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MAX-PLANCK-INSTITUT FÜR PHYSIK

WERNER-HEISENBERG-INSTITUT

MPI-PhE/93-34
Dezember 1993

MPI-PhE 93-34
SW 9414

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Abstract

Massive cryogenic particle detectors are being developed for use in a search for dark matter particles. Results with a 31 g sapphire crystal and a superconducting phase transition thermometer operated at 44 mK are presented. The observed signal includes a fast component which is significantly larger than the expected thermal pulse. The energy resolution is 210 eV (FWHM) for 6 keV X-rays.

1 Introduction

Massive cryogenic calorimeters are being developed as particle detectors with low energy threshold and good energy resolution [1, 2]. Such detectors can be used in experiments such as a search for dark matter particles (WIMPs) via their elastic scattering on nuclei. Calorimeters have the advantage of detecting the full energy of nuclear recoils, whereas ionization or scintillation detectors see only a part of the deposited energy. This is especially important for low-energy nuclear recoils, which have a low ionization efficiency [3, 4].

A cryogenic calorimeter consists of an absorber crystal, in which the particle interaction takes place, and a thermometer which measures the resulting temperature rise. Operation at very low temperature (10–100 mK) reduces thermal noise and takes advantage of the small heat capacities of materials at these temperatures. Several groups are working on cryogenic detectors using doped germanium crystals as thermometers [5, 6, 7].

We are developing detectors using superconducting phase transition thermometers [8, 9, 10], with the goal of achieving very good resolution at low energies in massive detectors. Our thermometer is in intimate contact with the crystal and efficiently absorbs the high-frequency phonons caused by a particle interaction before they thermalize in the crystal [10, 11]. These phonons heat the thermometer above the expected thermal signal $\Delta T = E/C$, where E is the deposited energy and C is the heat capacity of the calorimeter. This enhanced signal provides an excellent energy resolution. In this paper we report on results obtained with an iridium/gold thermometer on a 31 g sapphire absorber crystal.

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2 Description of the Detector

Our superconducting phase transition thermometer consists of a small film of superconducting material deposited by electron-beam evaporation onto the surface of an absorber crystal. The detector is operated within the narrow transition region around the critical temperature T_C of the film, where the film's electrical resistance decreases from its normal-conducting value to zero in the superconducting state.

The T_C of the thermometer film determines the operating temperature of the detector. We have previously used pure iridium [8, 9], which has a nominal $T_C = 112$ mK. A lower operating temperature is needed to improve the sensitivity, but there are only a few superconductors with a T_C that is lower but still within the range easily reached with a dilution refrigerator. One way of achieving a desired T_C is to use the proximity effect to reduce the T_C of a thin layer of iridium by overlaying it with a thin layer of gold [12].

The calorimeter described in this paper uses such an iridium/gold thermometer consisting of an iridium film of area 1.0×2.5 mm² and thickness 1350 Å completely covered by a gold film of area 1.5×2.5 mm² and thickness 1000 Å. The absorber is a sapphire single crystal of dimensions $4 \times 2 \times 1$ cm³ and mass of 31.4 g. The thermometer was evaporated directly onto one of its 2×1 cm² faces.

The experimental setup is very similar to that described in detail in Refs. [13, 14], and only a brief description is given here. The detector assembly is shown in Fig. 1 a. The detector is held on ruby tips within a massive copper housing (wall thickness 7 mm) which serves as the heat bath. Thermal contact between the housing and the detector is made by a single gold wire of diameter $25\text{ }\mu\text{m}$ bonded to one end of the thermometer and to the copper housing. Electrical contact between the thermometer and the external circuit of Fig. 1 b is provided by three aluminum wires of diameter $25\text{ }\mu\text{m}$ bonded to each end of the thermometer; during calorimeter operation these wires are superconducting and have negligible thermal conductivity. The housing is attached to the mixing chamber of a dilution refrigerator and is thermally isolated from it except for a thin copper wire. This weak thermal link (time constant 1 s) together with a small heater allows good stabilization of the temperature of the housing. After the first few runs a lead shield of thickness 2–3 cm was installed around the copper housing. This shield reduces the background counting rate above 3 keV from about 7 Hz to 2 Hz.

The thermometer has a low electrical resistance, varying between zero in its superconducting state and about 75 mΩ in its normal-conducting state. This low resistance is well suited to being measured with a dc-SQUID, using the circuit shown in Fig. 1 b. When a particle deposits energy in the absorber crystal, the temperature and thus the resistance of the thermometer rises, so that a larger fraction of the current flows through the SQUID coupling inductor and is detected by the SQUID as a change in magnetic field. The particle-induced temperature rise is small compared to the width of the transition, so that the thermometer remains well within its transition region. For recording pulses the temperature of the housing is stabilized and the SQUID output voltage is passed through a low-pass filter and then fed ac-coupled to a trigger unit and dc-coupled to a transient recorder.

The superconducting phase transition of the thermometer as measured with this setup is shown in Fig. 2. The first part of the transition is very steep, with the resistance increasing by 45 mΩ between 43.5 and 44.2 mK, and it is this part of the transition that is used for the detector operation. (The transition continues more slowly to 75 mΩ.)

(a)

(b)

Figure 1: (a) Cross section of the detector assembly. (b) Schematic of the readout circuit. The thermometer is the resistance R_{th} , the SQUID coupling inductor is $L_s = 2\mu\text{H}$, and $R_{ref} = 50\text{ m}\Omega$ is a reference resistor. A constant current I_0 of about $12\mu\text{A}$ is provided by an adjustable external battery-powered source.

Figure 2: Superconducting phase transition of the Ir/Au thermometer measured with a current of $I_0 = 12 \mu\text{A}$. The points above the curve are due to accidental pulses. The operating point for the spectrum of Fig. 3 is indicated by the arrow.

3 Results

The detector is irradiated with an ^{55}Fe source emitting 5.89 and 6.49 keV X-rays in an intensity ratio 8:1. The source is placed inside the lead shield so that the X-rays strike one of the $4 \times 2 \text{ cm}^2$ sides of the detector (see Fig. 1 a). The X-rays are collimated and reduced to a rate of about 1 Hz by a lead foil with two holes of diameter 0.4 mm placed between the source and the detector, so that the X-rays strike the detector at two positions separated by about 3 cm. This separation is designed to test for a position dependence of the measured pulse heights.

A typical pulse from a 5.9 keV X-ray is shown in Fig. 3 a. Close examination shows that it consists of two components: one with a large amplitude and a fast decay time of about 2 ms, and a second of smaller amplitude with a slower decay time of about 10 ms. The rise time is about 0.4 ms. When translated into temperature units using the slope of the transition the amplitudes of the fast and slow components bracket the pulse height of $3.5 \mu\text{K}$ expected in a naïve calorimeter model where $\Delta T = E/C$ with E the deposited energy and C the detector's heat capacity. This behaviour can be understood in a detailed calorimeter model [10, 11, 14]. The fast part of the pulse is due to the absorption of high-frequency phonons in the thermometer before the deposited energy has thermalized. The temperature of the thermometer rises substantially above that of the absorber crystal, providing an enhanced signal. The slow part of the pulse corresponds to that expected in

(a)

(b)

Figure 3: Results obtained when irradiating the detector with a ^{55}Fe source. The low-pass filter cutoff is 15 kHz and the transient recorder sampling rate 100 kHz. (a) Typical 5.89 keV pulse. The SQUID signal is converted into μK using the slope of the phase transition. (b) Pulse height spectrum after smoothing each pulse by averaging the transient recorder data over 200 time bins and applying a small correction for the curvature of the phase transition. The energy scale is set by normalizing the position of the main peak to 5.89 keV. The threshold of 300 eV is a due to a software cut.

the naïve calorimeter model. Its amplitude is a factor of two below the value of E/C due to the fact that the thermal coupling of the thermometer to the heat bath is stronger than its coupling to the crystal. The best energy resolution is obtained by using the maximum of the total pulse height, which is dominated by the fast component.

The maximum of each pulse is found after smoothing the transient recorder data to reduce noise by calculating a running average over 200 adjacent time bins ($10\mu\text{s}$ per bin). The spectrum shown in Fig. 3b is for a run of 9 hours duration, during which the SQUID baseline varies over a range corresponding to $10\mu\text{K}$. Within this range the pulse height of the 6 keV X-rays decreases linearly by 8%, which can be explained by a slight curvature of the phase transition. We then include this curvature as a small quadratic term in the conversion of the pulse height from SQUID units to energy; the energy scale is set by the known 5.89 keV energy of the Mn K_α line. In the resulting pulse height spectrum, shown in Fig. 3b, the resolution of the 5.89 keV line is $209 \pm 6\text{ eV}$ (FWHM). The fitted position of the second line is $6.46 \pm 0.02\text{ keV}$, which is in good agreement with the known value of 6.49 keV for the Mn K_β line.

In this experiment two spots on the calorimeter are simultaneously irradiated, separated by 3 cm along the 4 cm side of the calorimeter. The observed X-ray peak shows no double-peak structure, indicating that there is no significant position dependence to the pulse heights. Also no difference in the pulse shapes is seen.

Our energy resolution of 210 eV (FWHM) for 6 keV X-rays compares favorably to that of other massive cryogenic detectors, where the best FWHM resolutions are: 1.9 keV for 60 keV X-rays in a 58 g germanium detector [5], 2 keV for 6 keV X-rays in a 24 g sapphire crystal [6], and 9 keV at 65 keV in a 334 g TeO_2 crystal installed in a low-background environment [7]. A resolution of 7.3 eV has been obtained in a much smaller ($9\mu\text{g}$) cryogenic detector [15].

High-quality germanium ionization detectors are available in sizes similar to ours and with similar resolutions for 6 keV X-rays [16]. The low ionization efficiency of low-energy recoil nuclei [3, 4] should then give our detectors, detecting the full energy, an approximate factor of 5 advantage over ionization detectors in measuring nuclear recoil energies of around 1 keV. The actual factor achieved could be determined by calibrating our detector in a neutron scattering experiment [4].

4 Conclusions

An energy resolution of 210 eV (FWHM) for 6 keV X-rays has been achieved in a 31 g sapphire detector using a superconducting phase transition thermometer and operated at 44 mK. To our knowledge this is the best reported resolution per unit detector mass for a cryogenic detector. It is comparable to the best ionization detectors for X-rays, and should be significantly superior to them for low nuclear recoil energies. The good energy resolution at low deposited energies allows the use of a low threshold for a detector for dark matter particles and thus good sensitivity to particles with mass below 10 GeV [17]. Further progress towards more massive detectors with similar resolution probably requires a low-background environment.

Acknowledgements

The dilution refrigerator was designed by A. Singaas, built by A. Rulofs, and brought into operation by J. Igalson. It is operated with the use of thermometers provided by K. Neu-

maier. We are very grateful to our colleagues at the Technische Universität München for their collaboration, especially E. Kellner for producing the phase transition thermometer and the Crystal Laboratory for polishing the sapphire crystal.

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