Cryogenics 48 (2008) 166–168

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Measurement of thermal conductivity of the supports of CUORE cryostat

M. Barucci, L. Lolli, L. Risegari, G. Ventura *

Dipartimento di Fisica, Universita' di Firenze, Via G. Sansone 1, 50019 Sesto Fiorentino (FI), Italy

ARTICLE INFO

Article history:
Received 3 October 2007
Received in revised form 12 March 2008
Accepted 14 March 2008

Keywords:
Thermal conductivity
Cryogenic supports
Titanium alloy
Stainless steel

ABSTRACT

The CUORE cryogenic system consists of a large cryogen-free cryostat cooled by five pulse tubes and one high-power specially designed dilution refrigerator. About 5×10^3 kg of lead shielding are to be cooled to below 1 K and a mass of 1.5×10^3 kg must be cooled to 10 mK. Several tie-rods are used to support the different parts of the experiment. We have measured the thermal conductivity below 4 K of two candidate materials for the CUORE suspensions: the Ti6Al4V alloy $(k(T) = 0.075 \cdot T \exp(-1.636 \frac{4.38\mathrm{K}}{T})\,[\mathrm{W/m\,K}])$ and the 316LN stainless steel $(k(T) = 0.0556 \cdot T^{1.15}\,[\mathrm{W/m\,K}])$.

1. Introduction

The CUORE (Cryogenic Underground Observatory for Rare Events) [1] experiment uses a large array of detectors for the search of $\beta\beta - (0\nu)$ decay. The detection of the double β decay is done by the measurement of the energy of the electrons emitted in the process. CUORE, to be installed in 2010 at the underground National Laboratory of Gran Sasso (LNGS), consists of a tightly packed array of 988 TeO_2 detectors. The experiment is housed in a large cryogen-free cryostat cooled by five pulse tubes and one high-power specially designed dilution refrigerator [1]. The cryostat is ~3 m high and has a diameter of ~1.6 m. Approximately 5×10^3 kg of lead shielding must be cooled to below 1 K and a mass of 1.5×10^3 kg must be cooled to 10 mK. Several tie-rods are used to support the different parts of the experiment. One end of each rod is at low temperature (10 mK for the detector frame, 50 mK for the coldest radiation shield and lead shield, 700 mK for the radiation shield linked to the refrigerator "still") with the other end usually at room temperature. A thermalization of the rods at the temperature of the first and the second stage of the pulse tubes will be realized. Hence, knowledge of the thermal conductivity of the material up to room temperature is important.

At the lowest temperatures, the thermal conductivity has great influence in establishing the thermal load on the dilution refrigerator. The thermal conductivities of candidate materials available for use in such tie-rods is usually known down to 4.2 K. We have measured the thermal conductivity of two candidate materials for the CUORE suspensions: the Ti6Al4V alloy, below its superconductive transition temperature (4.38 K), and the 316LN stainless steel, below 4.3 K. A comparison over the full temperature range of operation is also done with other materials, such as Torlon and Kevlar, candidates for the realization of the tie-rods.

Titanium alloys are frequently employed in the construction of superconducting magnet support systems for their high mechanical strength associated with their low thermal conductivity [2]. However, their use requires a careful attention to their crack tolerance at cryogenic temperature [2]. Stainless steel 316LN is an austenitic SS with 18% of Cr and 8% of Ni. The presence also of 2–3% of molybdenum assures a good corrosion resistance. The 316-type steels are replacing the formerly used 304-type steels in recent applications. SS 316LN, for example, is one of the leading candidates for next-generation tokamaks such as the International Thermonuclear Experimental Reactor (ITER) [3,4].

2. Experimental technique and measurements

The thermal conductivity of the two materials was measured by the longitudinal steady heat flow method. A known power P was supplied to one end of the sample to establish a difference of temperature $T_1 - T_0$ between the ends of the sample. By derivation of the integrated power (at constant T_0)

$$P(T_1) - P(T_0) = \frac{S}{L}\int_{T_0}^{T_1} k(T)\mathrm{d}T = g\int_{T_0}^{T_1} k(T)\mathrm{d}T \qquad (1)$$

the thermal conductivity $k(T)$ was obtained. The dimensions and the shape of the titanium alloy sample are show in Fig. 1. The sample along which the gradient of temperature is produced has a length $L = 76.5 \pm 0.1$ mm. At room temperature, the form factor is

---

* Corresponding author. Tel.: +39 055 4572291; fax: +39 055 4572122.
E-mail address: ventura@fi.infn.it (G. Ventura).

0011-2275/$ - see front matter
doi:10.1016/j.cryogenics.2008.03.018

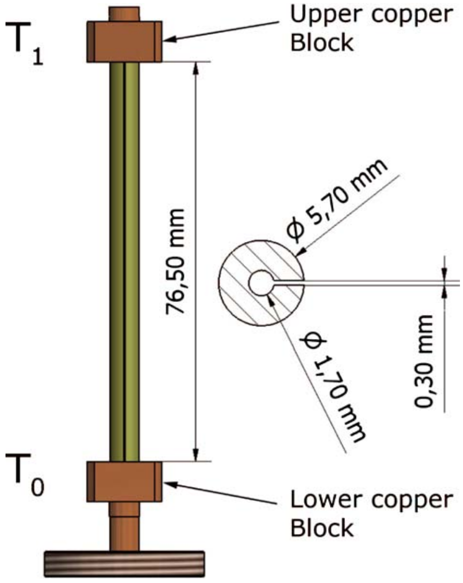

Fig. 1. Shape and dimensions of the titanium alloy sample at our disposal.

$g = \frac{S}{L} = 0.295 \pm 0.003$ mm, where $S = 22.6 \pm 0.2$ mm^2 is the section area of the sample.

The thermal contacts at the ends of the sample have been realized by means of two copper blocks and two copper screws 3 mm in diameter. Since the thermal contraction of titanium is lower than that of copper [5], the thermal contact between the blocks and the two ends of the sample becomes better on cooling. A SMD (surface mount device) NiCr heater and a RuO_2 thermometer were glued onto the two copper blocks at the ends of the sample (see Fig. 1).

The upper electrical connections to the heater and to the thermometer were made with NbTi wires. The NbTi wires (∅25 μm) were electrically connected by tiny crimped Cu tubes. At the ends of the NbTi wires a four lead connection was adopted. The bottom copper block was screwed onto a copper support in thermal contact with the mixing chamber of a dilution refrigerator. The two RuO_2 calibrated thermometers were used for the measurement of T_1 and T_0. The thermometers were calibrated by means of a SRD 1000 (superconductive reference device) and a NBS-SRM 767a fixed point device [6–8]. A copper shield, in thermal contact with the mixing chamber of the dilution refrigerator, surrounded the experiment. An AVS 47 a.c. resistance bridge for the thermometer and a four wire *I–V* source for the heater were used.

A similar experimental configuration and measuring technique were used for the stainless steel conductivity measurements. The shape of the sample of SS 316LN was a cylinder with $d = 5.00 \pm 0.01$ mm of diameter and an effective length $L = 82.6 \pm 0.1$ mm. In this second measurement the same thermometers and heater were used.

To control that the contact thermal resistances could be neglected, a second run of measurement was carried out on both materials with a different geometrical factor (about the double). Within the experimental error, the same values of thermal conductivity were obtained in the overlapping temperature range.

3. Results and conclusions

For both samples a $P(T_1)$ plot was obtained (see formula (1)). The thermal conductivity was obtained by derivation by $P(T_1)/g$.

Ti6Al4V is a superconducting material. The critical temperature T_C was obtained by a measure of mutual inductance: a small titanium alloy sample was placed inside a transformer. T_C is about 4.38 K, in good agreement with the data reported in Ref. [9]. This is an important information for $k(T)$ measurements.

The measured thermal conductivity of Ti6Al4V in the 55 mK–3 K temperature range is shown in Fig. 2. The correction due to the thermal contraction ($\Delta g/g < 0.2\%$) was neglected [5]. Data of $k(T)$ are fitted by the formula

$$k(T) = A \cdot T \exp\left(-b\frac{T_C}{T}\right) = 0.075 \cdot T \exp\left(-1.636\frac{4.38\ \mathrm{K}}{T}\right) [\mathrm{W/m\ K}] \qquad (2)$$

There is a good match between our data and data of $k(T)$ for temperature $T > 4$ K reported in the literature [9].

The thermal conductivity of the stainless steel 316LN in the 45 mK–4.3 K temperature range is shows in the Fig. 3. Data of $k(T)$ are fitted by the formula

$$k(T) = A \cdot T^n = 0.0556 \pm 0.0006 \cdot T^{1.15\pm0.01} [\mathrm{W/m\ K}] \qquad (3)$$

For the low temperature range (below 220 mK) $k(T)$ shows only the linear electronic contribution (see Fig. 4)

$$k(T) = A \cdot T^n = 0.0495 \pm 0.0004 \cdot T^{1.048\pm0.004} [\mathrm{W/m\ K}] \qquad (4)$$

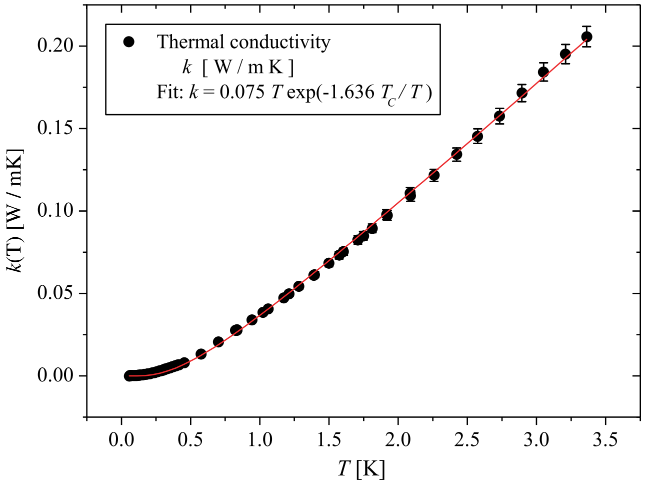

Fig. 2. Thermal conductivity of Ti6Al4V in the 55 mK–3 K temperature range. The full line represents the fit of Eq. (2).

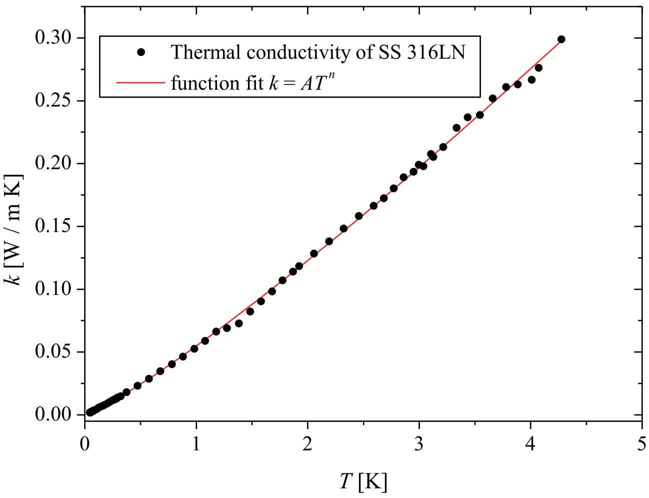

Fig. 3. Thermal conductivity of SS 316LN in the 45 mK–4.3 K temperature range. The full line represents the fit of Eq. (3).

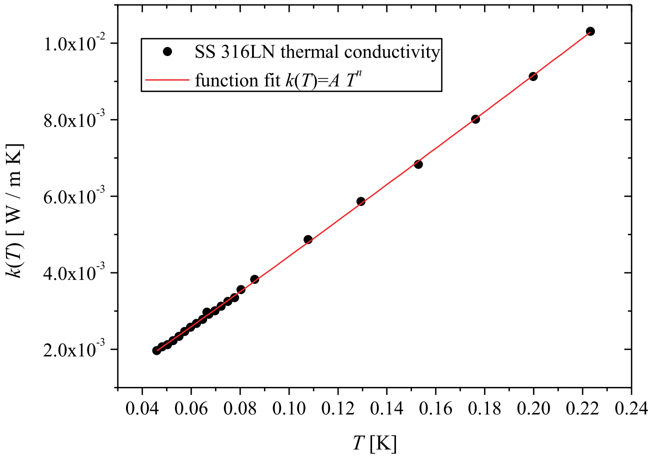

Fig. 4. Linear thermal conductivity of SS 316LN in the low temperature range. The full line represents the fit of Eq. (4).

Around 4 K there is a very good match between our data and data of $k(T)$ for temperature $T > 4$ K of NIST (National Institute of Standards and Technology).

There are three main contributions to the relative error in $k(T)$:

- the power supplied to the sample: we can estimate that the relative error of P is of the order of $\sim$0.1%;
- the measurement of the form factor g. The error in the measurements of g has been estimated as 1%;
- the uncertainty on the temperature due to the accuracy of the thermometers in this temperature range. A conservative value of $\frac{(\Delta T)}{T}$ is $\sim$2% for $T > 1$ K and $\sim$1% for $T < 1$ K.

Taking into account these contributions, the maximum relative error in $k(T)$ is about 3%.

In Fig. 5 the thermal conductivity of Ti6Al4V and SS 316LN up to room temperature is compared with other candidate materials for the CUORE supports [9–12]. From a purely thermal point of view, the Ti6Al4V alloy is a very good candidate for the realization of the supports. The choice of the tie-rod materials will be done on the base of both thermal data and mechanical data.

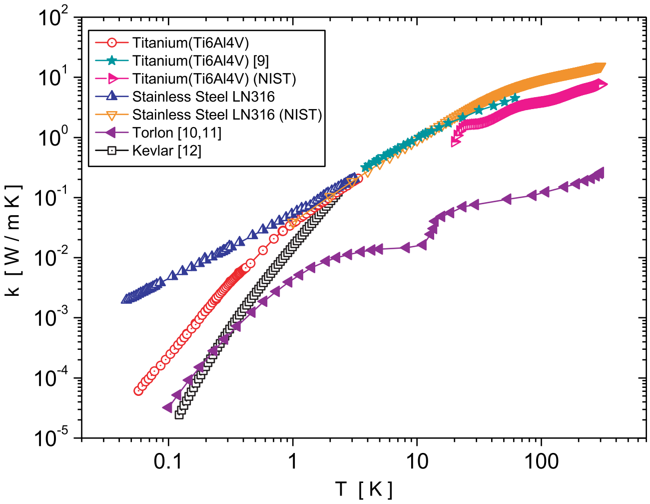

Fig. 5. Thermal conductivity of Ti6Al4V and of SS 316LN compared with other candidate materials for the CUORE supports [9–12].

References

[1] Ardito R et al. CUORE: a cryogenic underground observatory for rare events, http://www.arxiv.org/abs/hep-ex/0501010; 2005.
[2] Reytier M, Kircher F, Levesy B. In: Advances in cryogenic engineering: proceedings of the international cryogenic materials conference – ICMC, AIP conference proceedings, vol. 614; 2002. p. 76.
[3] Summers LT, Miller JR, Heim JR. Adv Cryo Eng Mater 1990;36:769–76.
[4] Bulanova T, Fedoseev A, Kalinin G, Rodchenkov B, Shamardin V. J Nucl Mater 2004;329–333(1):639–42.
[5] Marquardt ED, Le JP, Radebaugh R. In: Ross Jr RG, editor. Cryogenic material properties database, vol. 11. Cryocoolers: Springer US; 2002. p. 681.
[6] Bosch WA et al. In: Fellmuth B et al., editors. Proceedings of TEMPMEKO, vol. 397. Berlin: VDE Verlag; 2001.
[7] Schottl S et al. J Low Temp Phys 2005;138:941.
[8] Schooley JF, Soulen Jr RJ, Evans Jr GA. NBS special publication 260-44. Washington, DC: US Govt. Printing Office; 1972. p. 1–35.
[9] Umezawa O, Ishikawa K. Cryogenics 1992;32(10):873.
[10] Barucci M, Olivieri E, Pasca E, Risegari L, Ventura G. Cryogenics 2005;45(4):295.
[11] Ventura G, Bianchini G, Gottardi E, Peroni I, Peruzzi A. Cryogenics 1999;39(5):481.
[12] Ventura G, Barucci M, Gottardi E, Peroni I. Cryogenics 2000;40(7):489.