MPI-PHE-92-24B

Dec 1992

Calorimetric Particle Detectors with Superconducting Absorber Materials

G. Forster, P. Ferger, F. v. Feilitzsch, R. L. Mößbauer

Munich, Tech. U.

Technische Universität München, Physik-Department E 15, D-8046 Garching bei München, FRG

We use massive superconducting absorbers made of Molybdenum and Vanadium as low temperature calorimetric particle detectors. The high resolution of our thermometry system, consisting of a superconducting phase transition thermometer monitored with a dc-SQUID, enables us to detect α and γ particles with large single crystals. Heat pulses generated by passing current through an metal film on the surface of the crystal are used to study the response of the calorimeters.

With a 35 g Molybdenum single crystal we obtain an energy resolution of 10 % FWHM on 5.8 MeV α particles at an operating temperature of 120 mK. The observed temperature rise of 1.2 μK is a factor of eight less than expected from the calculated heat capacity.

Using a 15 g Vanadium single crystal, the energy resolution on 5.8 MeV α particles is 1.2% FWHM. In this case, the pulse height of 6.1 μK is a factor of eight smaller than expected from the calculated heat capacity. A possible reason for the large deviations from the expected heat capacity is the presence of hydrogen dissolved in Vanadium. Impurities and defects on the surface of the crystals probably also contribute to the heat capacity.

The pulse shapes of all observed events are very similar, whether they are created by absorption of α or γ radiation or by an electrically created heat pulse, and consists of two exponential decaying parts. A comparison of the pulse heights of heater and radiation pulses leads us to the conclusion that all the energy deposited in the absorber crystal is converted into phonons.

Fermilab Library 0 1160 0020148 5

I, E

1. INTRODUCTION

The development of low temperature calorimetric particle detectors is motivated by the need for detectors with large mass and high energy resolution. In fact, the highest energy resolution obtained with a non-dispersive detector is now 7.35 eV and is achieved by a low temperature calorimeter [1].

An important limit to the energy resolution for this kind of detector comes from statistical fluctuations of the fraction of the deposited energy actually converted into phonons. During the thermalization of the deposited energy in an absorber, an appreciable part may excite meta-stable states (e.g. electron-hole pairs trapped by impurities). The lifetime of this meta-stable states can be very long at low temperatures. Therefore, the thermal signal does not contain the full amount of energy. The energy resolution in this case is dominated by the fluctuation of the number of excited meta-stable states. This effect has been verified experimentally [2].

Optimal energy resolution requires an absorber material where the entire energy thermalizes rapidly. Alternatively, the excitation energy of the states trapping energy should be kept as low as possible. While semiconductors with small or zero band gap constitute one possibility, we chose to study superconductors as absorber material, where the energy gap is in the order of meV.

In a superconductor, due to electron-phonon interaction, the deposited energy will relax very fast into phonons of energies less than 2Δ and into quasiparticles at the energy gap. These two systems must then be treated separately. Subgap phonons can no longer interact with the quasiparticle system, and quasiparticles have a small recombination probability as the density of thermally excited quasiparticles is very low.

Calculations [3] of the lifetime for quasiparticles predict a very large value at low temperatures. These calculations assume a constant energy gap over the whole crystal, which may be incorrect for real crystals. Regions with smaller energy gap can be caused by trapped magnetic flux or by a nonuniform impurity or defect concentration. Quasiparticles may become trapped

To be published in NIM-A.

CN Munich Cryogenic Detector Collaboration

in these regions. Then their concentration can increase far above the thermal equilibrium value, with the consequence of an increase in the recombination probability and a reduction of their lifetime, thus speeding up thermalization.

Another possibility to decrease the quasiparticle lifetime is to coat the absorber crystal with a material of lower T_C, where quasiparticle trapping occurs. When the quasiparticle trap is made of normal conducting material, it should lead to a very fast conversion of quasiparticles to thermal phonons.

The phonons with energy less than 2Δ have no thermal frequency distribution and will thermalize only slowly in the absorber, as the inelastic phonon-phonon scattering cross section is $\sim \omega^5$ and therefore decreases rapidly with the phonon frequency ω. The only obvious thermalization process exists in the absorption and thermalization of phonons in any metal film in contact with the absorber, for example in the thermometer. In the metal film, the phonons thermalize rapidly and will be emitted back into the absorber with a thermal spectrum. The thermalization time could be calculated from the probability for phonons to cross the interface between absorber crystal and metal film, which can be derived from acoustic mismatch theory.

During the thermalization time, the temperature of the thermometer is governed by the ratio of the phonon flux entering and leaving the thermometer. As the electron-phonon coupling is frequency-dependent and $\sim \omega$, it should lead to an increase in the thermometer electron temperature during the thermalization time, as the absorption rate for the non-thermal phonons is larger than the emission rate for thermal phonons. After the thermalization is complete, the thermometer is in thermal equilibrium with the absorber crystal.

To study the thermalization process in superconductors, we use a metal film heated by an electric current as a source of phonons with thermal frequency distribution and compare the resulting temperature signals with the events originating from absorbed α particles.

2. EXPERIMENTAL SETUP

Our calorimeters consist of a superconducting absorber crystal (Molybdenum or Vanadium) of approximately cylindrical shape (diameter 13 mm × 25 mm) with polished front and back faces. On one of the polished faces we evaporate the thermometer structure, the opposite side is irradiated with α particles. This thermometer structure consists of several layers: An insulation layer from Silicon monoxide (thickness 200 nm) prevents the superconducting absorber from electrically shorting the thermometer film. This thermometer film of 400 nm Iridium (dimensions 1 mm × 3.5 mm) and the contact pads of Aluminum or Gold (1 mm × 1.5 mm) are evaporated on top of the insulation layer. Electrical and thermal contact is established by bonding 25 μm Aluminum or 50 μm Gold wires to the contact pads on the calorimeter and to pads heat sunk to the calorimeter housing.

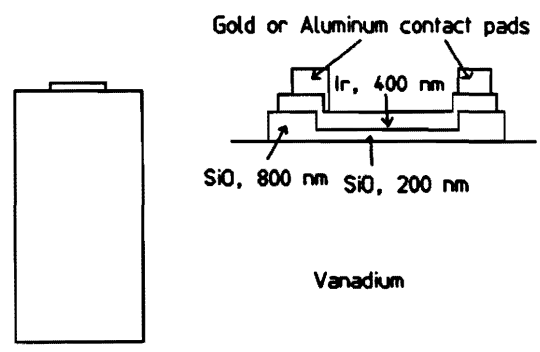

Figure 1. Schematic drawing of the Vanadium absorber crystal and the thermometer structure evaporated onto it.

The calorimeter rests on glass tips glued into copper screws, which in turn are held by the calorimeter housing from tempered OFHC copper. The temperature of the housing is stabilized at the operating temperature of the calorimeter by means of germanium thermistors. The temperature stability is about 1 μK FWHM.

To measure the temperature change of the calorimeter, we employ a current branching

scheme with a dc-SQUID (BTI model 440) measuring the current distribution. The phase transition thermometer is shunted with a reference resistor of 52 mΩ. The normal conducting resistance of the thermometer is 250 mΩ. The SQUID input coil is located either in the branch of the thermometer or in that of the reference resistor. The whole system is biased with a constant current. If the thermometer changes its resistance, the current distribution in these two branches and consequently the current flowing through the SQUID input coil also changes.

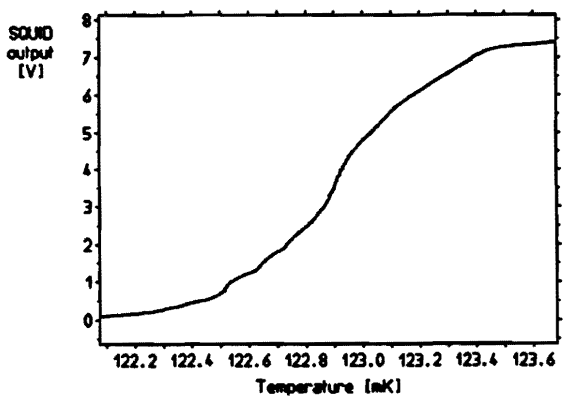

Figure 2. Superconducting to normal conducting phase transition of the Iridium thermometer film on the Vanadium crystal. The picture shows the SQUID output voltage against the temperature of the calorimeter housing.

3. MOLYBDENUM CALORIMETER

The Molybdenum crystal has a mass of 35 g. The insulating layer of SiO does not extend under the whole Iridium thermometer. A part of it has metallic contact with the Molybdenum to make quasiparticle trapping possible. The bonding pads are made of Aluminum. On one side of the thermometer Gold wires provide both electrical and thermal contact to the calorimeter, while on the other side the bonding wires are made of Aluminum, providing thermal insulation.

When irradiating the crystal with a 3-line α-source with energies of 5.1, 5.5 and 5.8 MeV, essentially step-shaped signals are observed. The pulse shape consists of an exponential rise with a time constant $\tau_r = 70\,\mu s$ and an exponential decay with a time constant τ_d of approximately 10 s. The rise time is limited by the time constant of the electric circuit, which arises from the inductance of the SQUID input coil and the combination of the reference and thermometer resistors. The very large decay time can be explained by the high thermal boundary resistance due to the small interface area between the superconducting contact pads made of Aluminum and the Gold bonding wires. A calculation of this "Kapitza" resistance gives a thermal conductance of $8 \cdot 10^{-8}$ W/K, which agrees with the value obtained by dividing the total heat capacity C, calculated from the observed temperature increase, by the decay time τ_d, $g = C/\tau_d \approx 7 \cdot 10^{-8}$ W/K.

The temperature increase due to the absorption of an α particle was measured to be 1.2 μK. Evaluating the heat capacity of the Molybdenum crystal, we would expect a temperature increase of 10 μK, taking into account both the phonon heat capacity with a Debye temperature of $\Theta_D = 423$ K and the electronic heat capacity at the operating temperature of 120 mK. Thus the pulse height is smaller by a factor of eight than expected, which might be attributed to an additional heat capacity of unknown origin.

The energy resolution achieved for 5.8 MeV α particles is 10% FWHM. This corresponds to a temperature resolution of 120 nK, which is comparable to the value of 50 nK reached in earlier experiments with dielectric absorbers [4].

4. VANADIUM CALORIMETER: IRRADIATION EXPERIMENTS

A series of experiments was performed with a Vanadium crystal. In the first experiment, the crystal was not particularly treated, with only front and back polished. Its mass was 17 g. We used the same thermometer structure as for the Molybdenum calorimeter, except that we changed the material of the contact pads from Aluminum to Gold. Thus no "Kapitza" resistance could

develop between the normal conducting bonding pads and the bonding wires, as conduction electrons provide the thermal coupling. Consequently, the pulse decay time was much faster. The pulse height measured when irradiating the crystal with α particles was a factor of 40 lower than expected.

To reduce possible heat capacity contributions from surface impurities, we have tried to clean the crystal. We abraded and etched all faces of the cylindrical crystal until its mass was 15 g. Again a thermometer structure was evaporated on the front side, now with the insulating layer totally separating the entire thermometer film from the absorber crystal (compare Fig. 1). Gold pads were used as contacts.

The crystal was again irradiated on the side opposite the thermometer. The temperature increase due to an 5.5 MeV α particle is now 6.2 μK. Because of the high T_C of Vanadium (5.3 K), the electronic part of the heat capacity can be neglected. From the Debye temperature of 380 K we would expect a temperature increase of 50 μK. The actually measured pulse height is therefore still smaller by a factor of eight than expected from the calculated heat capacity.

The pulse shape consists of an exponential rise with a rise time of $\tau_r = 130\,\mu$s, a fast exponential decay with $\tau_f = 2.3$ ms time constant and a slow exponential decay with $\tau_s = 50$ ms time constant. The amplitude of the fast decaying part is about 50% of the amplitude of the slow decaying component. The slow component constitutes the thermal relaxation of the calorimeter temperature to the temperature of the heat sink, and its amplitude was taken to determine the temperature increase. The fast component could be interpreted as the temperature increase of the thermometer due to the thermalization process mentioned in section 1.

The pulse height spectrum of the measured α pulses is shown in Fig. 3. The three lines are clearly resolved, the resolution is 70 keV or 1.2% for 5.8 MeV α particles. The temperature resolution is now 77 nK. To demonstrate the sensitivity of the Vanadium calorimeter to gamma radiation, we used a ^{60}Co-source outside the cryostat. The resulting spectrum is shown

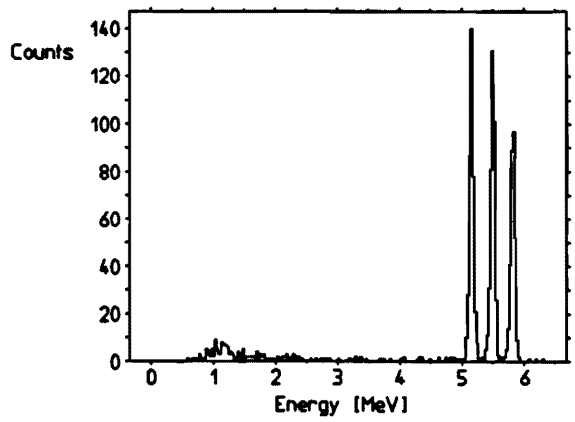

Figure 3. Pulse height spectrum for α particles, taken with a 15 g Vanadium calorimeter. The three α energies (5.1, 5.5 and 5.8 MeV) are clearly separated. The energy resolution is 70 keV.

in Fig. 4. The 1.3 MeV line appears as small peak right from the large background resulting from Compton-scattering off the cryostat materials. The 1.1 MeV line vanishes in this background. Due to increased pile-up, the energy resolution is not quite as good as in the preceeding spectrum.

To study the mechanism which leads to the fast decaying part of the pulses, we employed a second metal film in electrical contact with the Vanadium crystal. After removing the natural oxide, a Platinum film of a thickness of 4000 Å and a size of 1.1 mm × 2.9 mm was sputtered onto the crystal. When irradiating the modified calorimeter with α particles, single α events like the one shown in Fig 5. were observed. Compared to the pulse shape of the preceeding experiment, we could detect no significant change. The presence of the platinum film does not shorten the decay time of the fast component. This is in disagreement with the interpretation of the fast decay time as the phonon thermalization time, as the presence of an additional metal film should speed up the thermalization process.

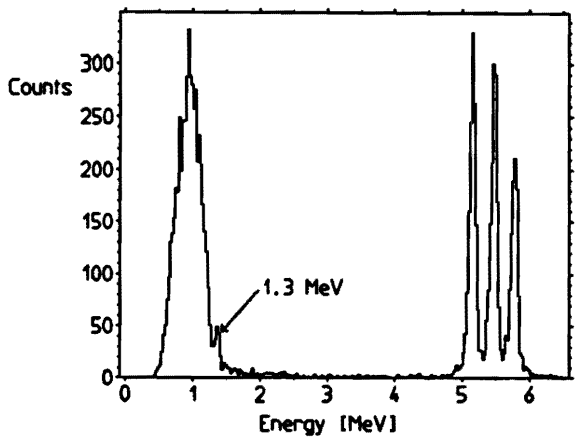

Figure 4. Pulse height spectrum for α and γ irradiation, taken with a 15 g Vanadium calorimeter. The α-source is located inside the cryostat. The ^{60}Co-source is outside the cryostat and causes the large Compton background. The 1.3 MeV γ-line is visible as a small peak right from the Compton background.

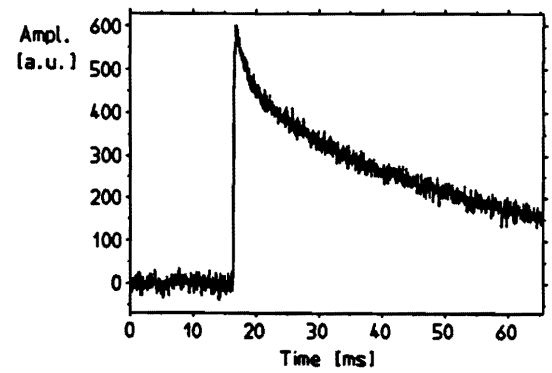

Figure 5. Single α event obtained when irradiating the 15 g Vanadium crystal with a α source. The pulse shape consists of a fast exponential rise with a rise time of $\tau_r = 130\,\mu$s, a fast decay with a time constant of $\tau_f = 2.2$ ms and a slow decay with a time constant of $\tau_s = 50$ ms.

5. HEATER EXPERIMENTS WITH THE VANADIUM CALORIMETER

To further study the thermalization mechanism in the calorimeter, we equipped the calorimeter with an electrical heater. We used a strain-gauge resistor fabricated from a Platinum-Tungsten alloy on a Capton foil. The Capton foil was glued with GE-varnish on the side opposite the thermometer. Electrical contact was established with Nb-Ti superconducting wires of 35 μm diameter, which were soft soldered at both ends. Their thermal conductance is negligible.

We used the heater to measure the thermal coupling of the calorimeter to the heat sink. We applied a current of 1 μA to the heater with a resistance of 112 Ω. The resulting temperature rise of the calorimeter was 43 μK, hence the thermal conductance was g=$2.6 \cdot 10^{-6}$ W/K. Together with the thermal decay time of 50 ms, we calculated a heat capacity of C=$1.2 \cdot 10^{-7}$ J/K from the relation $\tau = C/g$. This value is about 15% smaller than the value of $1.4 \cdot 10^{-7}$ J/K arrived at by dividing the temperature increase due to an α particle by its energy. The discrepancy is compatible with our experimental error. The fact that the measurement of the thermal coupling, the temperature rise due to an α-particle and the thermal decay time fulfill the relations used above proofs that the long decay time really is the thermal relaxation time, and its corresponding amplitude is the temperature of the calorimeter after reaching internal equilibrium.

We then applied current pulses to the heater to test the calorimeter response for nearly thermal phonons. Typical values used were a duration of 10 μs and a current of 20 μA. From the estimated heat capacity of the heater of $1.8 \cdot 10^{-9}$ J/K we concluded that the temperature rise of the heater could be at maximum 250 μK. The pulse shape obtained with this method is slightly different from the preceeding ones. The rise time increases to $\approx 350\,\mu$s, all other parameters stayed the same. The increase of the rise time τ_r can be explained as the thermal relaxation time of the heater film against the calorimeter, as there are three interfaces which cause a high thermal boundary resistance. This pulse shape is now undoubtedly caused by thermal phonons, as the heater cannot create quasiparticles and its temperature rise is small. The fact that an identical pulse shape

is observed, especially that the amplitude ratio of fast and slow component stays the same, is a hint that the phonons arriving at the thermometer have a similar frequency distribution. This implies that the phonons are thermalized in the crystal itself. The pulse shape, i.e. the existence of a fast and a slow decaying component, is therefore not due to the thermalization of high frequency phonons in the thermometer.

An other explanation of the pulse shape can be given by treating the absorber crystal as consisting of two separate heat capacities, namely the phonon system and the hydrogen system. The fast decay would then be interpreted as the reaching of thermal equilibrium between the phonon system, were the energy was initially deposited, and the hydrogen system with its large heat capacity. But, as the magnitude of the thermal coupling between phonon and hydrogen system is unknown, and a controlled change of the hydrogen content of the Vanadium crystal is very difficult, it is hard to proof this interpretation.

Comparing the heat capacity obtained from the pulse height of α particles and from heater pulses, one finds that the heat capacity for α particles is about 10% smaller than for heater pulses, which can be attributed to experimental errors.

This agreement shows clearly that all absorbed energy is converted into phonons in this calorimeter. Especially there are no long-living quasiparticle states which could trap a part of the deposited energy. Whether this is due to intrinsic properties of Vanadium, to its hydrogen content or to the additional Platinum film in electrical contact with the Vanadium crystal, cannot be discerned.

6. CONCLUSION

We have shown that massive calorimeters can be constructed with superconducting absorber materials. In all cases, the measured pulse height is much smaller than expected from the calculated heat capacity. Our experimental work suggests that there may be a contribution to the heat capacity from surface impurities or defects. Other authors [5] have shown that there is a large contribution to the heat capacity in such transition metals in this temperature range caused by dissolved hydrogen.

A comparison between heater pulses and α pulses shows that all the deposited energy is converted into phonons. Also, this comparison leads to the supposition that the thermalization process happens in the Vanadium crystal. Possibly the hydrogen content is responsible for the thermalization.

Regarding the possible energy resolution, it is very encouraging to note that the thermalization is in fact complete, i.e. all the deposited energy is converted into phonons. Therefore no worsening of the energy resolution due to a partition of the deposited energy into different systems storing energy is expected.

REFERENCES

1 D. McCammon, Proceedings of the 6th European Symposium on Semiconductor Detectors, Milano (Italy), February 24-26, 1992, to be published in Nucl. Instr. Meth.

2 D. McCammon, S. H. Moseley, J. C. Mather, R. F. Mushotzky, Jou. Appl. Phys. 56 (1984) 1257.

3 S. B. Kaplan, C. C. Chi, D. N. Langenberg, Phys. Rev. B 14 (1976) 4854.

4 W. Seidel, G. Forster, W. Christen, F. Feilitzsch, H. Göbel, F. Pröbst and R. L. Mößbauer, Physics Letters B 236 (1990) 483.

5 G. J. Sellers, M. Paalanen, A. C. Anderson, Phys. Rev. B 10 (1974) 1912.