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Munich Cryogenic Detector Development 1995

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At the Technical University of Munich and the Max Planck Institute of Physics we are developing cryogenic detectors for the detection of small deposited energies, for example from the elastic scattering of WIMP dark matter particles, or the absorption of X-rays. Together with the University of Oxford and the Laboratori Nazionali del Gran Sasso we are preparing the CRESST experiment which uses our detectors to search for WIMP dark matter. This preprint contains reports of our work which we have presented at the Sixth International Workshop on Low Temperature Detectors (LTD-6) in Beatenburg/Interlaken, Switzerland, 28 Aug. - 1 Sept. 1995. This work has been supported in part by the "Sonderforschungsbereich 375 für Astroteilchenphysik" and the EU ERBCHRXCT930341 Network on Cryogenic Detectors.

Contents:

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Cryogenic Particle Detectors with Superconducting Phase Transition Thermometers

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Abstract

A tungsten superconducting phase transition thermometer on a 32 g sapphire crystal has given an energy resolution of 100 eV (FWHM) for 1.5 keV X-rays, increasing to 440 eV at 14 keV. A possibility to obtain similar resolution in much larger crystals by using Al films as phonon collectors is presented.

We have been developing massive cryogenic detectors [1, 2, 3, 4, 5] for use in applications such as a search for dark matter particles [6]. Our type of detector consists of a superconducting phase transition thermometer evaporated directly onto a dielectric crystal. The energy deposited in the crystal by a single particle interaction is measured via the resulting temperature rise in the thermometer. The device is operated within the superconducting-to-normal transition of the thermometer, where a small temperature rise ΔT of the thermometer leads to a relatively large rise ΔR of its resistance. The ΔT induced by a particle is usually much smaller than the width of the transition, which leads to an approximately linear relation between ΔT and ΔR. We are using two types of thermometers: films of iridium overlaid with gold, using the proximity effect to reduce the T_c of the combination below that of pure iridium [5]; and films of pure tungsten, which are the subject of this paper.

Since we want to operate at low temperature, it is critical that we produce films of the α phase of tungsten, which is known to have a transition temperature $T_c \sim 15$ mK in the bulk material, rather than the β or γ phases which have been observed to give much higher T_c's in films. The tungsten is deposited [3] on the r-plane ($1\bar{1}02$) of a sapphire (Al_2O_3) single crystal in a dedicated UHV system. During deposition the sapphire is heated to around 500°C. X-ray diffraction studies of tungsten films produced in this way have shown clear peaks corresponding to the b.c.c. structure of α tungsten and no evidence for the presence of the β or γ phases. This is confirmed by measurements of the T_c of the films, which are consistent with the 15 mK of bulk α tungsten.

A detector was made [3] by depositing a tungsten film of thickness 280 nm on a 32 g ($4 \times 2 \times 1\,cm^3$) single crystal of sapphire. The shape of the thermometer was defined after deposition by photolithography and wet etching to an area of $3 \times 5\,mm^2$. Gold contact pads were deposited at each end of the thermometer using sputtering and lift-off photolithography. The detector was placed in a copper housing on sapphire-ball tips which provide good thermal isolation. Electrical and thermal contact to the thermometer were made with Al and Au bond wires, respectively. The detector was installed in a dilution refrigerator which could cool the operating detector to 9 mK. The resistance of the thermometer (8–46 mΩ) was monitored by passing a constant current I_0 of several μA through a circuit in which the thermometer was in parallel with a 50 mΩ resistor and the pickup coil of a commercial DC-SQUID. A rise in the thermometer resistance caused a rise in the current through the pickup coil of the SQUID. The output voltage of the SQUID electronics left the Faraday cage through a 50 kHz low-pass filter and was fed to a 12-bit transient recorder and a trigger module. The data were written to disk for offline analysis.

The data described here [3] were taken after the shielding against the earth's magnetic field was removed from the cryostat. This shifted the thermometer's transition down by about 2 mK, so that for a readout current of 15 μA it started becoming superconducting at about 12 mK and the transition continued to below 9 mK. The detector was irradiated with an X-ray fluorescence source using ^{55}Fe for the primary X-rays and Al and Ti targets. A collimator which

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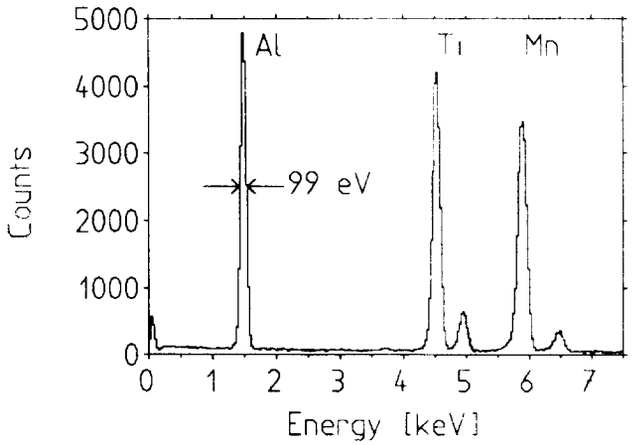

Figure 1: Pulse height spectrum measured while irradiating a 32 g sapphire detector with W thermometer with an Al/Ti fluorescence X-ray source [3].

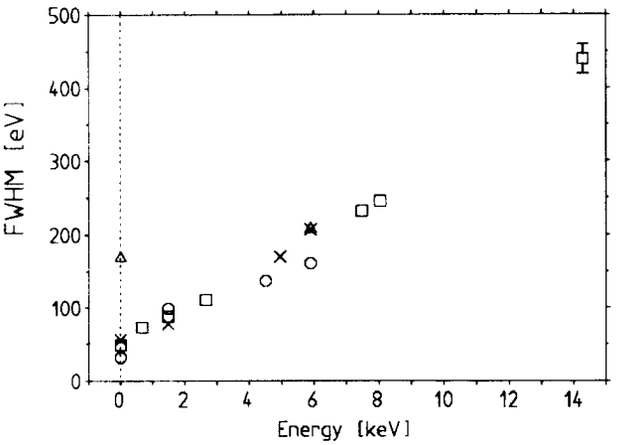

Figure 2: Energy resolution (FWHM) obtained with various detectors: (circles) 32 g sapphire with W thermometer operated at 13 mK with Al/Ti source [3] and (squares) with multi-line source; (crosses) 4 g sapphire with W thermometer operated at 11 mK [3]; (triangles) 32 g sapphire with Ir/Au thermometer operated at 44 mK [2]. The points plotted at zero energy are the baseline widths. The error bars when not shown are smaller than or comparable to the size of the plot symbols.

gave a 3.6 mm spot size on the detector was used to reduce the event rate to about 10 Hz (including background). An on-line filter eliminated events with large pulses which exceeded the range of the transient recorder, reducing the rate written to disk by a factor of about 10. A sample of 140 000 events was obtained in a 30 h run with the holder temperature stabilized at 12 mK and using a readout current of 15 μA, which split about equally between the thermometer and the 50 mΩ parallel resistor. Offline cuts rejected events with obvious pile-up or if the tilt of the baseline, as seen in the 2.5 ms pre-trigger region, was more than 100 eV/ms. The final sample contained 86 000 events.

The pulse height was determined after smoothing each pulse with a 50-channel moving average and extrapolating the baseline using a straight-line fit to the 256 channels of the pre-trigger region. The resulting spectrum is shown in Fig. 1. The energy scale was set by fitting the positions of the three K_α lines to a straight line passing through zero. The linearity of the detector was better than 0.3%. Fitting Gaussian curves to the K_α lines gave a FWHM energy resolution of 99 $\pm$ 1 eV at 1.5 keV, 137 $\pm$ 1 eV at 4.5 keV, and 161 $\pm$ 2 eV at 5.9 keV. Due to pile-up the baseline often had a significant slope and its position varied by more than 10 keV. The noise relevant to our pulse-height determination was found by making a linear fit to the 2.5 ms pre-trigger region for each event and taking the distance of this line to a 50-channel-averaged point in the pre-trigger region. This resulted in a baseline width of 32 $\pm$ 1 eV FWHM.

To further study the energy dependence of the resolution a second run [7] was made using α particles from a ^{244}Cm source to excite X-rays from F, Al, and Cl (K_α of 0.7, 1.5, and 2.6 keV). Additional lines at 7.4, 8.0, 14.1, and 11.3 keV came from Ni in the source housing, the Cu detector holder, and Pu from ^{244}Cm decays. In this run the baseline width was 47 $\pm$ 1 eV. This source gave much more background than the previous one, and the statistics in the peaks was much less, so that the errors on the peak widths are larger.

The resolution found in these runs and with two other detectors operated in this energy range is plotted in Fig. 2. The resolution clearly has an energy-dependent component which quickly exceeds the baseline noise. It varies somewhat from detector to detector, and part of it seems to come from slight non-linearities in the transition, as cuts on the baseline position sometimes improve the resolution.

We have recently published a model [4] which describes the size and shape of the observed signals of our detectors operated at higher temperatures with Ir-Au thermometers. The absorption of an X-ray in the absorber crystal creates high-frequency phonons. The phonons are quickly distributed homogeneously in the crystal by elastic scattering at the crystal surface. They are then either transmitted into the thermometer and absorbed by free electrons or thermalized by inelastic processes on the crystal surface. The temperature pulses measured with the thermometer consist of two exponential components with very different decay time constants. The dominant fast component can be attributed to the absorption of high-frequency non-thermal phonons in the thermometer. The strong interaction among the electrons in the thermometer quickly shares and thermalizes the phonon energy, raising the temperature of the thermometer's electron system. Part of the thermalized energy is radiated back as thermal phonons into the crystal, raising its temperature; the rest escapes via the thermal coupling of the thermometer to the heat sink. The slow component of the measured signal reflects the temperature rise of the crystal.

A preliminary application of this model to our detectors with W thermometers [7] indicates that the model needs

some extension to fully explain these detectors, but we think it is correct in its main features. The model again attributes the fast part of the pulse to the absorption of non-thermal phonons in the thermometer. For these detectors the lifetime τ_n of the non-thermal phonon population is smaller than the intrinsic time constant τ_{in} of the thermometer, so the thermometer effectively integrates the phonon flux. The amplitude of the pulse is then given roughly by $\epsilon \Delta E/C_e$, where ϵ is the fraction of the phonons which thermalize in the thermometer (rather than on the surfaces of the crystal), ΔE is the deposited X-ray energy, and C_e is the heat capacity of the thermometer. In this model, ϵ could be increased by increasing the area of the thermometer, but this would also increase C_e.

A possibility of effectively increasing the collecting area of the thermometer without increasing its heat capacity is to use an Al film as a "phonon collector". At 15 mK Al is far below its superconducting transition and thus has negligible heat capacity. Phonons absorbed in the Al film create quasiparticles, which propagate by diffusion into an attached W thermometer, where they transfer their energy to the free electron system. Released from its task of collecting phonons, the W thermometer can have small area and heat capacity, giving it a high sensitivity. The Al film must be very pure so that the quasiparticles can diffuse quickly into the thermometer. We have set up a new UHV system dedicated to the deposition of high-purity Al films, and have succeeded [8] in making films of sufficient quality (residual resistivity ratio > 100 for 1 μm thick films). Work is proceeding on combining them with W thermometer films. It is hoped that this development will allow us to increase the size of our detector crystals without loss of resolution

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