an ellipse encompassing the signal events in a plane of PI and PHA from a run where a photon source at \( \lambda = 1064 \) nm was coupled to a single mode fiber which guides the photons to the TES. The ellipse is chosen to encompass 97.2 \% (3 \( \sigma \)) of the laser induced events. We have verified that the locus of the event distribution does not change when maintaining similar settings of the working-point of the TES and fiber positioning, for further details on this calibration step see Dreyling-Eschweiler (2014), Dreyling-Eschweiler et al. (2015). In order to determine the dark count rate of the TES, we have disconnected the fiber and operated the TES in a similar mode as previously. After an exposure of \( 49.2 \times 10^3 \) s, the resulting distribution of background events is shown in Fig. 2 left panel. Finally, we show in Fig. 2 right panel, the events registered with the sodium and cobalt sources mounted outside the ADR. The distribution of events falls in two regions marked in the PI-PH planes. The green band encompasses short pulses with an effective pulsewidth \( (PI/PH \approx 2 \mu s) \), while a larger number of events is characterized by a longer effective pulse width \( (PI/PH \approx 10 \mu s) \). When comparing the two measured distributions, the overall shape is similar. Some differences are noteworthy: in the case of the MeV-energy of the radioactive gamma-rays of the sodium and cobalt sources, the long duration events are on
Ambient radioactivity induced background in W-TES

Table 1. Summary of the data taken with and without radioactive sources. The errors shown are statistical only.

| Source name | activity $A$ [kBq] | time $\Delta t$ [10$^3$ s] | $\dot{n}_{\text{trigger}}$ [10$^{-3}$ s$^{-1}$] | $\dot{n}_{\text{signal}}$ [10$^{-3}$ s$^{-1}$] |
|-------------|-------------------|----------------|----------------|----------------|
| $^{60}\text{Co}$ | 53 | 5.4 | 66(4) | 0.4(3) |
| $^{22}\text{Na}$ | 280 | 6.3 | 256(6) | 1.3(4) |
| $^{60}\text{Co},^{22}\text{Na}$ | 333 | 6.3 | 291(7) | 0.5(3) |
| w/o src. | unkn. | 49.2 | 23(7) | 0.14(5) |

average depositing more energy. This may be the result of different energy losses of lower-energy ambient gamma-rays which tend to loose energy predominantly via photoelectric interaction while at MeV energies, Compton scattering starts to dominate.

4. Results

The results of the measurements carried out are summarized in Table 1. The numbers listed have been extracted after selecting the pulse height (PH) and pulse integral (PI) of events as shown in Fig. 2.

4.1. Triggered and signal rate increase

In our case, we measure a raw rate (before selecting signal-like events) increase

$$\Delta \dot{n}_{\text{trigger}} = \dot{n}_{\text{trigger}} - \dot{n}_{\text{w/o src}}$$

normalized to the activity of the source of

$$\frac{\Delta \dot{n}_{\text{trigger}}(\text{Co})}{A_{\text{Co}}} = (0.8 \pm 0.1) \times 10^{-3} \frac{\text{s}^{-1}}{\text{kBq}}$$

$$\frac{\Delta \dot{n}_{\text{trigger}}(\text{Na})}{A_{\text{Na}}} = (0.81 \pm 0.03) \times 10^{-3} \frac{\text{s}^{-1}}{\text{kBq}}$$

$$\frac{\Delta \dot{n}_{\text{trigger}}(\text{Na} + \text{Co})}{A_{\text{Na}} + A_{\text{Co}}} = (0.80 \pm 0.03) \times 10^{-3} \frac{\text{s}^{-1}}{\text{kBq}}$$

for the two different sources and their combination. The increase of the activity normalized rate is consistent for the two different types of radioactive sources. Note, this is not trivial given that the energy spectra of the emerging photons are quite different. The majority of these additional events however are filtered out by their distinctively different pulse shape. After selecting events which fall into the signal region selected for 1064 nm photons, the rate remains increased. We find for the excess rate

$$\Delta \dot{n}_{\text{signal}} = \dot{n}_{\text{signal}} - \dot{n}_{\text{w/o src}}$$

normalized to the activity $A$:

$$\frac{\Delta \dot{n}_{\text{signal}}(\text{Co})}{A_{\text{Co}}} = (5 \pm 5) \times 10^{-6} \frac{\text{s}^{-1}}{\text{kBq}}$$

$$\frac{\Delta \dot{n}_{\text{signal}}(\text{Na})}{A_{\text{Na}}} = (4 \pm 1) \times 10^{-6} \frac{\text{s}^{-1}}{\text{kBq}}$$

$$\frac{\Delta \dot{n}_{\text{signal}}(\text{Na} + \text{Co})}{A_{\text{Na}} + A_{\text{Co}}} = (1.1 \pm 0.9) \times 10^{-6} \frac{\text{s}^{-1}}{\text{kBq}}.$$ 

Clearly, longer exposures are needed to determine these rates more accurately. The number of signal-like events accumulated in all three measurements is $n_{\text{signal}} = 13$ with an expected background of 2.5 events which corresponds to a significance of $\approx 3$ standard deviations using the likelihood method given by Eqn. 17 in [Li & Ma 1983].

Taking this excess to be significant, we can estimate the ratio of events which contaminate the signal region to the triggered event number. We call this quantity $\xi = n_{\text{signal}} / \dot{n}_{\text{trigger}}$. For the background data sample (without radioactive source), we find a ratio of $\xi(\text{background}) = (0.6 \pm 0.3) \%$. This can be compared readily with the corresponding ratio for the data samples taken with radioactive sources taking the combination of the three

§ Prior to these measurements, the crystal unit of the ADR deteriorated leading to short holding times.
data sets $\xi_{\text{Na,Co}} = (0.3 \pm 0.1) \%$, consistent with $\xi$(background) within the uncertainties.

From this estimate, we can draw the conclusion, that the observed fraction of signal-like events in our background sample is consistent with the one observed for events generated by energetic particles hitting the cryostat.

4.2. Detection efficiency for energetic photons

We can use the measurement to determine the efficiency for the detection of energetic photons impinging from outside the cryostat. Assuming for simplicity that we can estimate the $\gamma$-ray flux $\phi_\gamma$ at the location of the sensor at distance $d$ related to the activity of the source $A$ to be

$$\phi_\gamma = \frac{A}{4 \pi d^2_{\text{source}}}. \quad (1)$$

We can then proceed to estimate the effective area $\pi r_{\text{eff}}^2$ of the TES for detecting these gamma-rays by requiring

$$\frac{\Delta \dot{n}}{\dot{n}} = \frac{r_{\text{eff}}^2}{4 d_{\text{source}}^2}, \quad (2)$$

and therefore calculating an effective radius $r_{\text{eff}} = 2 d \sqrt{\Delta \dot{n}/\dot{n}} = (350 \pm 36) \mu$m. Given the side length of the active sensor of 20 $\mu$m, this implies that most gamma-rays must be detected via the coupling of the sensor to the substrate where most of the energy of the gamma-rays will be deposited. Going one step further, the effective radius for signal-like events is reduced by a factor of $\sqrt{\xi} \approx 10^{-1}$ or correspondingly a radius similar to the geometrical extension of the sensor.

5. Discussion

The obvious result of this measurement is that we detect clearly the presence of the radioactive sources mounted outside the cryostat as an addition to the background rate. Through this measurement, we can quantify the fraction of ionising events which are registered with the TES and appear identical to a $\lambda = 1064$ nm single photon. This fraction ($\xi = n_{\text{signal}}/n_{\text{trigger}}$), is very similar to the one determined from observations without radioactive sources mounted. This would
be consistent with the hypothesis that the insuppressable background rate of $10^{-4}$ s$^{-1}$ is caused by ionizing radiation from ambient radioactivity.

The efficiency for detecting gamma-rays is quantified by an effective radius $r_{\text{eff}}$ up to which photons and Compton scattered electrons are detected when impinging on the substrate. The estimated $r_{\text{eff}} = (350 \pm 36) \, \mu$m is much larger than the geometrical extension of the TES which implies that energy deposited in the Si substrate is indirectly detected with the TES very likely through heating. A very small fraction of these events is finally detected with signal properties identical to photons with a wavelength of 1064 nm. The similarity of these events implies a very similar type of energy deposition and heating/cooling of the TES - even though the energy is initially released as ionization.

The measurement carried out indicates that the signal-like events are very likely the result of secondary effects related to the energy deposition and possibly even re-radiation of locally heated substrate. Finally, we can estimate the background rate using the detection efficiency determined from our measurements. We assume the level of ambient radioactivity to be similar as determined in Banjanac et al. (2014) which translates into an isotropic flux of $I_\gamma = 2 \times 10^4$ photons m$^{-2}$s$^{-1}$ (4$\pi$)$^{-1}$ for energies larger than 100 keV. Given that the value found for $r_{\text{eff}} \approx 275 \, \mu$m (roughly the thickness of the substrate), we assume that the setup has a sensitivity close to isotropy and therefore can readily estimate the background event rate $\dot{n}_{\text{trigger},\gamma} = (8 \pm 2) \times 10^{-3}$ s$^{-1}$, which accounts for roughly a third of the measured background rate listed in Table 1. Note, additional background will be induced by Compton-scattered electrons from the shield (see also previous section) as well as from radioactive nuclei present in the ambient material.

6. Conclusion

The measurement described in this article has helped to understand the intrinsic dark count rate of a transition edge sensor operated at 80 mK. A small fraction $\xi \approx 0.5$ % of the measured background events is indistinguishable from individual photons detected at 1064 nm wavelength. Based upon our preliminary results, we find that a large fraction of the residual background is produced from ambient radioactivity - mainly gamma-rays that can deposit energy in the TES or its environment in such a way that the pulse shape is indistinguishable from that in single photon events. Other sources of background (e.g., ambient light or cosmic muons have been excluded (Bastidon 2017)). The underlying mechanism for pulse generation is however not yet identified. It seems plausible, that local heating of the substrate could either propagate through phonons to the TES layer or more indirectly, via photons emitted from the surface. Future studies are required to find a remedy to reduce this dark count rate even further in order to improve the sensitivity of TES detectors for rare process searches. In principle, the reduction of background could be achieved through careful selection of the materials (radio purity) in the immediate vicinity of the detector as well as by installing additional shielding. For an optimized design of the detector assembly, a deeper investigation of the mechanism of signal generation is required.

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