



SPECTRAL BROADENING BY QUASIPARTICLES PILE-UP IN X-RAY MICROCALORIMETERS WITH SUPERCONDUCTING ABSORBERS

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ABSTRACT

Long-living quasiparticles can pile-up in a superconducting absorber of an X-ray microcalorimeter when photons are detected at high count rate with respect to the rate of relaxation of quasiparticles. These quasiparticles can give a non negligible contribution to the total heat capacity of the detector thus affecting the pulse height spectrum of detected photons. We investigated this effect with numerical simulations and evaluated the resulting spectral broadening as a function of the photon absorption rate, the lattice heat capacity of the detector and the quasiparticle recombination life time in the absorber.

SCIENTIFIC RATIONALE

In an X-ray microcalorimeter with superconducting absorber, a significant fraction of the energy deposited by a photon can remain trapped in quasiparticles for a time longer than the thermal pulse of the resistive sensor.

If the rate of arrival of the photons is high with respect to the relaxation rates of the quasiparticle system in the superconducting absorber, quasiparticles pile-up can occur with a non negligible contribution to the total heat capacity of the detector and thus on the measured pulse height spectrum of the detected photons.

Using numerical simulations, we investigate this effect for an X-ray microcalorimeter with NTD germanium thermistor and pure Tin absorber, as a function of the rate of arrival of the photons and the total heat capacity of the detector.

THE THERMALIZATION MODEL

We use a microscopic approach to model the thermalization processes in an X-ray microcalorimeter with superconducting absorber. A set of differential coupled equations describe the spectral and spatial evolution of the excess quasiparticles and phonons produced by the absorption of a photon in the superconductor [Perinati et al. 2002].

Numerical simulations of the absorption of a single 5.89 KeV photon in a high purity Sn absorber (see Figure 1 for the detector geometry) show that, on the time scale of the thermal pulse (few tens of μ s) only about 40% of the deposited energy is thermalized and converted into phonons. The incomplete thermalization is due to energy trapped in long living quasiparticles in the superconducting absorber. In the simulated case, nearly $6 \cdot 10^6$ excess quasiparticles are still present in the absorber when the resistive sensor has already detected the thermal pulse.

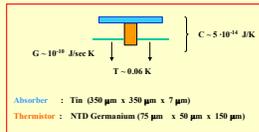


Figure 1. Schematic of the geometry of the modeled detector

At temperatures lower than 100 mK, the life time of quasiparticles at nearly the gap energy in high-purity Sn is very long. In our detector geometry we obtain a quasiparticle life time of about 0.4 msec, which implies that an effective time of many seconds is necessary before all the trapped energy can be released to the thermistor in form of low energy phonons. Actually, there are experimental evidences that quasiparticle life times in pure Sn are a few microseconds or even shorter [Krauss et al. 1990] (nearly one hundred times smaller than predicted theoretically). With a quasiparticles lifetime of few μ s, the quasiparticle system relaxation time would be several tens of milliseconds.

NUMERICAL SIMULATIONS

Since we do not have yet an experimental estimate for the quasiparticle recombination lifetime in our specific detector absorber we have performed numerical simulations of the pile-up effect adopting two different values of this lifetime that can likely be considered as the lower and upper limits for the actual value, namely 4 μ sec, and 0.4 μ sec corresponding to values 100 times and 1000 times smaller than theoretically predicted for pure Tin. Figure 2 shows the number of quasiparticles as a function of time theoretically predicted for pure Tin (red curve) and for the two other simulated cases where the quasiparticle lifetime in the absorber is 100 times (green curve) and 1000 times (blue curve) smaller, respectively.

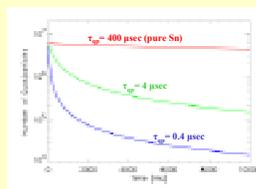


Figure 2. Time evolution of the number of quasiparticles in the absorber for three different values of the quasiparticle recombination lifetime

When photons are detected in sequence, each photon will find in the absorber a certain number $N_{qp}(t)$ of quasiparticles left by the previously absorbed photons. These excess quasiparticles in the absorber contribute a quantity $N_{qp}(t) \cdot K_{qp}$ to the total heat capacity of the detector. The signal pulse produced by each photon depends on the total heat capacity of the detector at the time of the absorption and therefore on the number of excess quasiparticles present in the absorber. The presence of excess quasiparticles in the absorber produces an average decrease of the signal pulse due to the increased heat capacity, and also a spectral broadening given the random nature of the arrival times of the photons.

In order to evaluate the effect of quasiparticles pile-up onto the pulse height spectrum we have generated random sequences of monoenergetic 5.89 keV photons at given rates, and have computed for each photon the signal pulse considering the number of quasiparticles left by the previous photons. We have assumed that each photon adds $6 \cdot 10^6$ quasiparticles to the absorber while in between photon arrivals the number of quasiparticles follows the decay law derived from our model and shown in Figure 2.

RESULTS

Figures 3 and 4 show the pulse height spectra of monoenergetic 5.89 keV photons at various rates (0.5-100 cts/s) for the two cases with the quasiparticles lifetime 100 and 1000 times smaller than pure Tin, respectively. Notice that the peak broadening shown in these figures takes into account only the quasiparticle pile-up effect while any other broadening, including the thermodynamic fluctuation of the detector energy content due to the link with the thermal bath, is neglected.

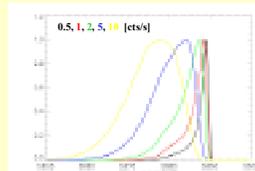


Figure 3. Normalized pulse height spectra of 5.89 keV photons at various rates for the simulation with quasiparticle recombination lifetime 4 μ sec (100 times smaller than pure Sn).

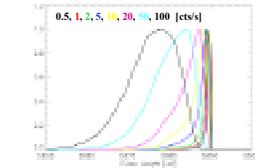


Figure 4. Normalized pulse height spectra of 5.89 keV photons at various rates for the simulation with quasiparticle recombination lifetime 0.4 μ sec (1000 times smaller than pure Sn).

Figure 5 and 6 show the FWHM of the 5.89 keV peak as a function of the rate of arrival of the photons for the two cases with the quasiparticles lifetime 100 and 1000 times smaller than pure Tin, respectively. For these simulations the heat capacity of the detector is $5 \cdot 10^{14}$ JK, which is the typical value of the detectors that provided the best energy resolution in laboratory (5 eV at 5.89 keV) at low counting rates [Silver et al. 2002]. Superimposed on these plots are two horizontal lines defining the presently best measured energy resolution at low counting rates (5 eV FWHM, solid line), and the thermodynamic limit to the energy resolution for this detector (dotted line).

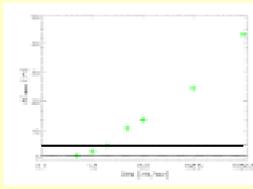


Figure 5. $\Delta E_{50\%}$ of the 5.89 keV peak as a function of the photon count-rate for the simulation with quasiparticle recombination lifetime 4 μ sec (100 times smaller than pure Sn).

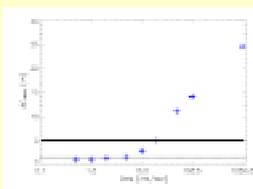


Figure 6. $\Delta E_{50\%}$ of the 5.89 keV peak as a function of the photon count-rate for the simulation with quasiparticle recombination lifetime 0.4 μ sec (1000 times smaller than pure Sn).

The effect of the quasiparticles pile-up is less important if the total heat capacity of the detector is higher. Figure 7 and 8 show the FWHM of the 5.89 keV peak as a function of the total detector heat capacity at various photon rates for the two cases with the quasiparticles lifetime 100 and 1000 times smaller than theoretically pure Tin, respectively. Superimposed on these plots are two curves defining the presently best measured energy resolution at low rates (5 eV FWHM, solid line), and the thermodynamic limit to the energy resolution for this device (dashed line).

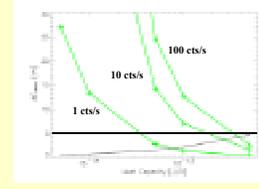


Figure 7. $\Delta E_{50\%}$ of the 5.89 keV peak as a function of the detector heat capacity at various rates for the simulation with quasiparticle recombination lifetime 4 μ sec (100 times smaller than pure Sn).

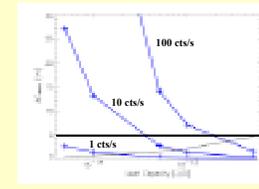


Figure 8. $\Delta E_{50\%}$ of the 5.89 keV peak as a function of the detector heat capacity at various rates for the simulation with quasiparticle recombination lifetime 0.4 μ sec (1000 times smaller than pure Sn).

SUMMARY AND OUTLOOK

We have identified, with numerical simulations, a possible effect of spectral broadening in a microcalorimeter with superconducting absorber, originating from the microscopic processes of energy thermalization inside the superconductor.

In an X-ray microcalorimeter with superconducting absorber, a significant fraction of the energy deposited by a photon can remain trapped in quasiparticles for a time significantly longer than the thermal pulse of the resistive sensor. If the rate of arrival of the photons is high with respect to the relaxation rates of the quasiparticle system in the superconducting absorber, quasiparticles pile-up can occur with a non negligible contribution to the total heat capacity of the detector and thus on the measured pulse height spectrum of the detected photons. In this paper we show that this effect can be a limiting factor on the energy resolution of X-ray microcalorimeters with pure Tin superconducting absorber operated at medium-high rates 100-1000 cts/s. This effect is less critical when the detector has a higher heat capacity, provided that the thermodynamic limit to the energy resolution remains sufficiently low.

We plan to perform dedicated experimental tests on new and optimized NTD Ge microcalorimeters with Tin absorbers to try to derive a better estimate of the quasiparticles recombination lifetime in this specific absorber material, and to confirm the predictions of our simulations.

This work has also stimulated a search for new superconducting absorber materials that might be more efficient and faster in thermalizing the photon energy thus minimizing the QP pile-up effect.

References

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